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Aboveground Biomass Estimate for Amazonian Dense Tropical Moist Forests

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Introduction

The climatic changes on Earth brought on by anthropic action have motivated studies to be undertaken to obtain reliable estimates of the deforestation rates and aboveground biomass in the Brazilian Amazon. In order to have a correct understanding of the influence of the present Amazonian land-use on the climatic changes in the world, it is necessary to count on the reliable deforestation-rate data and the estimation of the biomass having the potential to be converted into carbon dioxide or other greenhouse gases, over a certain period of time.

Today, controversies on the deforestation rate estimates in the Brazilian Amazon have been lessened after the latest figures of Fearnside et al. (1990b). Their works were carried out at INPE (National Institute for Spatial Research), in Brazil, with the conclusions that the annual deforestation rate was 21,218km^2/year during 1978-1989, and that total cleared area (up to 1989) was approximately 400,000km^2. At the United Nations Environmental Conference, Rio-92, INPE (1992) presented annual deforestation rates for 1989, 1990 and 1991 which were, respectively, 17,860, 13,810 and 11,130km^2/year. This information refers to the Legal Amazon (total area of almost 5 million km^2) extending beyond the river basin proper (3.9 million km^2).

However, the aboveground, fresh or dry, biomass estimates still raise a lot of questions and controversies. Some estimates come from direct, or destructive methods; and others, from indirect methods. Both have suffered severe criticisms from many researchers around the world, particularly because of the aboveground dry biomass estimates derived from the different sources which are variable.

Nearly all of the estimates based on indirect methods depend on information derived from forest inventories made for harvesting purpose only. Also, the volume-based estimates are obtained by using wood density (mean value for all Amazonian tree species at dbh), and a correction factor for trees with dbh smaller than 25cm.

The most recent estimates of Brown and Lugo (1990), based on inventories made by FAO (Food and Agriculture Organization) experts during the fifties and sixties in the whole Amazon areas, vary from 90 to 397 metric tons per hectare, with a weighted average of 268t/ha. Fearnside (1991) pointed out that Brown and Lugo's (1990) weighted estimate is now closer to his own, 290t/ha. Their first estimate was 155t/ha for dense Amazonian forests. On the other hand, Fearnside (1987) concluded that the best estimate for aboveground dry biomass in the Brazilian

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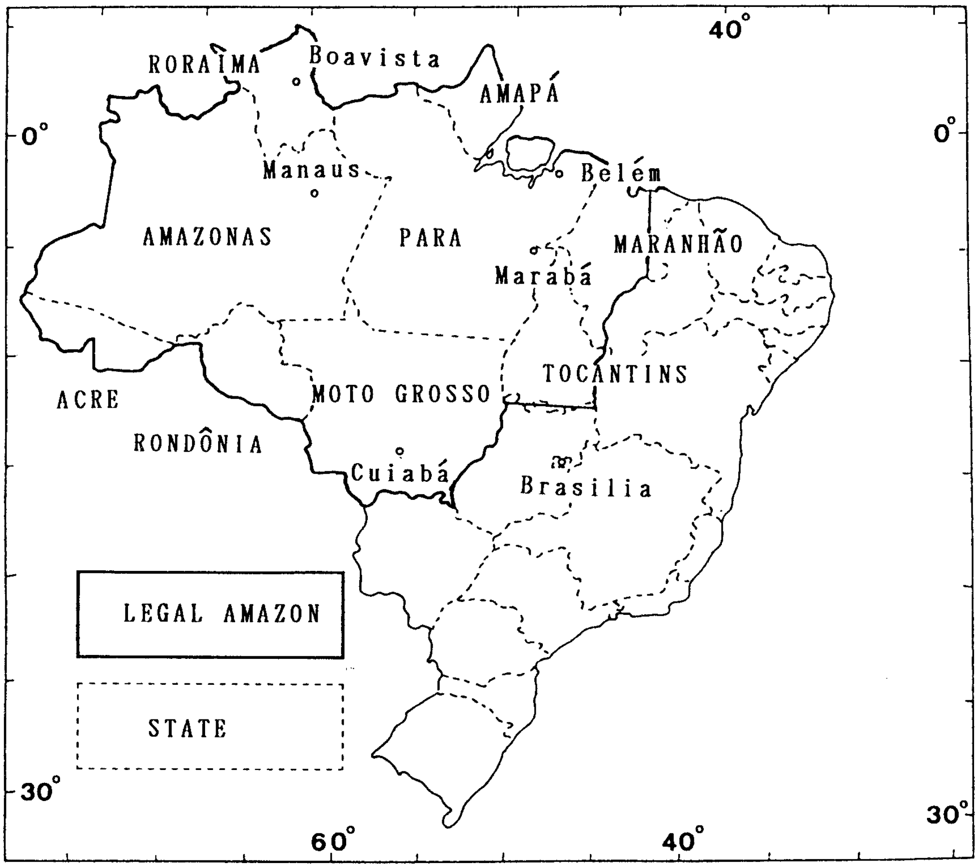

Fig. 1. Legal Amazon in Brazil.

Amazon was 215t/ha (S.D. =61.7), based on data from 13 inventories made by FAO experts.

Direct methods involve the felling and weighting of all the trees in an fixed-area sample plot. Brown et al. (1989) have pointed out that this method usually produces unreliable estimates on account of their relying on data from sample plots that are too small, too few, and often selected with bias. Based on literature, estimates from direct methods vary from 330 to 550t/ha (Brown and Lugo, 1990). Fearnside's (1990a) estimates vary from 155 to 610t/ha for the same Amazon region.

Klinge and Rodrigues's (1973) study is one of the most frequently cited with respect to Amazonian biomass. Their study, conducted at a site near Manaus, Amazonas State, revealed a dry biomass estimate of 400t/ha, based on a 0.2 ha plot. At a spot situated not very far from this site, researchers from INPA (National Institute for Research in the Amazon) and INPE came up with almost the same figure, approximately 400t/ha (results not yet published). According to Lescure et al. (1983), the aboveground dry biomass estimate for forests in French Guyana is 570t/ha.

Fearnside (1987) proposed 254.5t/ha as a conciliatory aboveground dry biomass estimate for the Brazilian dense tropical moist forests.

One thing that these two approaches share to some extent is that aboveground biomass estimate for Amazonian forests using direct measurements is almost impossible. For this reason, it is necessary to improve the indirect methods before obtaining reliable estimates.

We conducted a forest inventory directed at estimating standing aboveground biomass, and the data were collected according to the previous instructions fixed on how to obtain the fresh weight of trees with different dbh and total heights.

Materials and Methods

1. Mathematical Models

In temperate forests, mainly in the United States, the use of mathematical models to estimate standing aboveground biomass is a routine practice with a high level of refinement. According to the different models which have been tested, the allometric equations (1) and (2) have shown the best results.

$$W = a \cdot dbh^{b} \quad (1)$$

$$W = a \cdot (dbh \cdot ht)^{b} \quad (2)$$

where: W = fresh or dry weight
dbh = diameter at breast height
ht = total height
a and b = regression coefficients

In the tropical moist forests, especially in the Brazilian Amazon, there are no records, in forestry literature, of the development of mathematical models used to estimate biomass. In French Guyana, Lescure et al. (1983) used the allometric equation to fit their observed biomass data.

One of the main obstacles has been that it is the time-consuming data collection as well as the fit of the data to hypothesized models. Moreover, species diversity of Amazonian forests is a natural barrier for this kind of initiative.

In this study, aboveground biomass data came from the following different regions in the Brazilian Amazon: Tucurui, Xingu, Babaquara, Samuel and Balbina—collected by the Botany Department of INPA. Data collected by the Tropical Forestry Department came from an experimental station, 50km north of Manaus. The descriptive statistics of those data are presented in Table 1.

Table 1. Descriptive statistics of the data used in developing mathematical models for aboveground biomass

DC	Variable	N	Min	Max	Mean	S.D.
	WF	257	9.1	680.0	102.3	125.8
5≦DC<20cm	D	257	5.0	19.8	9.6	3.8
	H	257	1.3	28.4	13.6	4.6
	WF	113	112.5	15798.0	1926.6	2448
≧20cm	D	113	20.0	120.0	35.3	16
	H	113	10.1	38.0	25.0	6

DC = diameter classes
N = number of stems
WF = fresh weight in kg
D = diameter at breast height, 1.3m, in cm
H = total height in m

The following regression models for biomass estimation were tested:

$$W=a \cdot D^b \quad (3)$$

$$W=a \cdot (D \cdot H)^h \quad (4)$$

$$W=a+b \cdot D+c \cdot D^2 \quad (5)$$

$$W=a+b \cdot H+c \cdot D^2 \cdot H \quad (6)$$

$$W=a \cdot D^b \cdot H^c \quad (7)$$

where: W =total (trunk and crown) fresh or dry weight in kg
D =dbh (diameter at breast height) in meter
H =total height in meter
a, b, c =regression coefficients

According to Santos (1992) the biomass model used in eguation (7) produced the best results for both of the diameter classes, $5 \leqq dbh < 20cm$ and for trees with $dbh \geqq 20cm$. This equation was linearized, using natural log; and the ordinary least squares method was used for regression analysis. This model had the lowest standard error of estimate, the highest determination coefficient, and the best residual distribution. The summary of this result is presented in Table 2. This model has been used quite often to estimate the volume of Amazonian forests.

Table 2. Results of regression analysis in each diameter class

DC	Coefficients			R^2	S.E.
	a	b	c		
$5 \leqq dbh < 20cm$	-2.4768	2.2301	0.6518	0.97	0.2451
$dbh \geqq 20cm$	-3.8102	1.4631	1.8190	0.92	0.3728

R^2 =determination coefficient
S.E. =standard error of estimate

2. Forest Inventory

Systematic sampling method was used according to Higuchi's (1986-87) findings for Amazonian dense forests. In each sample unit, the following information was taken: site characteristics, the common names of tree species, and the independent variables dbh and total height (10% of trees observed in each sample unit).

The sample unit shape was rectangular, 20 by 200m or $4{,}000m^2$ as recommended by Higuchi et al. (1982) for inventories in Amazonian forests. Four sub-samples of 20 by 50m were established. Within the sub-sample, 10 by 10m was established to measure trees with dbh counting less than 20cm.

3. Regions covered by the forest inventory

(1) South of Pará

Marabá is the reference town in this region, about 600km south of Belém (Capital of Pará State), and about 2,000km east of Manaus (Capital of Amazonas State). Big farms are predominant in the area.

The forest inventory was carried out in seven different localities of the region. These localities and the number of sample units in each point are presented in Table 3.

Table 3. South of Pará -localities sampled and the number of sample units in each point

Locality	S.U.
Pioneira Farmer, COSIPAR, 40km SW Marabá	8
São José Farmer, COSIPAR, 45km SW Marabá	6
Forest Reserve, CVRD, 45km SW Marabá	8
Iron Mining, Carajas, 100km SW Marabá	4
Environmental Protection, Carajás, 100km SE Marabá	4
Tapirapé Biological Reserve, Carajás, 100km SE Marabá	7
Tapirapé-Aquiri National Forest, Carajás, 100km SE Marabá	20
Total	57

S.U. = number of sample units

This area with a significant presence of "brazil-nut" (*Bertholletia excelsa*), locally known as "castanheira" represents the last forest reserves partially conserved along the PA-150 highway. In fact, most of the forests look intact irrespective of the fact that they have suffered prior selective logging of "mahogany" (*Swietenia macrophylla*) or "mogno".

The main activities converting natural forests into other land use forms are: mining, cattle ranching and logging. The deforestation rate in this region is one of the highest in the Brazilian Amazon. The speed of this conversion is impressive. During the dry season, for instance, many airports have been closed because of the large amount of pollutant particles in the air, due either to smoke, provoked by pasture or agriculture area preparation, or to dust from the timber transportation on the unpaved roads.

The number of forest industries, consisting of mainly sawmills, is also impressive. According to Verissimo et al. (1989), in Tailandia (about 200km north of Marabá, on the PA-150 highway), in 1989, 48 sawmills were in operation, and these consumed approximately 400,000m^3 of roundwood. This volume represents the total consumption of all the timber-oriented industries of the State of Amazonas in 1991. In Paragominas (300km NE of Marabá, along the Belém-Brasília highway) there were 238 sawmills in operation and these consumed almost 3 million cubic meters of roundwood annually in 1990 (Verissimo et al., 1991). Today, more than one hundred tree species are being processed by forest industries in this region.

Up to the 1970s, forest activities had functioned only as sub-product of other development projects in the region, consisting mainly of subsidized agriculture and cattle ranching programs. Today, however, the situation has been inverted. Forest products are now being used as indispensable subsidies for those programs. When federal subsidy programs were discontinued in the beginning of the 1990s it was expected that deforestation rates would begin to be decreasing, but the increased value of forest products maintained it at the same level.

(2) South of Roraima

Caracaraí is the reference town in this region, situated about 150km south of Boa Vista (Capital of State of Roraima), and about 700km north of Manaus. Small farms are predominant in the area.

The forest inventory was carried out in three different localities of the region. These localities and the number of sample units in each are presented in Table 4. This work covered the following municipalities: Caroebe, São João da Baliza, São Luiz do Anauá e Caracaraí-along the "Perimetral Norte", BR-210 highway.

Table 4. South of Roraima-sampling points and the number of sample units in each point

Locality	S.U.
Caroebe, Lote Sr. Joaquim, 200km SE Boa Vista	20
São João da Baliza, Lote Sr. Oliveira, 200km SE Boa Vista	20
São Luiz do Anauá , 150km S Boa Vista	17
Total	57

S.U. =number of sample units

The landscape is dominated by secondary forests, or some "Campina" type vegetation (forest on white sandy soils), and is scattered with primary dense tropical moist forests.

This region is labeled qualified as a high risk area for deforestation, because it has been colonized since 1970s according to the traditional programs of INCRA (National Institute for Colonization and Agrarian Reorganization). The peculiarity of the colonization process in this region was the participation of the State Government. INCRA gives a plot of land (50ha in average) to farmers coming from elsewhere in Brazil. They immediately cut down the forest to guarantee land tenure, and burning is the only process taken by them to prepare the areas for plantation.

Simultaneously with the State Government's reduction of its participation the agriculture production zone of Roraima failed. In addition, the climatic conditions, tropical diseases, lack of adequate technical assistances and the high living costs have contributed to the failure. Many small holders have insisted on pursuing their survival through agriculture, and some have shifted to another "eldorado", some being now gold miners in Roraima.

In south of Roraima, logging is still a secondary activity, or a sub-product of clearing for agriculture and other development projects. Only small sawmills with totally obsolete equipments are operating. The following tree species are the mostly used ones: "angelim pedra" (*Dinizia excelsa*), "cardeiro" (*Scleronema micranthum*), "cedrorana" (*Cedrelinga cateniformis*), "louro gamela" (*Nectandra rubra*), "piquia" (*Aspidosperma* sp.) and "sucupira" (*Andira* sp.).

4. Additional information

(1) Floristic composition

A floristic survey was carried out at the same time as the forest inventory. This was done by researchers from the Department of Botany of INPA, and the final report is going to be presented separately. For the forest inventory purposes common names of tree species or morpho-species were used.

(2) Morpho-species abundance and frequency

This information is presented to determine the dominant tree species or morpho-species in the inventoried regions. For a better understanding of the forest structure of those regions the work done by Department of Botany is more appropriate.

(3) Fresh and dry weight ratio

Fresh and dry weight ratios were determined from data collected in the Biomass Project area, at the Tropical Silviculture Experimental Station of INPA, 50km north of Manaus. Samples from trunk, branches, leaves and flowers or fruits were dried at 105 degrees Celsius until weight stability was reached. Preliminary results show that the total dry weight represents an average of 60.4% of the fresh weight (N=76 trees and S.D.=7.8). Also, the trunk weight represents 68.6% of the total tree weight (N=76 and S.D.=14).

Results

1. Biomass equation

The best equations for estimating standing aboveground fresh biomass are as follows:

$$\ln WF = -2.4768 + 2.2301 \cdot \ln(D) + 0.6518 \cdot \ln(H) \quad (5 \leqq dbh < 20cm)$$

$$\ln WF = -3.8102 + 1.4631 \cdot \ln(D) + 1.8190 \cdot \ln(H) \quad (dbh \geqq 20cm)$$

where: WF=fresh weight in ton

Fresh weight is usually more dependent on the total height than the dbh of a tree. Therefore, the previous model produced the best results. In addition, according to Gillespie and Cunia (1989) models not including height as an independent variable, produce biased estimates of the parameters, particularly when data collection is based on the proportional probability to the tree size.

2. Aboveground biomass estimates

The results of the forest inventory for the South of Pará and the South of Roraima are summarized in Table 5. Visually, one has the impression that forests in Pará are higher than those of Roraima because of the significant presence of the huge "brazil nut" trees. However, this was not confirmed by the inventory. The forests inventoried in Roraima presented a mean basal area, per hectare, being 30% higher than in the Pará ones, as does the aboveground biomass. On the other hand, Pará forests are likely to be more homogeneous since the coefficients of variation for number of individuals per ha (N), basal area per ha (BA) and fresh weight (WF) parameters from Roraima were always greater than those of the Pará ones.

Table 5. Estimates on hectare basis in each inventoried region

Variable		South of Pará			South of Roraima		
		5≦D<20cm	D≧20cm	All	5≦D<20cm	D≧20cm	All
Mean values	N	1027	131	1158	1096	168	1264
	BA (m^2)	7.60	16.26	23.92	11.15	20.87	32.02
	WF (ton)	79.53	227.27	306.80	134.61	242.75	377.36
	WF (ton)	48.04	137.27	185.31	81.30	146.62	227.92
Coefficient of variation	N	30.5	26.1	27.9	37.3	22.6	35.3
	BA	32.3	43.7	31.6	41.7	44.7	43.7
	WF	36.0	47.0	35.6	46.0	41.1	42.9
Minimum	N	350	59	495	350	60	490
	BA (m^2)	2.64	6.39	10.81	3.61	7.20	15.11
	WF (ton)	26.04	75.20	115.32	42.23	86.23	184.79
Maximum	N	1800	220	1978	2250	280	2347
	BA (m^2)	13.44	44.32	50.05	23.30	45.92	58.39
	WF (ton)	148.80	584.24	636.64	319.39	495.04	643.32

N =number of individuals
BA =basal area in m^2
WF =fresh weight in ton
WD =dry weight in ton

Fresh weight (WF) estimates for South of Pará and South of Roraima (for vegetation with dbh≧5cm) are as follows, respectively:

WF=306.8t/ha (South of Pará)

WF=377.4t/ha (South of Roraima)

Dry weight (WD) estimates for South of Pará and South of Roraima (for vegetation with dbh≧5cm) are as follows, respectively:

WD=185.3t/ha (South of Pará)

WD=227.9t/ha (South of Roraima)

A simple comparison of these estimates with others obtained elsewhere is not quite relevant. Dry weight estimates of this work, 185.3t/ha and 227.9t/ha, are comparable to the conciliatory estimate of Fearnside (1987), 254.5t/ha, and to that of 268t/ha from Brown and Lugo (1990), or to that of 215t/ha, based on 13 inventories carried out by FAO experts (Fearnside, 1987). If all these estimates were obtained, using the same diameter class limits, the dry biomasses of the South of Pará and of the Roraima forests are, respectively, 24% and 8% smaller than the others. However, this comparison does not make much sense because the methodologies used to obtain all estimates vary greatly even for data collection.

In this study the number of individuals per ha and the basal area per ha, were also estimated to facilitate comparison among different forest inventories which have been carried out in the Brazilian Amazon. Inventories carried out in different localities in the Amazon, excepting those carried out by FAO experts are presented in Table 6.

Table 6. Mean values estimates on hectare basis in different localities in the Brazilian Amazon (dbh≧20cm)

Locality	N	BA (m^2/ha)	Source
Trombetas	171	23.09	INPA/CPST, 1982
Rio Arinos	119	13.58	INPA/CPST, 1983a
PIC Altamira	146	21.97	UFPr/CPF, 1976
UHE Balbina	191	29.38	INPA/CPST, 1983b
EEST	254	22.74	INPA/CPST, s/d
UHE Santa Izabel	131	15.22	INPA/CPST, 1983
PDRI/Acre	135	17.72	INPA/FUNTAC, 1989

Taking into account only the dbh≧20cm class, the estimates for the N and BA variables are as follows:

N=131 trees/ha and BA=16.26m^2/ha (South of Pará)

N=168 trees/ha and BA=20.87m^2/ha (South of Roraima)

In the South of Pará, N and BA estimates are 20% smaller than the average of the seven localities inventoried (Table 6), while those are greater than it only in relation to Rio Arinos and UHE Santa Izabel (only BA). This means, on the same comparison basis, that the quantitative potential of the South of Pará region is smaller than the average of the most Amazonian forests. However, South of Roraima is within the Amazonian average.

The difference of 24% in the aboveground dry biomass estimated by this work in comparison with those of Brown and Lugo (1990) and Fearnside (1987) is better understood, concerning the South of Pará region. Since N and BA are 20% smaller than the Amazonian average, it is expected to have the same difference in terms of biomass.

In comparing the estimates of the dry weight obtained in this survey, 185t/ha and 228t/ha, with the results from direct method the difference is quite high and difficult to be explained. These estimates are in the inferior range for Amazonian forests, which is from 155 to 610t/ha (Fearnside, 1990a). This difference can partially be explained by the distinct methodologies used in both the methods. Direct methods have to be applied more extensively in different localities in the Brazilian Amazon, with more replicates and larger sampling plots, mainly for the purpose of feeding back the current mathematical models used to estimate the standing aboveground biomass.

Mean values of the fresh weight of the compartments (trunk, branches and leaves) for both inventoried regions are presented in Table 7. Trunk has the biggest participation in the total aboveground biomass, reaching almost 70%, while leaves contribute to it with only 4%. This type of information is important because when fire is used to prepare the land for plantation, each compartment behaves differently. In general, the leaf biomass is totally burned during the first burning, while less than 50% of the trunks are burned.

Table 7. Mean value estimates of fresh weight in each tree compartment (metric ton per hectare)

Region	Compartment	5≦D<20cm	D≧20cm	All
South of Pará	Trunk	54.56	155.91	210.46
	Branches	21.63	61.82	83.45
	Leaves	3.34	9.54	12.89
	Total	79.53	227.27	306.80
South of Roraima	Trunk	92.35	166.53	258.88
	Branches	36.61	66.02	102.63
	Leaves	5.65	10.20	15.85
	Total	134.61	242.75	377.36

3. Abundance and frequency

The number of species, for forest inventory purposes, means individual, grouped or morpho species. Each inventoried region presented 250 different species with an overlap of 70%. This figure quite well represents Amazonian forests.

Taking into account only trees with dbh≧20cm, 32 species (or morpho-species) represent more than 80% of the total individuals sampled in both the regions. In South of Pará, the following species are the most frequently observed and abundant: "breu-vermelho" (Burceraceae), "pau-pretinho" (Leguminosae), "inga" (Leguminosae) and "gito" (Meliaceae) — which are not actually sold in the region. In South of Roraima the most important species are: "abiurana" (Sapotaceae), "matamata" (Lecythidaceae), "breu-vermelho", "faveira" (Leguminosae) and "inga".

For the diameter class "between 5 and 20cm" (5≦dbh<20), 25 species represent more than 80% of the total sampled individuals. In South of Pará the most important species in terms of abundance and frequency are: "branquinha" (Sapotaceae), numerous species of lianas from different botanical families, "inga", "breu-vermelho" and "joao-mole" (Chrysobalanaceae). In South of Roraima the most important species are: "abiurana", "breu-vermelho", lianas, "envira" (Anonaceae), "inga" and "matamata".

The most valuable species in the South of Pará is "mogno" or "mahogany" (Meliace), but its abundance in the inventoried region is quite insignificant. Only 3 individuals were found in 22.8 ha sampled (13 trees in each 100 ha) for dbh≧20cm class, and there is no record of natural regeneration or for 5≦dbh<20cm class. On the other hand, "castanheira" or "brazil-nut"

(Lecythidaceae) is very important to the forest structure at least in the dbh≧20cm class. Thirty one individuals were found in 22.8ha (more than one tree per ha), and it was found in almost 90% of the sampled plots. However, natural regeneration is almost absent.

Discussions

For the South of Pará and the South of Roraima regions, the dry aboveground biomass estimates of 185t/ha and 228t/ha, respectively, for all the vegetation with dbh greater than 5cm, are quite reliable, because they come from forest inventories carried out exclusively for biomass estimation, within a limit of error smaller than 10%. The basal area estimates are 23.9m^2/ha and 32.0m^2/ha, respectively for South of Pará and South of Roraima.

From a quantitative point of view, the aboveground biomass estimates of the inventoried forests are smaller than the Amazonian average. However, it is quite important to point out that the inventoried forests do not fulfill the profile of primary Amazonian forest. Most of the South of Pará forests, for instance, have been submitted to a prior high selective "mahogany" harvesting even in the protected forest reserves. The same can be said of the South of Roraima forests where the only difference lies in respect to the tree species harvested earlier. Nevertheless, these forests represent the "most" virgin stands in these regions.

There is no doubt about the fact that these two regions are seriously threatened by deforestation, followed by the degradation of the environment. They have presented the highest deforestation rate in the last five years, and probably will maintain this rate for some time, still. The speed of the transformation from forests to other land uses is impressive. Any sustainable development principles have not been considered yet by most projects in both the regions. Compared to other portions of the Brazilian Amazon, these inventoried regions have good access, at least in the form of six hundred kilometers of paved road.

Forest activities are also intensive principally in the South of Pará. Based on the number of sawmills in operation in this region it is probable that forest products are economically of not a small interest. This means that farmers do not burn all existent biomass when they are preparing areas for plantation. For this reason, the amount of gases finally released to the atmosphere, due to the burning can not be taken as a due to the biomass estimates of the original forest. So, the information from this work is important to calculate the biomass of Amazonian forests which has been transformed into other forms of land use, but the estimates of the amount of gases released to the atmosphere will require more specific studies.

Summary

The making of a forest inventory was carried out exclusively to obtain an estimate of aboveground biomass for Amazonian dense tropical moist forests, particularly in the South of Pará and South of Roraima. These regions have suffered excessively high deforestation rates in the last five years. Aboveground biomass was estimated through mathematical models for total (stem and crown) fresh and dry weight of whole vegetation with a diameter at breast height (dbh) counting greater than 5cm. The selected model contained tree dbh and total height. Besides biomass, this also presents estimates for number of trees and basal area on a hectare basis. Sampling size was 22.8ha, and plot dimensions were 20 by 200m for both regions. Dry weight estimates for South of Pará and South of Roraima are 185t/ha and 228t/ha, respectively.

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