ABOVEGROUND BIOMASS ESTIMATES FOR TROPICAL MOIST FORESTS OF THE BRAZILIAN AMAZON

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One of the issues of major global concern is the increase in atmospheric carbon dioxide and its potential to change world climate. Most of the contribution to atmospheric carbon dioxide is from burning of fossil fuels and cement production by the industrial nations. Changes in forest land use in the tropics also contribute to the problem, however, there is much debate about how much (Houghton et al. 1987, Detwiler and Hall 1988, Houghton 1990). These authors estimated that the net flux of carbon dioxide to the atmosphere due to tropical land-use change in the early 1980s was between 8% and 47% of that produced by fossil fuel combustion and cement production.

Brazil is one of the most important tropical countries whose forest lands contribute to the atmospheric concentration of carbon dioxide. According to a recent estimate, conversion of closed forests to other uses in the Brazilian Amazon produced a flux of carbon to the atmosphere of 0.2 Pg C/yr (Fearnside 1989) or the equivalent of 10 to 20% of the carbon attributed to global tropical deforestation. Ironically, the fraction of Brazil's tropical forests that are being deforested is small (<0.5 %/yr as of the late 1980s [Fearnside 1989]), but the area of tropical forests in this country is so large (about 420 million ha in the Legal Amazon [Fearnside 1987]) that even a small rate of conversion can result in a large contribution of carbon to the atmosphere. Clearly, the future state of Brazil's Amazonian forests is of importance to the carbon composition of the atmosphere. This importance stems from the large pool of carbon stored in soil and vegetation and whether it will remain as organic matter, function as a net carbon sink, or be liberated as a result of burning or decomposition.

Estimates of carbon flux from changes in tropical land use are derived from models whose results depend in part on estimates of biomass in forests. As land-use changes occur, carbon accounting models partition forest biomass according to the fate of carbon. Some enters the atmosphere, is stored in soil, remains on site as dead matter, or is exported. The accuracy of the biomass estimates of forest undergoing conversion is of critical importance because they determine the actual estimate of carbon that reaches the atmosphere and the models are very sensitive to these estimates (Detwiler and Hall 1988, Houghton et al. 1987).

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TABLE I

DESCRIPTION OF FOREST INVENTORIES AND SMALL PLOTS USED TO
ESTIMATE FOREST BIOMASS IN THE BRAZILIAN AMAZON BASIN (FOR
LOCATION REFER TO FIG. 2). ALL FORESTS IN THE INVENTORIES ARE
DESCRIBED AS MATURE TERRA FIRME FORESTS BY AUTHORS. ALL
TREES WERE MEASURED TO A MINIMUM DIAMETER OF 25 CM IN 1 HA
PLOTS UNLESS NOTED OTHERWISE

Area & Map Number	Inventory location	Nº of forest types [1]	Nº of plots	Length of transect lines (km)	Area inventoried (1000 ha)	Source
1.	Tapajós National Forest [2]	1	161	1000	162.4	FAO 1978
2.	Between R. Caete & R. Maracassume	3	104	361	444.8	Glerum 1960
3.	Along road BR-14 from Sao Miguel do Guama to Imperatriz	6 [3]	178	620	900	Glerum and Smit 1962
4.	Between R. Tapajós & R. Xingu	7	415	1017	1500	Heinsdijk 1957
5.	Between R. Xingu & R. Tocantins	3	240	811	1800	Heinsdijk 1958a
6.	Between R. Tapajós & R. Madeira	3	252	824	4340	Heinsdijk 1958b
7.	Between R. Tocantins & R. Guama and R. Capin	3	200	622	3300	Heinsdijk 1958c
8.	Forest Management Basin (Bacia 3), 90 km N of Manaus	1	95	—	600	Higuchi et al. 1985
9.	Ducke Forest Reserve [4]	1	1	—	1 ha	Lecbtbaler 1956
10.	At km-30 on Manaus to Itacoatiara road [2]	1	1	—	1 ha	Prance et al. 1976
11.	Serra do Navio, Amapa [2]	1	2	—	2.6 ha	Rodrigues 1963
12.	Between km 64-200 on Manaus to Itacoatiara road	1	27	> 160	137	Rodrigues 1967
	TOTAL		1676	5415	13184	

1. Generally based on subregional similarities of types within the terra firme.
2. Minimum dbh measured = 15 cm.
3. Forests varied from tropical moist to dry forest life zones.
4. Minimum dbh measured = 8 cm; biomass estimate based on minimum dbh of 10 cm.

Biomass estimates for the Amazon Basin have been made by Fearnside (1985), and we questioned these estimates (Lugo and Brown 1986a). In response, Fearnside (1986) provided additional details of the methodology and the assumption used. More recently, Fearnside (1987, 1989) revised his biomass estimates for the Legal Amazon relying for the most part on data from relatively small-scale studies.

We have developed new methods (building and improving on the ideas in Brown and Lugo 1984) for estimating tropical forest biomass from forest inventory data (Brown et al. 1989, 1991, Gillespie et al. 1992) which can be applied to the large inventory data base for Amazonian forests. We believe that forest inventory data sampled over extensive areas is the only data base to use for estimating forest biomass at the landscape level because it is collected at the scale

of the problem (Brown et al. 1989, 1991). The scale of sampling must match the scale of the subject to be measured, in this case the biomass of all the Amazon's dense forests. Data obtained by the direct measurement approach, as is generally used by Fearnside (1987, 1989) and others, relies on measurements from forest plots that are too few, too small, not randomly sampled from the population of interest, and are often biased in their selection (Brown and Lugo 1984, Brown et al. 1989). These small plots, however, are useful for small-scale ecological studies.

Specifically this paper addresses the following questions: (1) what is the aboveground biomass of moist tropical forests in Brazil's Legal Amazon, (2) how do sampling methods influence these estimates, and (3) how do our new estimates compare to those used in carbon models?

Methods

Data Sources

We used two main data sources for our biomass estimates. One is composed mainly of forest inventories that were done in parts of the Legal Amazon during the period 1954 to 1960 (Table I). These were supplemented with data from two smaller forest inventories done more recently (sites 1 and 8 in Table I). Data from studies done in a few plots were also included for comparison (sites 9-11 in Table I). We realize that the situation in most of these early inventories will most likely have changed by now, but they are useful for (1) estimating historical and geographical trends in forest biomass, (2) estimating biomass for remaining forests in these regions, and (3) setting bounds for similar forest types in other parts of the region undergoing change.

The total area that these inventory data cover is about 13.2 million ha or about 3% of the Legal Amazon (Table I), with a sampling intensity of approximately 0.01% of the inventory area. The majority of the data are for forests south of the Amazon River, extending from an area east of Belem to Manaus. The inventoried areas are mostly in the states of Para and Amazonas and a small part of Maranhão.

Most of the inventoried forests are in the tropical moist forest life zone (*sensu* Holdridge 1967; Tosi and Velez-Rodriguez 1983) and were described by the authors as "terra firme" forests. A small section south of about 4°S is in the tropical premontane moist forest transition to dry forest life zone. This parallels the classification used by Glerum and Smit (1962) who refer to the forests there as "evergreen seasonal forests".

The second main data base is from a Legal Amazon-wide inventory of forests done by the RADAMBRASIL project in the early 1970s. This project covered the whole of Brazil, divided into 6° (north-south) x 4° (east-west) grid cells. We had summary volume data for 17 of the approximately 20 complete or partial grid cells encompassing the Legal Amazon (Sampaio de Almeida 1979). For each grid cell, volumes of all trees with minimum diameters (dbh) ≅30 cm (± 95% confidence interval) were reported by the main forest types (e.g., dense forest, open forest, transition forest, etc.) and by subtypes. We focussed our efforts on the dense forests because our biomass estimation techniques are more applicable to this type. However, as the other-than-dense forests represented a fairly significant fraction of the forest area in the Amazon (about 18% of the total forest area in the early 1970s [Sampaio de Almeida 1979]), we also made estimates of their biomass from the volume data. Factors used to convert volumes to biomass (see next section) were developed from data obtained for closed forests for all three major tropical regions of the world, including mature and disturbed forests to different degrees (young secondary, late secondary, logged). If one accepts that these closed forests also represent the other-than-dense forests of the Amazon, then the estimates of their biomass that we present here can be considered reasonable.

Problems of Estimating Forest Biomass at the Scale of the Amazon

Estimating the biomass of large forest areas poses a serious sampling problem to ecologists. At the outset it is known that forest biomass changes with age, land-use history, climatic and edaphic condition, and topographic position. How can so much variation be encapsulated into values needed to model the carbon cycle? The problem is compounded by the small area of tropical forests in the world whose forest biomass has ever been assessed directly (some 30 ha; Brown *et al.* 1989). A logical way to partly deal with this problem is to use geographic information systems technology (GIS) to generate a geographically referenced data base of forest biomass so that the need to average data over large areas for use in models is eliminated. We have already completed such a data base
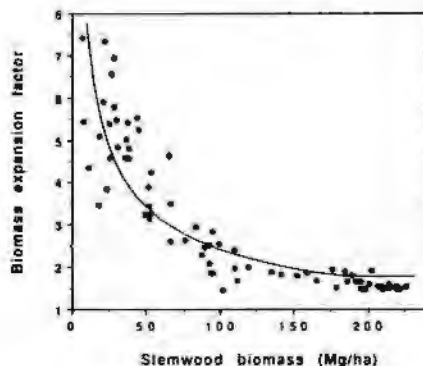

Figure 1. Relationship between stemwood biomass and biomass expansion factors (total aboveground biomass/stemwood biomass). A piecewise regression was fit to these data resulting in Equation 2 (see text). Data are from the forest inventory sources given in Brown *et al.* (1989) for forests of tropical America, Asia, and Africa.

for most of tropical Asia (Brown *et al.* in press, Iverson *et al.* in press) and are in the process of generating similar data bases for the rest of the tropics. These geographical data bases can be used as inputs to terrestrial carbon models. Although the use of GIS solves part of the problem, there is still a need to estimate biomass per unit area upon which geographical data bases can be built.

For estimating the biomass of a large area such as the Brazilian Amazon, samples must be obtained in a random or stratified random (if needed) design from the population of interest, in this case the Amazon. Data from the RA-

DAMBRASIL project come closest to this criterion, and data from sources 2-7 in Table I meet this criterion for a large region south of the Amazon River. Use of data from anything less than these two data bases to estimate biomass at a landscape scale makes one question the validity of the results.

Two aspects of forest biomass are of critical concern for models of terrestrial carbon fluxes from the tropical forest landscapes. First, is the total forest biomass which includes the aboveground and belowground living mass of trees, shrubs, palms, other understory components vines, epiphytes, etc., and the dead mass of fine and coarse litter. The quantity of biomass in a forest determines the potential amount of carbon (1 Mg biomass = 0.5 Mg carbon) that could be released to the atmosphere due to clearing and conversion to a non-forest land use. Second, is how each of these components responds to forest clearing and regrowth and how they should be represented in models. The structure of the models determines (1) what proportions of the biomass are immediately oxidized and what proportions decompose over longer time intervals, and (2) the rates of biomass accumulation during regrowth. Although progress has been made concerning these two aspects of tropical forest biomass, problems in biomass estimation of forest components and their representation in models still exist.

Most of the research to date on biomass estimation has focussed on the tree component of the forest because it accounts for the greatest fraction of the total biomass, its response to clearing and regrowth is reasonably well understood for modeling purposes, and forest inventories generally give information for this component only. We will indicate in the next sections what are some problems that still exist for biomass estimation and modeling of the non-tree components of tropical forests.

Living Aboveground Biomass

For purposes of this paper, we consider only the total aboveground biomass (TAGB) in trees of diameter 10 cm or larger, including leaves, twigs, branches, bole, and bark. We do not include estimates of the biomass of the other living aboveground components of a forest mainly because (1) the present data base for them is insufficient to make extrapolations to a larger scale and (2) they represent a small

fraction of the total biomass. For example, the contribution of understory shrubs, vines and herbaceous plants to aboveground mass can be variable but generally very small (about 3% or less [Hegarty 1989, Jordan and Uhl 1978, Tanner 1980]), although it is likely to be a larger proportion in disturbed forests. Palms can be common in Amazonian forests and forest inventories tend to ignore them. However, with respect to living biomass we believe that their contribution is generally small (e.g., assume, in addition to the trees, a forest has 100 palms/ha of average height of 10 m and diameter of 20 cm with a density of 0.2 Mg/m^3; their biomass is about 8 Mg/ha).

Belowground Biomass

The biomass of roots varies considerably and fine roots are generally the most important component. Biomass of roots can vary from 10 to 50% (with an average of 17%) of aboveground biomass for many tropical moist forests (Brown and Lugo 1982), most likely as a function of soil type, soil fertility, and moisture regime. Few studies have reported estimates of root biomass from any tropical forest with even fewer estimates from Amazonian forests. With such a poor data base, determining patterns and generalizations about the contribution of roots to forest biomass is difficult.

How roots should be treated in models of tropical deforestation is unclear as they tend not to be immediately oxidized during clearing and burning and little is known about their rates of decomposition. Forest roots can be highly lignified with slow decomposition rates and actually contribute to soil organic matter pools (Cuevas et al. 1991).

Dead Mass

Fine litter is not included in our estimate of biomass because its annual rates of production are balanced by decomposition with no appreciable accumulation. That is, the CO_2 fluxes associated with litter are in balance in advanced secondary and mature forests over an annual cycle.

The pool size and dynamics of coarse woody debris in tropical moist forests are poorly understood and like roots it is not included in this study. Coarse woody debris may be 10 to 40% of aboveground biomass (Saldarriaga

et al. 1986, Uhl and Kauffman 1990, Uhl et al. 1988), and can serve as a long term carbon pool (Brown and Lugo, in review). Excluding this potentially large pool of mass can underestimate the total biomass of forests. However, it is unclear whether much of it would be readily burned during forest clearing because of its high water content, particularly in the larger diameter size fractions. Furthermore, we have suggested that coarse woody debris is a carbon sink in forests recovering from disturbance for periods up to 100 yr or more (because of the slow wood decomposition rates for many tropical species [Brown and Lugo, in review]), which complicates the carbon accounting models.

In summary, an area of future research is to develop ways to estimate the biomass of all other forest components at the accuracy and scale necessary for landscape level analysis. Of particular importance is the need to investigate the effects of forest disturbance because the proportions of non-tree biomass in disturbed or secondary forests can be very different from mature forests (e.g., understory is generally significantly higher while coarse woody debris is lower in secondary than in mature forests [Brown and Lugo 1990]). In addition, there is a need to improve present understanding of how non-tree components should be incorporated into terrestrial carbon models of land-use change. 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. Carbon models will have to be modified to take into account the total carbon budget of forests using data based on a valid sampling design and an improved understanding of the factors that regulate biomass (e.g., environmental factors and condition of forest).

Volume Data

The use of volume data from the inventories and subsequent conversion to biomass is not without its errors. Errors include measurement error in original volume estimates, the problem of hollow trees, conversion of volumes measured at a larger minimum diameter to a smaller minimum diameter, use of appropriate wood densities, and final conversion of stemwood biomass to total biomass. Most of the measurement errors in volume estimates are probably random and tend to cancel each other out. Furthermore, the RADAMBRASIL project reported 95% confidence intervals

for the mean volumes (we used these to estimate confidence intervals around the mean biomass) which can account for most of the errors in volume estimation.

The presence of hollow trees can present a systematic overestimation of volume and further measurements of this problem may be warranted. However, hollow trees are only hollow for part of the main stem and only for some of the trees. To estimate the magnitude of this potential overestimation we offer the following calculation. We assumed a forest of 60 stems/ha with dbh $\geq$ 30 cm, a volume of 150 m^3/ha, and a mean diameter of 40 cm (based on data given in the RADAMBRASIL project), with 20% of the stems being hollow to about 2 m high. These values result in an overestimate of volume of about 2%. The overestimate of mass would be less (about 1.6%) because the tree is not completely hollow, but maybe be a shell of about 5 cm thick with a wood density of perhaps half of that for solid wood. Errors in the conversion of volumes to biomass will be dealt with in the next section.

Procedures for Estimating Biomass

Two approaches for estimating TAGB were used depending upon the data available

Method 1-Based on Volumes

For area numbers 2-8 and 12, graphs or tables of the number of all trees (stand tables) and gross volume overbark (stock tables) by diameter classes to a minimum diameter of 25 cm with 10 cm intervals, with trees $\geq$ 95 cm lumped into one class, were reported. We did not use the stand tables directly to estimate TAGB as was done in a similar analysis for forests of South/Southeast Asia (Brown et al. 1991; see also Method 2, next) because trees $\geq$ 95 cm were lumped into one diameter class and it is the diameter distribution of these large trees that can greatly influence TAGB estimates (see below).

The basic approach to estimating biomass from these type of data entailed using the volume reported to 25 cm and "expanding" this to volume at 10 cm, converting volume to stemwood biomass (multiplying by an average wood density), and then "expanding" the stemwood biomass to total aboveground biomass of trees (biomass expansion factor [BEF] = TAGB/stemwood biomass; Brown et al. 1989; Gillespie et al. 1992).
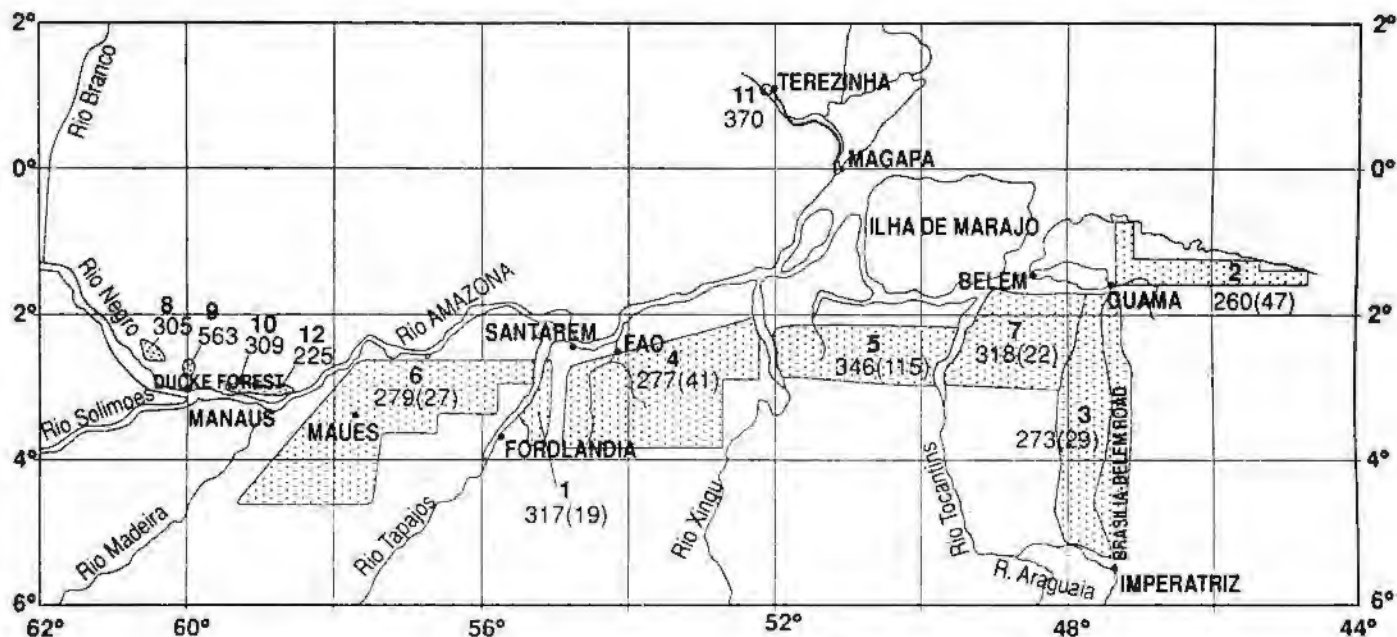
Figure 2. Map of the eastern and central region of the Amazon Basin in Brazil showing location (numbers in bold print for the sources given in Table I) and biomass estimates (Mg/ha with 95% confidence intervals in parentheses).

Volume Expansion Factors (VEF): For expanding volumes, we used a relationship between quadratic stand diameter (QSD, the diameter of the tree with the mean basal area; Husch *et al.* 1972) and VEF (volume to 10 cm/volume to 25 cm; Brown 1990). The rationale for this approach is described in Brown *et al.* (1989), and the relationship was based on data (stand and stock tables) from forest inventories done in all tropical regions described therein. A piecewise regression equation similar to Eq. 2, below, best described the function.

We first used the reported stand tables (to a minimum diameter of 25 cm) to estimate basal area (BA; a conservative estimate because of the problems due to lumping of large trees as described above) to the minimum diameter measured, and then calculated QSD as:

$$QSD = \sqrt{[(BA/\#stems)*(4/\pi)]} \quad \text{(Eq. 1)}$$

For all the inventory areas the QSD was >35 cm giving a VEF of 1.22.

Wood Densiy (WD): We used a weighted average wood density (WD) of 0.69 Mg/m³. This was calculated from data for two areas of Amazonian forests reported in Heinsdijk (1958b, c) and Prance *et al.* (1976). These two sources reported the diameter, species and volume of all trees

in two plots (1 ha each for Heinsdijk and 0.08 ha each for Prance *et al.*). Basically from this information, we estimated total stemwood biomass and total volume (details are given in Brown *et al.* 1989) and calculated a weighted wood density as the quotient of stemwood biomass and stem volume. Clearly, there is potential for error here as the data are based on only four plots and the density of all species was not known. However, we believe that this method produced a more reliable estimate of the weighted wood density than the simple arithmetic mean of tropical American species we used in our earlier work (Brown and Lugo 1984).

Biomass Expansion Factor (BEF): Finally, we used a relationship between stemwood biomass (SB) and BEF *(Fig. 1)* to estimate BEFs (based on forest inventory data for all tropical regions reported in Brown et al. 1989). A piecewise regression was fit through the points in Figure 1 to give the following functions:

$$\begin{aligned} BEF &= Exp\{3.213 - 0.506*Ln(SB)\} \\ &\quad \text{for } SB < 190 \text{ Mg/ha} \\ &= 1.74 \\ &\quad \text{for } SB \geq 190 \text{ Mg/ha} \quad \text{(Eq. 2)} \end{aligned}$$
(Adjusted $R^2 = 0.76$, n=56)

We have developed a similar relationship only using QSD (based on a minimum diameter of 10 cm) as the independent variable rather than stemwood biomass as used here (Brown *et al.*

1989; the asymptote being 1.75 at large QSDs). We feel that a relationship between BEF and SB is more practical for the Amazonian forests due to the difficulties of estimating QSD from incomplete stand tables. This method for calculating the BEF is an improvement on our earlier attempts (Brown and Lugo 1984) where we used a constant of about 1.4 (excluding roots) based on data from ecological studies. Our new expansion factors are more reliable than the earlier ones because they are based on a broad data base of forest inventories and tree biomass measurements and they allow for the effects of forest quality and disturbance (Brown *et al.* 1989).

Total Aboveground Biomas (TAGB), in units of Mg/ha, was calculated as:

$$\begin{aligned} TAGB &= Volume(m^3/ha) * VEF * \\ &\quad WD * BEF \quad \text{(Eq. 3)} \end{aligned}$$

The data for areas 2-8 were reported by subregions (3-7 subgions per area). We estimated TAGB for each subregion, and report the mean and 95% confidence interval (CI) based on these subregions for each area.

The data for area 9 reported volume to a minimum diameter of 8 cm, mostly in 2 cm diameter class intervals. We used the reported volume to 10 cm and used Eq. 2 and 3 to estimate TAGB.

For data from the RA-DAMBRASIL project, we used the same method for estimating TAGB as expressed in Eq. 2 and 3, after first estimating the volume to 10 cm diameter. We assumed that the QSDs for dense forests were generally the same as for those forests covered by the inventories described in Table I (> 35 cm), but because the minimum diameter measured in the RADAMBRASIL inventory was 30 cm, we used a VEF of 1.25.

For the other-than-dense forests, we assumed that the QSD would be smaller than for dense forests because they were likely to have more smaller diameter trees. We assumed a QSD of 25 cm giving a VEF of 1.5.

We used the 95% CI of the mean volumes reported in the RADAMBRASIL project to estimate a 95% CI for TAGB. We added the confidence interval to the mean volume, estimated the TAGB (Eq. 3), and then reported the difference between this and the mean as the 95% CI for the biomass estimate.

Method 2-Based on Stand Tables

For areas 1 and 10-11, tables of numbers of all trees per diameter class to a minimum diameter of 15 cm in 10 cm intervals (stand tables) were reported; no volume data were given. We applied biomass regression equations for tropical moist forests (given in Brown *et al.* 1989) to the mid-point of the diameter classes and multiplied this estimate of the biomass per tree by the number of trees in the class, and summed for all classes. We standardized these biomass estimates by multiplying them by 1.03 to account for the trees in the 10-15 cm class (based on information in Heinsdijk 1957 and Gillespie *et al.* 1992). We also calculated a 95% CI due to the error in the regression (Brown *et al.* 1989). This approach has been used successfully for forest inventories in tropical Asia (Brown *et al.* 1991).

Results and Discussion

Forest Biomass Estimates
Estimates for the 1950s

Aboveground biomass estimates, based on all large-scale inventories given in Table I ranged from 175-397 Mg/ha, with an area weighted mean of 298 Mg/ha (Fig. 2 and 3a). Most of the biomass estimates (78%) for these inventories were within the range of 240 to 340 Mg/ha (Fig. 3a); one subregion of area 5 had an estimate as high as almost
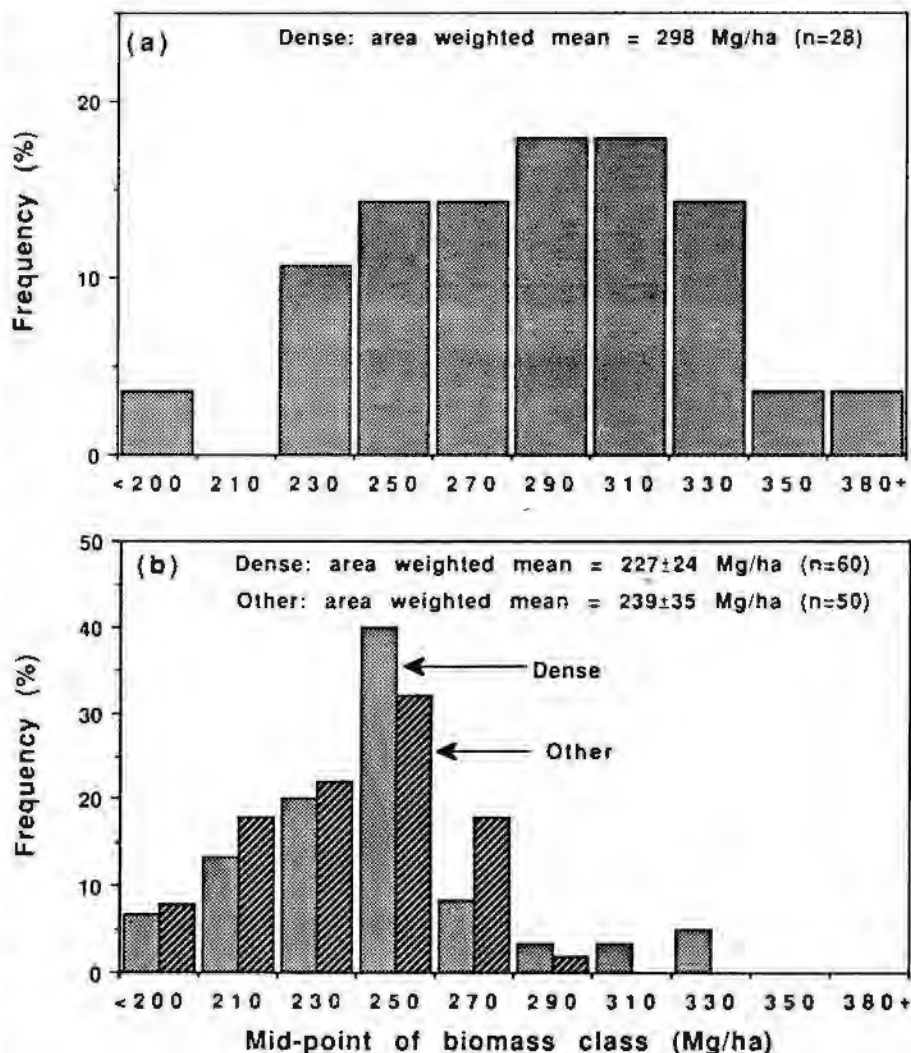

Figure 3. Frequency distribution of biomass (20 Mg/ha classes) for forest inventories of Amazonian forests of Brazil: (a) from the sources in Table I (except 9-11) and (b) from the RADAMBRASIL project for dense and other-than-dense forests. Note that the vertical scale of (b) is twice that of (a).

400 Mg/ha. The area weighted mean for only the 1950s data (areas 2-7) was also 298 Mg/ha.

The difference between the lowest and highest biomass estimate was more than two-fold demonstrating a large variation among the forest types within this part of the Amazon. Part of this variation can be attributed to localized differences in forest associations (measured by absence or presence of certain indicator species), soil, topography, and changes in climate as indicated in the original sources. For example, effects of topography and associated soil differences on biomass of forests is illustrated in area 4 where a 1.5-fold difference between plateau (about 335 Mg/ha) and low slope forests (about 230 Mg/ha) was exhibited. The general

decrease in biomass from north (about 290 Mg/ha) to south (175-260 Mg/ha) in area 3 represents a decrease in rainfall and increase in length of the dry season (i.e., change from moist forest to dry forest life zones).

Estimates Based on Small Scale Studies

The biomass estimates from the small-scale studies ranged from 309 to 563 Mg/ha (Fig. 2, areas 9-11) with a mean of 414 Mg/ha, values that are mostly outside the range of those based on inventories. For comparison, biomass estimates based on direct measurements for other forest plots in the Amazon Basin range from about 300 to 410 Mg/ha for terra firme forests
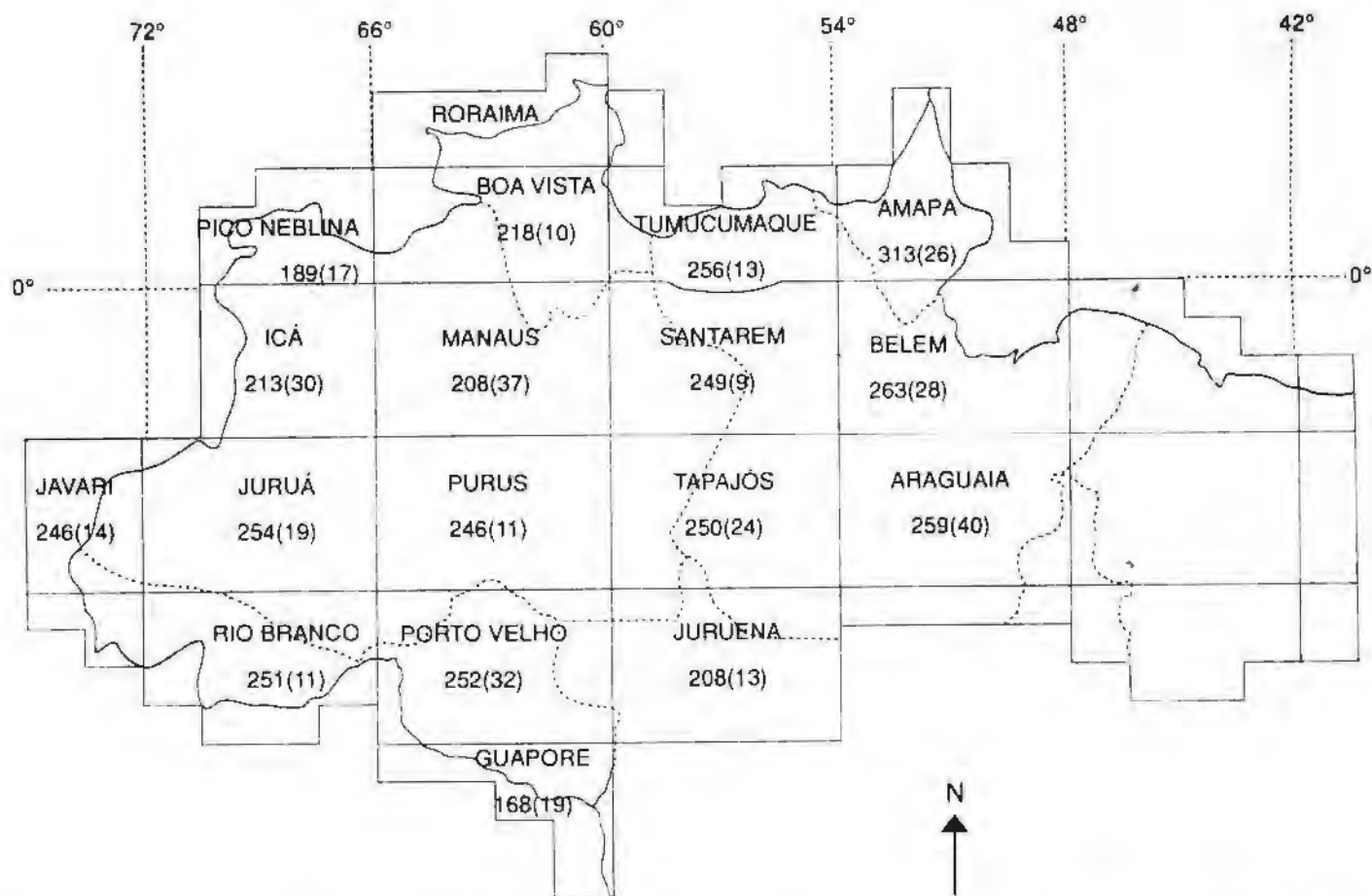
Figure 4. Spatial distribution of biomass estimates (weighted mean, Mg/ha with 95% confidence interval in parentheses) for dense forests of the Brazilian Amazon based on the RADAMBRASIL project (from Sampaio de Almeida 1979). The Santarem and Belem grid cells overlap with most of the region shown in Figure 2.

(Brunig *et al.* 1989, Fittkau and Klinge 1973, Jordan and Uhl 1978, Klinge and Herrera 1978, Russell 1983, F. Brown, Woods Hole Research Center, 1990, pers. comm.). These results illustrate that regardless of what method is used, whether biomass is estimated directly or indirectly using our methods, a similar range of values is produced if the plot sizes are small and not randomly selected.

Dense Forests of the
RADAMBRASIL Project

Biomass estimates of dense Amazonian forests based on the RADAMBRASIL project ranged from 166 to 332 Mg/ha with an overall area weighted mean of 227 Mg/ha (Fig. 3b). About 75% of these biomass estimates ranged between 200 to 260 Mg/ha (Fig. 3b), a narrow range of low values compared to the results for areas 2-8 (Fig. 3a). Furthermore, none of the biomass estimates resulting from the RADAMBRASIL project exceeded 340 Mg/ha.

Area weighted means for individual grid cells ranged between 168 Mg/ha in the southern part of Rondônia to 313 Mg/ha in Amapa (Fig. 4). It is clear that marked differences exist between the biomass estimates of dense forests based on data from the earlier inventories (Table I) and the RADAMBRASIL project with respect to weighted means, distribution of biomass classes, and range of values. Are these differences real or a result of different sampling and measurement techniques?

Comparison of the 1950s and
1970s Estimates for Dense Forests

Because of a general agreement between biomass estimates for some areas in both data sources that could be positively identified as overlapping, we feel confident that differences due to sampling, measurement, and our estimation techniques were minimal. As a general frame of reference, areas in Table I between 48° and 60° W (Fig. 2; all areas

except 2, 3, 8, and 11) were covered by the Santarem and Belem grid cells (Fig. 4). Within these cells, overlap occurred in area 4, and there was good agreement between the biomass estimates from the two data bases. For example, estimates for "alto" and "baixo" forests of area 4 (Heinsdijk 1957) were 335 and 230 Mg/ha, respectively and 332 Mg/ha and 240 Mg/ha, respectively, for the overlapping Santarem cell. For the area of overlap between area 4 and the Belem cell, the former had a biomass estimate of 278 Mg/ha and the later about 260 Mg/ha.

Despite the good agreement between overlapping sections of the two different data bases, the weighted mean for the Belem grid cell (263 ± 28 Mg/ha [95% CI]) was lower than the weighted mean of areas 4, 5, and 7 of 316 Mg/ha. Similarly for the Santarem cell which had a weighted mean of 249 Mg/ha (± 9 [95% CI]) versus a weighted mean of 279 Mg/ha for areas 1, 6, 12, and part of 4. For the Belem cell, the difference between the two biomass esti-

mates represents a gradual depletion of about 3.5 Mg ha^{-1}yr^{-1} (assuming about 15 yr time interval) or about 1% of the 1950s biomass per year. The difference between the biomass estimates for the Santarem cell represents a gradual reduction of about 2 Mg ha^{-1}yr^{-1}, or less than 1%/yr of the 1950s biomass.

Clearly, there is the potential for the biomass differences here to be statistically non-significant if estimates for confidence intervals were considered (no data available for computing a weighted CI for the areas in Table I). As discussed below, however, we suggest that these differences are real and may reflect the impact of human activities between the intervening period (between late 1950s and the early 1970s). For example, the above rates of biomass depletion could be easily accomplished by the removal of one large diameter tree/ha every 2-3 yr (see discussion below on the role of large trees).

Other-than-dense Forests of the RADAMBRASIL Project

Estimates of the biomass of other-than-dense forests ranged from 167 to 295 Mg/ha, with an area weighted mean of 239 Mg/ha (Fig. 3b). Most of these forests had biomass estimates that were less than 280 Mg/ha (98%), and none had mean estimates above 300 Mg/ha, unlike the dense forests. Statistically there was no significant difference between the mean biomass of these forests and the dense forests. This can be explained by certain factors relating to the structure of these forests, the inventory methods, and our estimation methods.

The RADAMBRASIL inventory was interested in measuring the potentially commercial component of the forests. In dense forests, this is likely to be a larger quantity than in the other-than-dense forests because the trees in the former are likely to have larger diameters. Certainly, the reported volumes/ha were generally higher for dense (54-220 m^3/ha) than for other-than-dense forests (46-128 m^3/ha). Furthermore, the fraction of the total volume to 10 cm represented by trees $\geq$ 30 cm is also likely to be higher in dense (80% or VEF of 1.25) than in other-than-dense forests (67% or VEF of 1.5); there will be fewer trees/ha in the < 30 cm size classes in the former versus the latter. Finally, we have shown, theoretically and empirically for forests from all tropical regions, that for stands with large average diameters (QSD), the BEF reaches a constant and as QSD becomes smaller, the BEF increases in an

exponential manner to an undefined value (Brown et al. 1989; see also Fig. 1). This trend was reflected in the use of BEFs of 1.7 to 3.4 for dense forests and 2.0-3.5 for other-than-dense.

All these factors working together result in mean aboveground biomass estimates for these two groups of forests to be similar to each other, but with different ranges. However, one factor that cannot be addressed in this analysis is the effect of canopy height. If the other-than-dense forests are shorter on average than the dense forests, we most likely have overestimated their biomass because constancy of height is implicit in the BEFs. This cannot be corrected at this time until information on height is provided.

Summary of Estimates

Fearnside's (1985) biomass estimate for dense forests of the Amazon region was 252 Mg/ha. His revised values for dense forests of the main states of the Amazon ranged from 248-324 Mg/ha (Fearnside 1989; we subtracted his estimates of roots and fine and coarse litter to be consistent with our values) with a weighted mean of 290 Mg/ha. Our weighted mean biomass estimate from the sources in Table I is the same as the mean reported by Fearnside, but our range of estimates is much wider (Table II). However, our estimated weighted mean based on the RADAMBRASIL project is lower than Fearnside's estimates, with a non-overlapping lower range. Fearnside used a different data base from us (except for one or two sources) which was composed mainly of results from small-scale and direct measurement studies covering a small total area compared to ours which covered about 3% of the Amazon (Table I sources) or Legal Amazon-wide.

In summary, there are four estimates of aboveground biomass (based on our definition) for dense moist forests of the Brazilian Amazon (Table II). The lowest estimate is based on the 1970s RADAMBRASIL project and the highest estimate is the one used by those that model the carbon cycle of tropical forests (320 Mg/ha [without roots]; Houghton et al. 1987). How can these differences and apparent similarities be explained? We have already discussed the importance of life zone, plant association, and other environmental factors (above and Brown and Lugo 1982). However these factors are already accounted for here because our values have been weighted by area and because the number of life zones under consideration is very limited (mostly the tropical moist life zone). The two most important factors for explaining the differences in weighted biomass estimates are methodological and human intervention (which may change the biomass of forests). We discuss these next.

Sampling for Biomass Estimation and the Role of Large Trees

In trying to understand the differences among the four available estimates for the Amazon Basin, we noted the importance of sample size. Areas 9-11, based on 1-2 plots of 1 ha or so gave high biomass estimates as do studies in similar forests in other parts of the Amazon Basin. As explained in Brown and Lugo (1984) and Brown et al. (1989) direct biomass determinations of a few small plots (about 0.1 to 1.0 ha or so) usually yield higher biomass estimates probably because plots were not randomly selected, were not sampled from the population of interest, and sample size was small (both number and plot size).

TABLE II

ESTIMATES OF TOTAL ABOVEGROUND BIOMASS OF DENSE FORESTS (AREA WEIGHTED MEANS) OF THE BRAZILIAN AMAZON

Source	Aboveground biomass	
	Mean	Range
	(Mg/ha)	
Sources in Table I (1950s) from large scale inventories south of the Amazon River	298	175-397
Fearnside (1989)	290	248-324
Houghton et al. (1987)	320	—
From RADAMBRASIL project (early 1970s)	227	166-332

As far as we can tell, plot selection for ecological studies related to forest biomass in the Amazon are not randomly selected from the population of interest, i.e., the forests of the Amazon Basin. Instead, they tend to be selected to characterize local forests. This is fine for studying those forests, but it is incorrect to later consider these study areas as being representative of the larger population (e.g., the Amazon) and to try to make inferences about larger populations.

In addition to the problems of using data from a few plots outlined above, is the role of large diameter trees on biomass estimation. Biomass per tree increases geometrically with increasing diameter. We believe that in ecological studies, selection of plots tends to be biased based on the notion of what a "primary" forest should look like, i.e., one with many large trees (defined here as those with a mass of > 5 Mg/tree and a dbh > 70 cm). This tendency of adjusting the placement of plots to include large trees also has been considered to be a serious sampling bias in understanding dynamics of old-growth forests of the midwestern USA (McCune and Menges 1986).

Using the inventory data from sources 2-7 (Table I), we found that trees with diameters > 70 cm contributed no more than about 3% of the total number of trees (or about 6-10 trees/ha, Fig. 5a), no more than 40% of aboveground biomass (Fig 5b), and that TAGB generally increased with increasing number of large trees. In contrast, such trees accounted for as much as 10% of the number of trees and up to 90% of the biomass for 22 0.25 ha forest plots non-randomly scattered throughout several moist forest life zones of Venezuela (data from J. P. Veillon, 1986, Universidad de los Andes, pers. comm.). As another illustration of the problem with small plots, the biomass of 40 contiguous plots of 0.025 ha for a forest in Rondônia ranged from about 50 to > 1200 Mg/ha, with a mean of 300 Mg/ha (F. Brown, Woods Hole Research Center, pers. comm.). Many typical ecological studies would have measured biomass in only a few of these 40 plots which could have grossly over or under estimated biomass. These results underscore the dangers of extrapolating biomass data from a few small plots to large-scales. A few, non-randomly selected small plots are excellent for addressing small-scale questions, but they are not useful for addressing questions of large-scale phenomena such
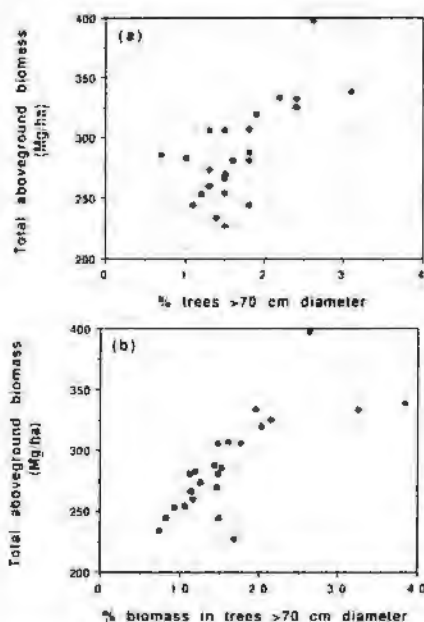

Figure 5. Scattergraph of aboveground biomass for the forests covered by sources 2-7 in Table I versus (a) % of the number of trees/ha with diameters > 70 cm and (b) % of the total aboveground biomass in trees > 70 cm diameter.

as biomass estimates for the Amazonian forests.

Human Disturbance of Amazonian Forests

Some of the spatial differences in biomass (Fig. 2 and 4) can be attributed to a history of different intensities of human disturbance. Although the authors of the reports from sources 2-7 in Table I described how they avoided sampling in secondary forests, we suggest that many of the forests were indeed disturbed. For most of these inventories, the authors constantly referred to observations of primitive logging roads, presence of tree stumps where trees had been exploited for local use, forest areas surrounded by shifting cultivation, and common occurrence of patches of forests that were described as open, with shorter trees and dense undergrowth, climbers and vines. All these factors point to the high incidence of human disturbance.

In area 5, for example, biomass for the three subregions varied from 307 to 397 Mg/ha. Part of the difference among the three associations was soil related (Heinsdijk 1958a), but we suggest increasing human disturbance was also responsible. In going west (397 Mg/ha) to east (307 Mg/ha) across this area, biomass decreased, whereas population

density, incidence of shifting cultivation, primitive logging (particularly for large *Manilkara huberi* trees for their latex), and primitive logging road density increased.

The average biomass of all three forest types in area 6 was one of the lowest yet the area was one of the most remote from large population centers (Fig. 2). However, the region had been a center for rosewood oil production. We suggest that the low biomass in the forest of this region is due largely to the past extraction of large rosewood trees (*Aniba rosedora* var. *amazonica*) as well as trees for fuel to run the factories extracting the oil, with little time since then for trees to grow into large diameter classes.

To extract the oil, trees were felled by axe and cut into smaller sections in the forest for transport to the factory. This practice was very destructive to the forest because of the poor felling techniques (Gachot *et al.* 1953). For one typical oil factory, we estimated that about 400 large trees of about 80 cm in diameter were needed a year (from data given in Gachot *et al.* 1953). At a density of 1-2/ha, up to at least 400 ha of forest could have been disturbed by this process for one factory for one year. To supply this need, almost 40 workers for 8 mo a year were needed to cut trees. In addition, copious quantities of firewood were needed to run the factories. Such exploitation in these forests clearly must have impacted forest biomass.

The removal of large trees by these type of activities may account for the low biomass of some Amazonian forests. We have found that for mature forests of parts of Southeast Asia, > 45% of their biomass was in large trees (Brown *et al.*, in press), compared to the Amazon forests where < 40% is in large trees (Fig. 5). It is the large trees that accumulate large quantities of biomass, but it can take of the order of hundreds of years for them to reach this size.

A similar pattern of insidious degradation of forests, often due to illicit cutting of larger, valuable trees or small-scale clearing has been found for most of the forests of tropical Asia (Brown *et al*, 1991). For this part of the world most of the forests had biomasses of < 250 Mg/ha, whereas a few tracts often exceeded > 400 Mg/ha. Apparently this problem of forest degradation in the tropics is widespread, and supports our suspicion that there are hardly any truly virgin tropical forests left anywhere in the world (Lugo and Brown 1986b, Brown and Lugo 1990).

Conclusion

Based on the above we propose the following interpretation for the estimates of biomass for the Amazonian moist, dense forests (Table II). The earliest estimates, for regions south of the Amazon River, were for the late 1950s and they reflect the wide natural variation in forest biomass within the region as well as evidence of former human degradation in the form of reduced biomass of most stands due to removal of large diameter trees. The estimate by Fearnside (1989) resulted in similar weighted biomass estimates as the one for the 1950s, but his data base is for two decades later. This means that there were either little differences in average forest biomass between the 1950s and 1970s or that the values agree by coincidence. Fearnside's (1989) estimates are, however, subject to the sampling and extrapolation problems discussed above. However, we agree that there is no reason to expect significant changes in the weighted biomass of undisturbed forests over periods of decades. Yet, we are not sure to what extent forests remain undisturbed during this time interval, even in the Amazon Basin.

The lowest biomass estimate based on the RADAMBRASIL project should reflect large-scale conditions in the Basin during the early 1970s. This estimate is lower than that of Fearnside (1989) and suggests continued human disturbance to these forests since the late 1950s (comparison of overlapping grid cells with sources in Table I). We are inclined to accept the RADAMBRASIL estimate, but the implication of this, when compared to the estimates in Figure 2, is that human degradation has reduced the average biomass of many Amazonian forests by about 1% or less a year. Such a conclusion must be considered an hypothesis until large-scale inventories with comparable techniques are systematically conducted on the same regions of the Amazon. What is clear from the analysis is that use of average aboveground biomass values of > 290 Mg/ha in models of contemporary tropical land-use change in the Amazon (e.g. Houghton *et al.* 1987, Fearnside 1989) are not justifiable.

A more accurate picture of the biomass of these forests will only be achieved when historical accounts of forest land use are well documented and more extensive and current forest inventories are made, with all results reported on a geographic basis. These inventories should measure all trees to at least a minimum diameter of 10 cm (or smaller if warranted) in 10 cm diameter classes. We believe that volume data are not necessary as our method (Brown *et al.* 1989, 1991) can estimate biomass (point and interval estimates) directly from stand tables. Furthermore, efforts should be made to gather data for estimating the biomass of other forest components such as understory, roots, and woody debris. Such a data base coupled with remote sensing data of changes in land use and used as inputs to carbon models will improve our ability to estimate the flux of carbon to the atmosphere. Until such an approach is used, one must question current estimates of carbon production by deforestation in the Amazon, and indeed in all the tropics.

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"Alguien que había empezado geometría con Euclides le preguntó, después que hubo aprendido el primer teorema. "Pero ¿qué voy a ganar aprendiendo estas cosas?". Euclides llamó a su esclavo y le dijo: "Dale un óbolo, ya que tiene que ganar algo por lo que aprende".

GEORGE SARTON