FOREST BIOMASS IN BRAZILIAN AMAZÔNIA: COMMENTS ON THE ESTIMATE BY BROWN AND LUGO

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The article "Biomass Estimates for Tropical Moist Forests of the Brazilian Amazon" by Sandra Brown and Ariel Lugo (1992), Vol. 17: (1) presents valuable information on forest volume and biomass with a view to estimating greenhouse emissions from deforestation. Particularly important are the data these authors present from summaries of the inventories done by the RADAMBRASIL Project (Brazil, Projeto RADAMBRASIL, 1973-1983). However, adjustments are needed to compensate for a number of problems affecting the way the biomass estimate is derived and the portions of the biomass to which it applies. Some of the omitted factors tend to exaggerate biomass, while a more powerful set of factors tends to underestimate it. The net result of these is to increase the biomass estimate by over 80% for purposes of greenhouse calculations for the dense forests to which the Brown and Lugo estimate applies.

Brown and Lugo's paper uses 420 million hectares as the area of forest in the Legal Amazon — but this is not the same as the "dense forest" category to which the biomass estimates apply. Deforestation rates specific to dense forest would be needed in order to make the biomass estimates of Brown and Lugo usable for greenhouse calculations. In addition, calculating emissions from the region would require estimates of biomass and rate of clearing for vegetation types other than dense forest.

On the high side, Brown and Lugo's estimate only includes forest types classified as "dense" forest. Dense forests make up only half of the forests of the Brazil's 5 x 10^6 km^2 Legal Amazon Region. The average biomass of the forests in the region as a whole is lower than that of dense forests alone. If valid calculations are to be made of greenhouse emissions, estimates are needed of both forest biomass and deforestation rate, and these estimates must refer to the same type of vegetation and to the same location (such as Brazil's Legal Amazon Region). Inconsistencies in these respects between existing estimates of deforestation and the biomass values calculated by Brown and Lugo prevent direct use of the biomass data presented by these authors.

Also on the high side, Brown and Lugo make biomass estimates for dense forest in approximately 70% of the Legal Amazon. The result gives the impression that clearing in the portion of the region for which Brown and Lugo lack data is to be ignored. Considering only forests (i.e. excluding scrub savanna or *cerrado),* slightly over half (53%) of the 1988 deforestation took place along the southern fringe of the Legal Amazon in the states of Mato Grosso, Tocantins and Maranhão — outside of the area to which Brown and Lugo's data apply (Fearnside 1990a). The southern part of the region has more of the less-dense forest types: the average biomass of forest cleared in 1988 (weighted by state deforestation rate) was 15% lower than the average biomass of forests in the Legal Amazon as a whole (Fearnside, 1990b, 1991). Georeferencing of the volume data is needed to minimize bias in applying the resulting biomass numbers to greenhouse calculations. This is underway at INPA.

Destructive Versus Volume-Based Methods

Brown and Lugo criticize use of measurements from direct weighing of biomass. The consistently higher values produced by direct measurements are attributed to ecologists being biased (presumably unconsciously) in their selection of study sites, with a tendency to select forests that are both less

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disturbed and of higher biomass in their pristine state than the average over a wider geographical region. This explanation is, in the least, incomplete. In reality, there *is* tremendous variation in forest biomass, even within a single forest type. This high variation adds to the potential for error from small sample sizes — a sufficient explanation without invoking investigator bias. Both direct and volume-based approaches have valuable contributions to make.

Brown and Lugo are quite correct in pointing out the need for volume-based estimates in order to obtain average biomass values for an area as large and diverse as Brazilian Amazônia. The amount of work would be prohibitive were direct methods used to obtain a sample with representativeness even approximating that in already-existing surveys based on forest volume. (a)

Direct weighing of biomass provides information that is different from, but equally important as, data from forest volumes. While volume achieves representativeness for regional estimates of carbon stocks, direct measurements are essential for quantifying the transfers of carbon into different compartments, such as greenhouse emissions, charcoal, and unburned remains subject to decomposition (*e.g.* Fearnside *et al.*, nd-a).

Direct measurements also provide a sort of "ground truth" for calibrating the volume-based measurements of intact forest. They provide important information on components other than large tree trunks — and, as is the case here, can indicate probable problems in the correction factors used (or not used) to adjust for these components. When differences between direct and indirect estimates are large, they can reveal problems with the volume calculation methodology. For example, when Brown and Lugo (1984: 1291) published an estimate of 155.1 metric tons per hectare (MT/ha) for average total biomass (including below-ground (in undisturbed productive broad-leafed closed forests of the New World tropics — less than half what anyone had found who had weighed biomass directly in Amazônia — it was clear that something was wrong with the volume-based estimate (as pointed out by Fearnside, 1986, 1987). This indeed turned out to be the case — Brown *et al.* (1989: 897-898) later found errors in the conversion factors they had used to calculate biomass from volume, resulting in an increase in the estimate by 28 to 47%. Among the changes that account for this are an increase in the volume expansion factors used to account for trees in the size range between 10 cm diameter at breast height (DBH) and the 25 cm minimum in the FAO forest inventories (1.2 used by Brown and Lugo, 1984, 1292 versus 1.22 used by Brown and Lugo, 1991), and an increase in the average wood density (from 0.62 g/cm^2 used by Brown and Lugo, 1984: 1291 to 0.69 used by Brown and Lugo, 1991). "Wood density" refers to "basic specific gravity", or oven-dry weight divided by wet volume.

TABLE I

ADJUSTMENTS TO BIOMASS ESTIMATES OF BROWN AND LUGO

Factor	*Correction multiplier*	*Percent adjustment*
Adjustments to above-ground live biomass:		
Hollow trees	0.9077	—9.23
Vines	1.0425	4.25
Other non-tree components	1.0021	0.21
Palms	1.0350	3.50
Trees < 10 cm DBH	1.1200	12.00
Trees 30-31.8 cm DBH	1.0360	3.60
Bark (volume & density)	0.9856	—1.44
Sapwood (volume & density)	0.9938	—0.62
Form factor	1.1560	15.60
Net Adjustment to Live Above-Ground:	1.2787	27.87
Adjustments for other components:		
Dead above-ground biomass:	1.0903	9.03
Below-ground:	1.3428	34.28
Net Adjustment for Other Components:	1.4331	43.31
TOTAL ADJUSTMENT:	1.8325	83.25

NOTE: the adjustments to above-ground live biomass are with respect to the biomass values as defined by Brown and Lugo, while the adjustments for other components are with respect to above-ground live biomass after the above corrections.

The revised estimates include only live above-ground biomass, but, since the other components are calculated as fixed proportions of the total, the total will increase by the same percentage. Brown and Lugo (1984) derived the 155.1 MT/ha value by multiplying above-ground live biomass by a factor of 1.16 (Brown and Lugo, 1989: 882). The switch from presentation of the absolute number from *total* live biomass (155.1 MT/ha for tropical America) to *above-ground* live biomass (268 MT/ha for Brazil based on the same FAO surveys that formed the basis of the earlier estimate) tends to mask the magnitude of the difference between these, which is a factor of two (133.7 versus 268 MT/ha considering only the above-ground portion. This increase in the Brown and Lugo estimate has now greatly reduced the differences between my estimates (290 MT/ha for dense forests above-ground live biomass) and theirs (162 MT/ha from RADAMBRASIL and 268 MT/ha from FAO surveys).

Improving Volume-Based Estimates

Despite the implication by Brown and Lugo that all difficulties have been overcome in the use of forest volume data, a number of areas of doubt remain in the conversion of volume to biomass. The forest volume datasets and the methods used to convert these to biomass estimates can be changed through a variety of adjustments to make them better fit our understanding of the forests and how they are measured.

Some aspects of the method for obtaining biomass from volume data lead to overestimation for the forest types to which the estimates can legitimately be applied. Large trees are frequently hollow. Certain species, such as angelim pedra *(Dinizia exelsa)* are virtually always hollow. Brown and Lugo calculate biomass by multiplying volume by wood density (as determined from small samples of solid wood). In forests near Manaus, Niro Higuchi and coworkers (N. Higuchi, personal communication, 1991) have found 27% of the trees with diameter at breast height (DBH) greater than 40 cm to be hollow (N = 486 trees); when a tree is hollow, about 30% of its stem volume is either air or light material such as debris from termite activity. Weighting the hollow percentage by the volume in each size-class leads to the conclusion that the overestimate as a whole from this factor is 9.2% for the RADAMBRASIL dataset. (b) For comparison, Martinelli *et al* (1988: 35) examined 53 stumps in a clearing near the Samuel Reservoir in Rondônia and found 20% to be hollow, with an average of 20% of the cross-sectional area empty in the hollow stumps *(i.e.* 4% of the total cross-sectional area and presumed volume).

Wood density is an important factor in converting volume data to biomass. Unfortunately, data are unavailable for many Amazonian tree species, making use of average values necessary — at least for the substantial portion of the forest that is invariably composed of species of unknown density. Most of the available datasets on wood density contain an inherent downward bias because one of the criteria used for inclusion of species in the surveys is wood density being in a range preferred by the timber industry. This is explicitly mentioned in the case of surveys done by the Brazilian Institute for Forestry Development (IBDF) in the Curuá-Una and Tapajós areas in Pará. In the Tapajós survey "species with values between 0.30 and 0.70 g/cm^3 were selected" although "some species with density greater than 0.70 g/cm^3 were also considered, due to their frequent occurrence" (Brazil, IBDF, 1981: 15). By deliberately excluding species with high densities, the average is artificially low. It is possible that this generic problem affects the U.S. Forest Service dataset (Chudnoff, 1980) that served as the source of most of the density values used by Brown and Lugo.

Published density measurements almost invariably refer to the density of heartwood, as this is of most interest to the timber industry and is where almost all wood samples are taken (Jadir de Souza Rocha, personal communication, 1991). Most of the sapwood (alburnum) is lost when logs are squared in preparation for sawing into lumber. For biomass estimates for greenhouse calculations, however, the density of the sapwood is also important. Unlike many temperate zone trees, the sapwood of Amazonian trees is, on average, lighter than the heartwood. For 15 Amazonian species for which data are available (Departamento de Engenharia, Centro de Pesquisas de Productos Florestais, INPA, unpublished data), the average basic density of the sapwood was 7.6% lower than that of the heartwood. For 13 species studied at Jari the density of sapwood was 2.9% lower than heartwood (Reid, Collins and Associates Limited, 1977). The correction for sapwood, considering the average differences in mean basic density data from the studies at Manaus and Jari given above, indicates an adjustment lowering the biomass estimate by 0.6%. The adjustment would be greater for trees below the size range included in the RADAMBRASIL forest volume surveys, but data are unavailable for making this adjustment. (c)

Bark is another factor for which an adjustment must be made. Brown and Lugo (1991) mention that the volume data used refer to VOB (volume over bark), but do not indicate that any correction was applied for the difference in density between bark and wood. It is worth noting that most results are presented in the summary tables of the original RADAMBRASIL publications as volume without bark; if the source from which Brown and Lugo worked (a letter to FAO summarizing the RADAMBRASIL results) reproduced the results in this form, then an additional adjustment would be needed for the full volume of the bark (an increase of 7.69% with respect to the volume without bark, using the standard adopted by the RADAMBRASIL project for deriving the volumes without bark from the original overbark measurements).

The basic density of bark averages about 80% that of the wood, based on approximately 40 trees near Manaus (Dimas Agostinho da Silva, personal communication, 1991). The percent of above-ground live dry-weight biomass represented by bark averaged 7.22% in dense forest destructive sampling plots at four hydroelectric reservoir sites in the region: 6.32% in dense riparian forest at Belo Monte (Kararaô) (Revilla Cardenas, 1987, p. 51), 6.57% in dense riparian forest at Babaquara (Revilla Cardenas, 1988, p. 76), 4.58% in terra firme forest at Babaquara (Revilla Cardenas, 1988, p. 77), and 11.41% in dense terra firme forest at Samuel (Revilla Cardenas, 1986, p. 39). These values include bark from branches, except for fine twigs. For comparison, RADAMBRASIL reports the volume of commercial boles without bark calculated by lowering the form factor from 0.70 to 0.65 (equivalent to 7.1% of the volume being bark) (Brazil, Projeto RADAMBRASIL, 1980, Vol. 20, Annex p. 15). In San Carlos de Rio Negro (Venezuela), Jordan and Uhl (1978) found 9.7% of stem biomass to be bark (NB: trees at this site are generally thinner than those in Brazilian Amazônia, which would make the proportion of bark found there overestimate this factor for Brazil). Using the average of the hydroelectric reservoir studies of dense forest, adjustment for density and volume bark would reduce the above-ground live biomass by 1.44%. At the Tapajós National Forest, bark averaged 4.8% of the cross-sectional area (and presumed volume) in 50 tree species surveyed (Brazil, IBDF, 1988).

One factor that acts to make Brown and Lugo's biomass estimate too low is the criterion used in the RADAMBRASIL studies for inclusion of trees in the surveys (Brazil, Projeto RADAMBRASIL, 1973: Vol. 5, p. IV/12). Although the reports present volume data in 10 cm DBH ranges starting with 30 cm DBH, the minimum size of the trees included in the field measurements was one meter circumference at breast height (CBH), which is equivalent to 31.8 cm DBH. Based on the volumes by size class found at INPA's Model Basin site (Coic *et al.*, 1991), the 30-31.8 cm size range represents 3.6% of the commercial volume in trees over 30 cm DBH, indicating that the RADAMBRASIL volumes should be adjusted upward by this amount.

Another factor making the biomass estimate lower than it should be is the form factor used by the FAO and RADAMBRASIL studies to convert tree diameter and height data into forest volumes. The volume of the cylinder described by the diameter at breast height (1.3 m above the ground or above the buttresses if these structures are higher than this level), and the height of the commercial bole (distance from the ground to the first branch) is converted to the volume of the commercial bole by multiplying by a form factor. The value for this used by both the FAO and RADAMBRASIL surveys was 0.70 — a standard

TABLE II

SUMMARY OF RADAMBRASIL FOREST VOLUME DATA

RADAMBRASIL VOLUME ("Grid cell")		*Forest areas reported by RADAMBRASIL (Km^2)*		*Volume over bark (area-weighted average calculated from RADAMBRASIL data) (m^3/ha)*		*Dense forest Biomass calculated by Brown and Lugo (MT/ha)*	*Dense forest total biomass with adjustments in Table I: 1.8325 X Column 7*	*Non-dense forest total biomass (MT/ha): 3.0822 X · Column 6*
number	*name*	*Dense*	*Non-dense*	*Dense (a)*	*Non-dense (b)*			
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*
4	Araguaia					202	370	
5	Belém			147	113	209	383	348
6	Amapá			176	110	295	541	339
7	Tapajós				101	187	343	310
8	Boa Vista		4,611		75	142	260	230
9	Tumucumaque				110	197	361	338
10	Santarém					185	339	
11	Pico da Neblina	8,477	1,196	81	102	106	194	313
12	Rio Branco	44,820	131,279	126	100	188	345	309
13	Javari/Contamana	12,700	60,625	103	101	181	332	310
14	Içá	86,052	81,785	113	111	134	246	341
15	Juruá	127,330	153,684	128	127	192	352	390
16	Porto Velho	30,235	199,485	134	112	190	348	344
17	Purus	192,333	73,724	129	108	180	330	332
18	Manaus	79,486	75,351	112	56	128	235	172
19	Guaporé	2,578	36,346	56	96	84	154	296

(a) Volumes 11, 12 and 13 unweighted mean.
(b) Volumes 5 and 11 unweighted mean.

value used in many studies but not one based on data from Amazônia. In fact, the form factor varies by diameter class (as well as by species and forest type). Form factors for 309 trees felled and measured in INPA's Model Basin study area range from 0.7708 for trees of 70 cm DBH or more to 0.8144 for trees in the 10-14.9 cm DBH class (Niro Higuchi and coworkers, unpublished data). The average for this forest (on the ZF-2 road 60 km north of Manaus) weighted for the volume in all size classes over 10 cm DBH is 0.7806; when weighted by volumes in size classes over 25 cm DBH (comparable to the FAO data) the form factor is 0.7778 (an 11.1% increase over the 0.70 value), and when weighted by volumes in size classes over 31.8 cm DBH (comparable to the RADAMBRASIL data) it is 0.8092 (15.6% greater than the 0.70 value).

Brown and Lugo define biomass as "the total above-ground living biomass in trees of diameter 10 cm or larger." This is not what most people think of when they hear the term "biomass," and defines away a number of components that are important in carbon calculations. One such category is trees < 10 cm DBH. Size-specific data are few for trees in this range. At a site in San Carlos de Rio Negro (Venezuela), Jordan and Uhl (1978: 392) found that dry-weight biomass in the 0-10 cm DBH range represented a quantity 12% as large as the above-ground live total for the diameter range considered by Brown and Lugo (> 10 cm DBH). This probably represents an overestimate for Brazilian Amazônia, as the trees at the Venezuelan site are, in general, thinner than those in Brazilian forests. Data more representative of forests in Brazilian Amazônia are lacking however.

Although Brown and Lugo state that the volume data refer to "all trees," the species lists published in the FAO and RADAMBRASIL reports reveal that neither survey included palms. The abundance of palms varies greatly in Amazonian forests. At the Egler Reserve near Manaus. Klinge *et al.* (1975: 116) found palms to represent only 0.3%

of the above-ground live biomass (fresh weight basis, but presumably approximately representing dry-weight proportions), while at Altamira (Pará) palms represent 6.7% of above-ground total biomass (Fearnside *et al.*, nd-b). Using the midpoint between these percentages as a rough approximation of the percentage of palm biomass, the biomass estimates should be increased by 3.5% due to this factor.

Another factor making the Brown and Lugo study underestimate biomass is the treatment of non-tree components of the live biomass (understory and vines). These are dismissed as "less than 2% of total (live) biomass" by Brown and Lugo (1984: 1291), and are left out of the calculation. No data are presented to justify the low percentage attributed to these components. In Brazilian Amazônia the percentage of total biomass represented by vines is extremely variable, and is sometimes quite high. Near Manaus we have found 3.1% of the total above-ground biomass (live+dead) dry-weight to be vines (Fearnside *et al.*, nd-a), or approximately 2.8% of above-ground live biomass. On the Transamazon Highway 50 km west of Altamira (Pará), vines represent 11.5% (Fearnside *et al.*, nd-b), or approximately 10.5% with respect to above-ground live biomass. In an area near Manaus, Klinge *et al.* (1975) found approximately 5.7% of the above-ground total (live+dead) biomass dry-weight to be vines, or 6.2% of the above-ground live biomass. (d) Data from studies in hydroelectric reservoir sites indicate percentages of vines with respect to above-ground live biomass of 1.5% at Belo Monte (formerly known as Kararaô) (Revilla Cardenas, 1987: 51), 1.2% at Samuel (Revilla Cardenas, 1986: 39), 3.3% in dense riparian forest at Babaquara (Revilla Cardenas, 1988: 76) and 4.6% in terra firme forest at Babaquara (Revilla Cardenas, 1988: 77). The average of these values, 4.3%, appears to be reasonable as an adjustment for vines as a percentage of above-ground live biomass for the region's dense forests.

Other non-tree components are only a very minor part of the above-ground live biomass: parasites and epiphytes represent 0.03% and trees < 1.5 m in height represent 0.19% (calculated from Klinge *et al.*, 1975: 116): It should be remembered, however, that strangler figs are a significant component of the biomass in many locations; the low proportion of parasites in the study by Klinge *et al.* (1975) is probably not an adequate reflection of their regional importance.

TABLE III

CURRENT BEST ESTIMATE FOR FOREST BIOMASS IN THE BRAZILIAN LEGAL AMAZON

State	*Area originally forested (km² x 10³)* (a)			*Forest biomass (MT/ha) (total biomass: above + below ground, live + dead)*		
	Dense	*Non-dense*	*All forests*	*Dense forests*	*Non-dense*	*All forests*
Acre	24	130	154	345	309	315
Amapá	111	6	117	541	339	530
Amazonas	969	579	1,548	293	285	290
Maranhão	95	546	642	194	150	157
Mato Grosso	25	546	571	194	83	88
Pará	764	425	1,189	365	398	376
Rondônia	172	43	215	268	332	280
Roraima	123	62	185	260	237	253
Tocantins	21	37	58	194	83	123
Total	2,303	2,375	4,678	320	226	272

(a) Forest areas measured from the IBAMA 1:5,000,000 scale vegetation map (Brazil, IBAMA, 1988) by N. Bliss.

(b) Non-dense forest biomass calculated from volumes estimated from RADAMBRASIL as follows with weighting by approximate area of coverage: Amazonas (Vols. 7, 8, 11, 12, 13, 14, 17, 18); Amapá (Vol. 6); Pará (Vols. 5, 7, 9); Rondônia (Vols. 16, 19); Roraima (Vols. 8, 9, 18); Other states from Fearnside 1990b.

A major factor lowering the biomass estimate is its restriction to live above-ground components. Dead biomass and roots are ignored, although earlier estimates (Brown and Lugo, 1984) included roots. The omission is justified by the lower reliability of data on these components (Brown *et al.*, 1989: 899). Based on the study of Klinge *et al.* (1975) near Manaus the below-ground biomass is a quantity 34.3% as large as the above-ground live biomass.

Brown and Lugo (1984) used a relationship of 16% for calculating below-ground biomass from above-ground live biomass (NB: the conversion factor used for roots is not separated from other non-stemwood components in the original publication, but is explained in Brown and Lugo, 1989: 882). This percentaje (16%) is roughly half the value (34.3%) measured near Manaus by Klinge *et al.* (1975). The basis for the percentage used by Brown and Lugo (1984) is not given, but the sources used for deriving the conversion factor lumping roots with non-stemwood above-ground biomass indicate Asian sources for tropical wet and moist forests. The low conversion factor used by Brown and Lugo (1984) for calculating root biomass contributed to the very low total (above + below ground) live biomass they found (151.1 MT/ha).

The same study (Klinge *et al.*, 1975) indicates that the dry-weight of dead biomass (excluding soil organic matter, which was included in this category in the original study) is a quantity 9.2% as large as the dry weight of above-ground live biomass. (d) Studies in dense forests at hydro-electric reservoir sites indicate total dead dry-weight biomass (wood + litter) as a percentage of the above-ground live dry-weight to be 10.5% at Belo Monte (formerly Kararaô) (Revilla Cardenas, 1987: 51), 3.9% at Samuel (Revilla Cardenas, 1986: 39), and 7.7% and 10.7% respectively in dense riparian forest and terra firme forest at Babaquara (Revilla Cardenas, 1988: 76-77). At the Samuel Reservoir in Rondônia, Martinelli *et al.* (1988: 35) found dead biomass equivalent to 12.2% of the above-ground live biomass. The average of these percentages, 9.0%, can serve as an adjustment for dead above-ground biomass.

Dead biomass is particularly important for emissions from burning because of its much greater flammability relative to the wood of trees that were living until they were felled shortly before the burn. In three sites near Altamira (Pará), for example, litter (including leaves and dead wood < 10 cm in diameter) made up an average of 11% of the dry-weight of pre-burn above-ground material, but accounted for 22% of the material that disappeared (presumed combusted) when the sites were burned (Fearnside *et al.*, nd-b).

The release of carbon is related to the difference in the *total* stocks before and after the conversion — including the dead and underground components. When forest is cleared and the land converted to other uses (mostly cattle pasture in the Brazilian Amazon), these components either burn or decompose. Estimates for these less-well-quantified components have to be combined with the Brown and Lugo data if valid greenhouse calculations are to be made.

In addition to emissions from reduction of biomass stocks when forest is converted to other uses, emissions also occur from the carbon pools in the soil. These calculations are done separately (*e.g.* Fearnside, 1985), and must also be included in global carbon budgets. Although the soil carbon is large (Post *et al.*, 1982), only a portion is released. Including soil carbon releases from the top 20 cm of soil results in increases of about 4% in the total amount of carbon released by conversion to cattle pasture (Fearnside, 1987).

A Current Best Estimate for Biomass

Where do we stand, then, with respect to biomass estimates for the forests of the Brazilian Amazon for purposes of greenhouse calculations? The factors outlined in the foregoing discussion indicate that the biomass data as presented by Brown and Lugo should be adjusted by the factors presented in Table I. The upward adjustments to above-ground live biomass represents a combined increase of 39.2%, while the combined downward adjustments represent 11.3%; taken together, the net adjustment to the above-ground live biomass estimates of dense forest is an increase by 27.9%. It should be remembered that two additional adjustments that are probably needed but are not included here would raise the estimate: 7.7% for bark if volumes were in fact "under bark," and an unquantified adjustment for the tree selection bias in the wood density dataset.

For use in greenhouse calculations one must add dead biomass (9.0% with respect to above-ground live biomass) and below-ground biomass (34.3%). The total biomass (above-and below-ground live and dead) can be determined from the adjusted above-ground live biomass by multiplying by 1.43, or from the values reported by Brown and Lugo by multiplying by 1.83.

The values for dense forest biomass derived as above can be incorporated into the data-set for all forest types (Fearnside, 1990a, 1991). Biomass for non-dense forests is calculated from forest volume data for these forest types in the RADAMBRASIL surveys where this information is available. Non-dense forest volume is obtained using the same assumptions given for dense forests (Table I), the wood density of 0.69 used by Brown and Lugo, the volume expansion factor of 1.22 used by Brown and Lugo for trees in the 10-25 cm DBH range, a factor of 1.097 to account for trees in the 25-30 cm DBH range (based on the INPA Model Basin study: Coic *et al.*, 1991), and the conversion factor of 3 derived by Brown and Lugo (1984: 1291) to convert stemwood volume (for trees at least 10 cm (DBH) to what these authors refer to as "total biomass" (above + below ground for live trees in this diameter range) for open forest. The combined conversion factor for non-dense volume (m^3/ha) as reported by RADAMBRASIL to total (above + below ground, live + dead) biomass (MT/ha) is 3.08. None of the conversion factors used in the calculation for non-dense forests can be considered satisfactory, but the rough approximations they yield are superior to the defacto alternative: assuming that greenhouse emissions are limited to dense forests.

Area-weighted values are presented by RADAMBRASIL volume in Table II, and approximate allocations by state are presented in Table III. Dense forest total biomass averages 320 MT/ha. Dense forests, however, represent only half (49.3%) of the forests in the Brazilian Legal Amazon. Including estimates for total biomass in non-dense forest lowers the average for the forests of the region to 272 MT/ha. These represent the best estimates at present, although we hope to be able to make substantial improvements on these numbers soon.

Degradation of Standing Forest

Brown and Lugo propose a major effect from thinning of standing forest through logging, rosewood extraction, and other perturbations short of deforestation. While the need to quantify this kind of forest degradation is apparent, the numbers advanced by Brown and Lugo appear to be in the wrong ballpark. Brown and Lugo suggest that, because of these activities, the "differences are real" between FAO forest surveys done between 1954 and 1958 (midpoint = 1956) (*) and RADAMBRASIL project surveys done in 1971 for most of the data used by Brown and Lugo, and in 1976 for RADAMBRASIL volumes 19 and onwards (outside of the area of the FAO surveys) (NB: Apparently using publication dates rather than survey dates, Brown and Lugo incorrectly describe the period as "between late 1950s to early 1960s and the late 1970s"). Based on the difference between the results of these two sets of surveys (done in 1956 and 1971 respectively), the dense forest biomass estimate for the Belém grid cell fell from 306 to 209 MT/ha (a decrease of 32%), while biomass in the Santarém grid cell declined from 233 to 185 MT/ha (a decrease of 21%). Changes of this magnitude are highly unlikely to have occurred in a span of only 14 years, especially since the period in question was not one of particularly intense human intervention (in fact, the end of the period — 1971 — happens to mark the beginning of greatly accelerated pressure on the forest in the following decades). Had the standing forest continued to be mined at the implied 1956-1971 rate from 1971 onwards, 74% of the original (1956) biomass in the Belém grid cell and 48% in the Santarém grid cell would be gone by 1991. Such massive degradation of the forests, even if on a much more modest scale than these numbers suggest, would be readily apparent to the most casual observer.

In summary, Brown and Lugo have made a useful contribution by pointing out the comprehensiveness of the FAO and RADAMBRASIL forest inventories and the potential importance of processes such as degradation of standing forest. However, considerable caution is needed in interpreting the results for application to greenhouse calculations. Adjustments needed for estimates of biomass in the dense forests to which the Brown and Lugo study applies indicate a total biomass over 80% higher than that presented by these authors. Inclusion of non-dense forest types reduces the average biomass for use in calculating carbon emission from deforestation in Brazil's Legal Amazon Region. All of these calculations, both those of Brown and Lugo and the adjustments presented here, indicate large quantities of biomass and significant contributions to global warming through greenhouse gas emissions from deforestation. (f)

Postscript

Brown and Lugo withdrew their original manuscript on 24 September 1991, when my commentary was already in the galley proof stage. The substantially revised version they submitted contains a number of changes in deference to my criticisms, although most of the commentary also applies to their new manuscript (published in this issue of *Interciencia*). Significant changes include the following:

The mean estimate for biomass (as defined by Brown and Lugo: live above-ground for trees ± 10 cm DBH) for dense forests from the RADAMBRASIL dataset increased from 162 to 227 metric tons per hectare (MT/ha), an increase of 40%. The range for the RADAMBRASIL estimate changed from 85-330 to 166-332 MT/ha. For the biomass estimate based on FAO surveys, the mean increased from 268 to 289 MT/ha (an increase of 11%), while the corresponding range changed from 90-397 to 145-397 MT/ha. It is unclear why the numbers have changed, as the corrections listed in Table I of my commentary appear not to have been applied in obtaining the revised numerical results.

Brown and Lugo have added mention in the text of a number of the problems raised in my commentary, but do not alter their calculations accordingly. Adding the word "above-ground" to the title makes the meaning of the numbers presented more apparent, but references to a "poor data base" on underground biomass and to an "unclear" role for roots in carbon models do not solve this problem. The addition of a discussion of dead mass, also emphasizing the paucity of data, also leaves the information incomplete from the point of view of computing carbon emissions. Mention is made that root decomposition could be contributing to soil organic matter pools and that coarse woody debris could be a carbon sink. It should be emphasized that for carbon emissions one must focus on changes in the carbon stock of the entire ecosystem, and that the change from an initial state of intact forest to a landscape of different types of replacement vegetation is invariably a massive release of carbon. All compartments must be considered to have a valid calculation.

In addition to dead and below-ground biomass, Brown and Lugo mention other components such as trees $<$ 10 cm DBH, palms, vines, understory, etc. Mention of hollow trees is also added. While the data Brown and Lugo present is valuable for improving the estimate for one important component (the above-ground portion of live trees $\geq$ 10 cm DBH, excluding palms), these authors go much further in advocating that the contributions from all other components be considered to be zero. They state that "until a better data base for all these tropical forest components is produced, more error is introduced into the analysis than is gained by their estimation." Unfortunately, this rationale is quite mistaken from a systems analysis point of view: if one makes models including only the components for which data are easily available, rather than the components believed to be important in system functioning, one will inevitably arrive at unrealistic results. The solution to the problem of "garbage in-garbage out" is to get better data, not to truncate the model in a "Procrustean bed." Carbon calculations must use the best data available for each component, with supplementary calculations being made to assess the effect of the range of uncertainty associated with each item. Leaving uncertain items out of the calculation does not make the result more reliable; it only makes it less realistic.

The revised paper includes an important addition of estimates for "other-than-dense" forests. The area-weighted mean for the area covered by the RADAMBRASIL data was 239 MT/ha, a value 5% higher than the 227 MT/ha area-weighted mean found for dense forests in the same area. This counter-intuitive result is probably the fault of the less reliable expansion factors available for non-dense forests (see discussion in my commentary).

The discussion of forest depletion in the new version of Brown and Lugo's paper contains significant changes in the numbers and a much-softened conclusion. Brown and Lugo's original estimate that in the interval between the FAO and RADAMBRASIL surveys the Belém grid cell mean biomass declined from 306 to 20 MT/ha (32%) was revised to a decrease from 316 to 263 MT/ha (17%); the change in the Santarém grid cell originally estimated at 233 to 185 MT/ha (21%) became 279 to 249 MT/ha (11%). The implications in terms of depletion rates are partially compensated for by correction of the dates associated with the estimates. Even with the revised depletion rates approximately half those suggested in the original version of the paper, the implication is unrealistic in terms of the level of human activity during the time period in question.

Brown and Lugo have dropped their original conclusion that average biomass values as high as those used by Fearnside (1990) and Houghton *et al.* (1987) are "unjustified." In fact, Brown and Lugo's revised estimate gives results almost identical to those of the papers formerly under attack. The new conclusion is a call for more research — something with which no one can argue. Research is underway at INPA in which we expect to improve substantially the reliability of biomass estimates for Amazonian forests. In the meantime, the values given in Table III of my commentary published here represent the best available estimates.

NOTES

(a) My study cited by Brown and Lugo (Fearnside, 1990b) used data from destructive sampling for deriving biomass values for approximately 40% of the dense forest present in the area covered by Brown and Lugo's study. For the area where I used destructive sampling data, the area-weighted average biomass is approximately 44% higher than the volume-based results (without adjustments to the volume based estimates). In the remainder of the area covered by Brown and Lugo's study the results in Fearnside (1990b) are 13% lower (area-weighted average). For all of the area covered by the Brown and Lugo (1991) estimates the area-weighted mean for dense forest biomass is approximately 23% higher in my estimate than in the Brown and Lugo estimate.

The RADAMBRASIL data presented by Brown and Lugo for dense forests are better founded than many of the numbers for these forest types in my earlier study (Fearnside, 1990b). My paper used data from all available sources (both volume-based and direct). As Brown and Lugo point out, the results are similar for the portions of the region covered by the FAO surveys (in eastern Amazônia), as the 1989 study cited by Brown and Lugo (Fearnside, 1990b, see also Fearnside 1991) used the same forest volume data set that these authors used.

(b) The overestimation in wood volume estimates resulting from hollow trees is calculated as follows. It is assumed that no trees below 40 cm DBH are hollow. For trees greater than 80 cm DBH it is assumed that the mean DBH is 90 cm. The basal area in each diameter class in the INPA Model Basin forestry management study area (Coic *et al.*, 1991) is converted to volume using the equation: Volume = basal area x stem height x form factor. The height for each diameter class is derived using the DBH corresponding to the midpoint for each diameter class in the equation developed for tropical moist forest by Brown and Lugo

(1989: 886): Height in meters $= \exp(1.0710 + 0.5677 \ln \text{DBH in cm})$. The form factors are specific to each diameter class as determined from field measurements in the study site by Higuchi and coworkers ($N = 309$ trees). The volume calculations of Brown and Lugo (1991) from the FAO dataset are based on measured survey data for trees of at least 25 cm DBH, while those from the RADAMBRASIL dataset are based on trees of at least 31.8 cm. DBH. Since these volume values are then expanded to derive total live above-ground volumes for the stands, the overestimation for trees in the surveyed diameter classes will be passed on in the same proportion to the estimate as a whole. To derive volumes for trees of at least 25 cm DBH, it is assumed that half of the volume in the 20-30 cm DBH class is for trees 25-30 cm DBH. To derive the proportion of the volume in the surveyed DBH classes that is represented by hollow trees, the proportion of stem volume of trees in the surveyed diameter classes that is represented by each diameter class is multiplied by the proportion of trees in the class that are hollow. This is 27% for trees $\geq$ 25 cm DBH (corresponding to the FAO dataset) and 31% for trees $\geq$ 31.8 cm DBH (corresponding to the RADAMBRASIL dataset). The proportion of overestimation of volume is obtained by multiplying this by 0.30, resulting in a value of 8.1% for overestimation of stand volume (and biomass) for the FAO dataset and 9.2% for the RADAMBRASIL dataset.

(c) The thickness and relative proportion of sapwood varies greatly among individuals of the same species, being generally greater for younger trees and where soil fertility is higher (Roland Vetter, personal communication, 1991). Using the volumes in size classes greater than 31.8 cm DBH (the minimum of the RADAMBRASIL dataset) that were measured in INPA's Model Basin (Niro Higuchi and coworkers, unpublished data), the diameter of the tree at the point accounting for a cumulative total of 50% the wood volume corresponds to 50.2 cm DBH. In 14 species for which sapwood thickness and diameter data are reported for the Tapajós National Forest (Brazil, IBDF, 1988), sapwood averaged 13.5% of the cross-sectional area (and presumed volume). The diameters of trees in the Tapajós survey averaged 58.4 cm DBH slightly higher than the 50.2 cm DBH that the volume distribution at INPA's Model Basin near Manaus would indicate as the size most representative of the forest for purposes of the needed adjustment for sapwood volume. At the Curuá-Una Experiment Station, sapwood averaged 9.8% of the cross-sectional area in 43 species surveyed (Brazil, IBDF, 1981), with an average diameter in the survey of 60.5 cm DBH. The larger diameters make the estimate of sapwood percentage conservative. Using the average of the two surveys, sapwood should be considered to represent 11.7% of the commercial volume.

(d) Dry weight for this estimate is approximate — derived from fresh weight data using the midpoint of the range given by authors of the study (Klinge *et al.*, 1975: 118).

(e) The FAO forest surveys were conducted at the following dates: 16 March 1956 to 1 March 1957 for Rio Xingú to Rio Tocantins (Heinsdijk, 1958a), 10 May 1957 to 12 Feb. 1955 for Rio Tapajós to Rio Xingú (Heinsdijk, 1957), 29 Oct. 1956 to 18 Nov. 1957 for Rio Tapajós to Rio Madeira (Heinsdijk, 1958b), 18 March to 5 Nov. 1957 for Rio Tocantins to Rios Guamá and Capim (Heinsdijk, 1958c), and 24 Feb. 1958 to 1 Oct. 1958 for Rio Caete to Rio Maracassume (Glerum, 1960).

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