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# TROPICAL FOREST BURNING IN BRAZILIAN AMAZONIA: MEASUREMENT OF BIOMASS LOADING, BURNING EFFICIENCY AND CHARCOAL FORMATION AT ALTAMIRA, PARÁ

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# ABSTRACT

Mass transformations were estimated in burns in the clearings of three colonist lots near Altamira, Pará, Brazil. In each lot, two groupings of six 60-$m^2$ plots were established in sites where the forest had been recently felled; plots were arranged as rays in a star-shaped pattern, with pre-and post-burn measurements made in alternate rays. Pre-and post-burn aboveground biomass was estimated by cutting and weighing the felled vegetation in 15 pre-burn and 18 post-burn plots (3 pre-burn plots could not be weighed before one of the colonists burned the clearing) and by line intersect sampling (LIS) done along the axis of each of the 36 plots. Because of the high variability of the initial biomass present in the plots, volume data from LIS were more reliable for assessing change in the biomass of material over 10 cm in diameter (because this technique permits measuring the same trees before and after burning); other quantities relied on data from direct weighing. The best estimate of the mean pre-burn aboveground biomass at the site is 263 metric tons per hectare (t $ha^{-1}$); considering available measurements of the proportion of belowground biomass elsewhere in Amazonia, the total dry weight biomass at the Altamira site corresponds to approximately 322 t $ha^{-1}$. Assuming 50% carbon (C) content for biomass, the aboveground biomass at Altamira represents a carbon stock of 130 t $ha^{-1}$. Assuming a carbon content of 75% for charcoal, 1.3% of the pre-burn aboveground carbon stock was converted to charcoal, substantially less than is generally assumed in global carbon models.

Measurements at Altamira imply a 42% reduction of aboveground carbon pools if calculated including the scattered trees that farmers leave standing in their clearings, or 43% if these trees are excluded from the analysis. These values are substantially higher than the 27.6% measured in an earlier study near Manaus. However, most of the difference between results at the two sites is explained by differences in the distribution of initial biomass among the fractions, especially greater quantities of vines and of litter (including dead wood <5 cm in diameter) than at Manaus. Smaller diameter pieces burn more thoroughly than larger ones. At Altamira, the large percentage of aboveground carbon in vines (12.0%) is less typical of Amazonian forests than the lower percentage at Manaus (3.1%). The lower overall burning efficiency found at Manaus is therefore believed to be more typical of Amazonian burning. High variability indicates need for further studies in many localities, and for perfecting less-laborious indirect methods. Both high biomass and low percentage of charcoal formation suggest significant potential contribution of forest burning to global climate changes from $CO_2$ and trace gases.

Keywords: Deforestation, Burning, Greenhouse gases, Carbon dioxide, Tropical Forest, Biomass, Rainforest

# 1. Introduction
## 1.1. Deforestation and Greenhouse Gas Emissions

Tropical deforestation releases carbon dioxide, methane and other gases that contribute to the global greenhouse effect (e.g., Houghton et al., 1996). Emissions estimates are generally derived by multiplying areas burned by biomass per unit area (biomass loading), carbon content of biomass, fraction of carbon burned (burning efficiency), and the emissions of each substance per unit of carbon burned (emissions coefficient: sometimes expressed per unit of biomass burned). The sequence can be extended in various ways--for example, by using one coefficient for $CO_2$ emitted per unit of carbon or biomass burned and a second for each of the other substances emitted per unit of emitted $CO_2$, or by adding terms to account for delayed post-burn releases. However, the sequence "area times biomass loading times burning efficiency" is invariably part of the calculation. In chain computations of this sort, uncertainties tend to explode when the coefficient of variation of individual terms exceeds 0.3 (Robinson, 1989).

In tropical forest, the uncertainties are large. Area burned is usually equated to area felled in tropical forest, and this assumption is a reasonable one in the case of Brazil. The range of values appearing in the literature for the rate of deforestation in Brazil greatly exceeds the range of real scientific error concerning this important factor due to known errors in a number of estimates (see Fearnside, 1997a); nevertheless, the coefficient of variation of this term probably approaches 30%. Biomass loadings and fractions of biomass burned are highly variable, and are difficult and expensive to measure in tropical forest. Few estimates of burning efficiency have been made, and those that exist indicate high variability among years and among sites on a micro scale at any given site.

This paper presents results of a field experiment designed to provide additional measurements of biomass loading and fraction of biomass burned, and to develop methods designed to yield, in a replicable and low-cost fashion, rough but unbiased estimates of both parameters. Our goal here is to document both methodological and quantitative findings in a fashion that contributes to reduction of uncertainties about emissions from tropical forest burning.

Primary forest in Brazilian Amazonia was converted to ranching, agriculture, hydroelectric dams and other uses at a rate of $20.4 \times 10^3$ $km^2$ $yr^{-1}$ over the 1978-1988 period (Fearnside, 1997a); the rate declined (beginning in 1987) to a low of $11.1 \times 10^3$ $km^2$ $yr^{-1}$ in 1990-1991, and climbed to $14.9 \times 10^3$ $km^2$ $yr^{-1}$ in 1992-1994; the rate then jumped to $29.1 \times 10^3$ $km^2$ $yr^{-1}$ in 1994-1995, and fell to $18.2 \times 10^3$ $km^2$ $yr^{-1}$ in 1995-1996; a preliminary estimate for 1997 indicates a deforestation rate of $13.0 \times 10^3$ $km^2$ $yr^{-1}$ (Brazil, INPE, 1998).

The 1990 deforestation rate implied a contribution from clearing in Brazilian Amazonia of 0.3 billion metric tons (Gigatons = G tons) of net committed emissions of carbon (Fearnside, 1997b).

Estimates of Amazon forest biomass vary (Brown et al., 1995; Alves et al., 1997). Because of the high biomass and vast area of dense upland forests of Amazonia, the differences in values used for their biomass have a great effect on conclusions drawn from calculations of release of $CO_2$ and other greenhouse gases.

## 1.2. The Study Area

The present study was done in three 100-properties (lots) in the Altamira colonization area of Brazil's Transamazon Highway (Figure 1). The lots (Gleba 15, lot 8; Gleba 18, lot 3; Gleba 18, lot 20) are located within 4 km of Agrovila Grande Esperança, 50 km west of Altamira in the state of Pará (3°22'S, 52°37'W, altitude approximately 100 m). The lots are within an area where a long-term study of human carrying capacity is underway; the physical features and agricultural system at the site are described in detail in conjunction with this work (Fearnside, 1986). The forest in the study area is classed as lowland Amazonian dense ombrophilous forest (Db) (Brazil, IBGE and IBDF, 1988). The most common species of large trees are Manilkara huberi (maçaranuba), Carapa guianensis (andiroba), Ocotea spp. (louro), and Vouacapoua americana (acapú)(Brazil, IBDF, 1975: 25). Burning is an essential part of the agricultural system in the area: planting is facilitated because burning removes much of the physical encumbrance of downed vegetation, and crop yields are improved by higher soil fertility that results from ash deposition. The increase in pH resulting from burning is particularly important for crop yields on these acid soils; pH is the soil factor that best explains productivity for most crops grown by settlers at this site (Fearnside, 1986).

[Figure 1 here]

Average annual rainfall at Agrovila Grande Esperança (at the center of the study area) is 1697 mm (1980-1992). Rainfall at this location is highly variable from year to year (cv=31% for annual total, based on 1931-1976; Fearnside, 1984, p. 138). For the burning season (September-December), mean precipitation is 282 mm, but cv is even higher at 53%, resulting in a great variation in quality of burns from year to year. There are substantial differences among colonists regarding dates of clearing and burning (Fearnside, 1986, p. 186), a feature probably encouraged by the unpredictable timing of the rains. Part of the variation in burn quality can be predicted from weather data in the period preceding the burn using discriminant analysis (Fearnside, 1989).

## 2. Methods

### 2.1. Sampling

The colonists (farmers in government-sponsored settlement projects) felled areas of forest as part of the preparation of land for slash-and-burn agriculture. The forest was primary (i.e., old growth or "virgin") in all cases, with no signs of disturbance perceptible. We set up sample plots in the clearings during the 1-2 month interval between the time colonists felled the trees and the time they burned the downed vegetation. Colonists sometimes leave a few scattered trees standing in their clearings; although none of these were located in the sample plots, a rough estimate of their biomass was made separately based on photographs taken in an overflight of the clearings.

The sampling design for the felled vegetation consisted of 2 m X 30 m plots in the form of rays or spokes, grouped into "stars" of six rays each. The rays emanated from a common center at angles of 60°, each beginning at a distance of 10 m from the central point. Each ray was subdivided into three ray segments of 2 m X 10 m. The stars were laid out in groups of two, each of the stars making up a pair being within about 100 m of the other. Stakes marked the corners of each plot, with iron reinforcing bars being used in the case of post-burn plots. The rays and stars design seeks to 1) avoid heavily sampling the area under one or a few trees, as tends to happen when one uses conventional quadrats in a forest, 2) minimize angular bias (because trees are often felled roughly parallel to one another) by adopting 60° angular orientation, and 3) be simple to lay out in the field.

Six stars were set up (Figure 1). Each star was considered a sampling point, denominated by letters from A to F. Two (B and E) were in Gleba 15, lot 9 (belonging to Sr. Manoel Soares) located beside the Transamazon Highway (BR-320), km 48 west of Altamira; two (A and F) were in Gleba 18, lot 3 (belonging to Sr. Adolfo Soares) located beside the Transamazon Highway at km 50, and two (C and D) were in Gleba 18, lot 16 (belonging to Sra. Tereza de Lima) located 3 km north of km 50 of the Transamazon Highway on Lateral Road No. 18. The rays were numbered from 1 to 6 in each star, and identified by the letter of the star and the number of the ray (Figure 2).

[Figure 2 here]

All pre-burn rays were destructively sampled except for C3, D1, and D3, which could not be harvested in the time available before the colonist burned the area. The pre-burn destructive sampling therefore totaled 15 rays of 60 $m^2$ each, or 900 $m^2$.

### 2.2. Collecting and Weighing Biomass

#### 2.2.1. Classes and Stocks of Samples

The material was categorized into the following biomass type and diameter classes: 1) Wood (including stumps) in diameter classes <5 cm, 5-10 cm and >10 cm; 2) Vines in the same diameter classes, 3) Litter, encompassing both the litter proper and materials such as leaves, fruits and flowers that fall to the ground when the biomass dries in the sun; also included in this class were small twigs and vines that are difficult to separate manually from other material on the ground; 4) Small palms and palm leaves (trunks and leaves of palms ≤10 cm in diameter + leaves of palms >10 cm in diameter), in classes for stem diameters <10 cm (including leaves of both classes) and palm trunks ≤10 cm; 5) Palm trunks >10 cm in diameter; and 6) Other materials, such as palm fruits (babaçu: Orbignya spp.), grasses (bamboos), and banana-like plants (e.g., Musaceae and Heliconiaceae). Roots were not considered; these were rarely encountered in the plots, and represented an insignificant portion of the aboveground biomass.

### 2.2.2. Collection Procedure

The plots in which destructive sampling was to be done were first outlined with nylon twine stretched between the corner stakes. The biomass was cut using a chainsaw for trunks, thick branches and stumps; pieces extending outside the plot were cut at the plot boundaries. The chainsaws were used to cut trunks and thick branches for weighing for samples. Smaller pieces, such as thin branches and vines, were cut using machetes. For obtaining wet weights, all pieces were cut into fractions small enough to allow placement on a tray that was suspended from a 90 kg-capacity spring balance.

For each class of biomass, a representative sample was separated out and weighed in the field, after which the sample was placed in a plastic bag and tagged with information on the ray segment, ray, biomass type and diameter class. These samples were drawn in a haphazard (presumably random) fashion from the piles of material that had been weighed from the plots for each biomass type and class, with the exception of the class with diameter >10 cm, which was taken from a disk cut from each piece.

Wet weights of the samples ranged from 246 g to 3.0 kg for wood <5 cm in diameter; 334 g to 3.1 kg for wood in the 5-10 cm diameter class; 102 g to 8.1 kg for wood >10 cm in diameter; 180 g to 2.9 kg for vines <5 cm in diameter; 274 g to 1.4 kg for vines in the 5-10 cm class and 231 g to 935 g for vines >10 cm in diameter. The samples of litter ranged from 20.4 g to 493 g; palms up to 10 cm in diameter and leaves ranged from 17.8 g to 998 g; palms >10 cm in diameter ranged from 27.0 g to 3.0 kg, and other types of material ranged from 247 g to 302 g. The balance used for weighing each sample was chosen in accord with the weight of the sample and the capacity of the balance.

### 2.2.3. Balances

The balances used for wet weight measurements were: a 90 kg-capacity Houston brand spring balance accurate to 1 kg; a set of Pesola spring balances with capacities of 50 g (accurate to 0.5 g), 300 g (accurate to 2.0 g), 500 g (accurate to 5.0 g), 1 kg (accurate to 10 g), and 2 kg (accurate to 50 g). To measure dry weights, two electronic balances (Sartorius 1309 MP and Marte AM5500) were used, both accurate to 0.01 g. The smaller capacity balances, including the electronic balances, were calibrated with a single set of standard bronze weights, while the 90 kg-capacity balance was calibrated using known volumes of water.

### 2.2.4. Drying of Samples

Samples were dried using a forced-air oven at 60°C, followed by final drying in an electric oven at 105°C. Dry weights were determined during final drying when constant weight was attained.

### 2.2.5. Dry Weight Estimation

Moisture content of each sample was calculated on a dry weight basis (the difference between wet and dry weight divided by the dry weight). Dry weight estimates for each sample were necessary because of variation in moisture content among different types of biomass, and because of differences in the state of drying of the biomass at each sample point because of the timing of felling and sampling at each plot.

Operational problems prevented us from achieving an individually determined moisture content for each biomass fraction and plot. Resolution of these problems is described in an appendix that is available from the authors.

The total stock of dry biomass was estimated by summing the means of each class (using each ray segment as a sub-sample). In the case of the >10 cm diameter wood class, the mean was derived from the post-burn ray segments (before burning) and the pre-burn ray segments not sampled by the direct method, including the ray segments that had lost data, in which the LIS (indirect method) was performed.

## 2.3. Sample Volume Measurement

Volumes of the samples were measured directly by displacement of water by immersion of samples. An empty 20 liter-capacity oil drum was used with a tap installed in the side 15 cm below the top of the drum. The drum was filled with water to the level of the tap (water was allowed to drain from the tap until the level in the barrel stabilized). The sample was then immersed, and the water overflowing from the tap caught and measured in a 1000 ml-capacity graduated cylinder accurate to 10 ml. Each sample was left submerged for approximately one hour to allow stabilization of the water level. Prior to volume measurement, samples had undergone a pre-drying in a homemade gas oven to avoid their deteriorating prior to volume measurement.

Procedures for weighing, calibration of balances, removal and drying of samples and sample volume determination were the same as in the pre-burn case for all other types of biomass.

### 2.4. Stock Volume by Line Intersect Sampling (LIS)

Line intersect sampling (LIS) was used to estimate the volume of all types of biomass (wood, vines) >10 cm in diameter. The procedure employed was based on the methodology developed by C.E. Van Wagner (1968) to estimate log volume in slashed forest areas. LIS consists of tallying the diameters of intersected pieces along a sample line to obtain an estimate of wood volume on the ground. The LIS was run down the length of all rays (2 m X 30 m) set up for destructive sampling, both in the pre- and post-burn plots. In the post-burn plots it was possible to evaluate volume both before and after the burn for the same pieces with the measurements made at the same point on each piece, thereby reducing to a minimum the effect of spatial variation in the biomass. The volumes could be converted into weights using densities from samples taken in the destructive sampling.

Trees were labeled with tags in order to follow individual trees through the transformations caused by burning. The marking also provided orientation in the field when drawing a sketch map of each plot. Aluminum tags were affixed to the trunks with nails. Tags were numbered and identified with respect to the sampled ray. They also served to mark the spot on the trunk where the diameter measurement was made, preferably with at least two points marked around the circumference of each trunk to relocate the diameter measurement point.

Some of the tags were melted or fell to the ground when the trunk was consumed by fire (the tags used were 0.2 mm thick. We recommend that aluminum tags at least 0.5 mm thick be used). We were able to identify all logs despite some lost tags thanks to having drawn a detailed sketch map showing locations of trees in each ray segment.

In the LIS estimates, only trees intersected by the transect line were measured (not all trees in the 2 × 30 m plots). Diameters of the trees were measured with tree calipers at the points where the line intersect transect crossed the longitudinal axis of each tree. The diameters were measured with a measuring tape (graduated in millimeters) when the diameter of the trunk was too large to permit use of the tree calipers.

Sketch maps of the tree locations were drawn at the same time as the measurements of diameters, with trees sketched in the same order as the diameter measurements. The maps included indication of orientation of tree boles with respect to the crowns, the location of trees within the ray segment and the location of the LIS line with respect to the longitudinal axis of the trees. The maps also included the ordering and numbering of trees in accord with the tagging, some fixed geographical features such as streams and precipitous slopes, and notations concerning the type of wood and the presence of palms.

A photograph of each ray segment was taken from the vantage of the end of the ray segment nearest the center of the star. A numbered placard appeared in each photograph. The photographs allow checking of any information that may be unclear from the sketch maps.

The thickness of charcoal was measured in the post-burn plots around the circumference of the trees where the LIS crossed the trunks. Because charcoal formation around the circumference of a fallen log is nonrandom, measurement points were distributed around the log in a fixed pattern to allow estimation of an average value. Measurements were made at four points: on the top of the fallen log, at the bottom, and at the two sides. The thickness of the charcoal at the bottom of the log was considered to be zero for logs that were buried in the soil. Measurement was made with a plastic ruler graduated in millimeters. Small incisions were opened with a knife at the measurement points to a depth where there was no charcoal, and the ruler was inserted.

## 2.5. LIS Estimate of Volume in Pre-burn Plots

Volume was estimated using LIS only for the classes >10 cm in diameter. The volume of this stock was estimated for each 10-m ray segment, and the total volume of the stock was estimated from the sum of the means of the ray segments. The volume in each segment was calculated using the formula of C.E. Van Wagner (1968):

$$V = \frac{(\Sigma d^2)\ \pi^2}{8L}$$

where:

V = volume of the stock (>10 cm diameter)
d = diameters of pieces (>10 cm diameter) that crossed the sampling line
L = length of the sampling line.

The measurements made in the post-burn plots prior to the burn were included to estimate the mean of the total volume of the biomass stock.

## 2.6. LIS Estimate of Percentage Burned

For wood >10 cm in diameter, the percentage burned was calculated by comparing pre- and post-burn volumetric (LIS) data. The volume data were not used for the >10 cm diameter classes of vines and palms, nor for the volumes of trees that fell into the plots (crossing the sampling line) during or after the burning.

The separation of ray segments and elimination of the trees that fell during burning were only possible using the description of the location and orientation of the trees recorded on the sketch maps and field notes.

## 2.7. Estimation of Volumes of Biomass Stocks

### 2.7.1. Pre-burn Phase

Volume of the biomass stock was estimated by direct and indirect methods, and the two methods were compared. The "direct" result for volume was obtained from the density of the samples (dry weight of the samples divided by sample volume for each biomass sample class). After obtaining the stock of dry biomass for each fraction in each plot, the total volume of biomass was obtained from the mean volume per area ($m^3$ $ha^{-1}$) derived from the sum of ray segments in each biomass class. The indirect estimate was obtained from the LIS (described earlier).

### 2.7.2. Post-burn Phase

The volumes of the post-burn biomass stocks were estimated in the same way as the pre-burn mass, dividing the dry weights by the density of the sample for that class. The total volume was calculated by summing all classes. For charcoal, which is only present in the post-burn phase, charcoal stocks were collected after biomass fractions had been weighed with the charcoal still attached to them. The charcoal measurement procedures will be described in a separate section.

## 2.8. Charcoal Data Set

### 2.8.1. Charcoal Weights

The samples of the biomass were removed with their respective charcoal. Following the weighing of the biomass, charcoal adhering to the stocks was scraped off and weighed. The biomass with charcoal in each class of material was kept on polyvinyl tarps while awaiting the charcoal scraping and weighing procedures. Scraping was done with machetes, keeping each piece within the area of the tarp. The limit between charcoal and fresh biomass was based on visual appearance (blackness). Charcoal removed in the scraping process was put in plastic bags for weighing on a spring balance. Charcoal present on the soil surface was also collected and weighed in each subplot; this charcoal comes from completely carbonized material and from charcoal that falls off the pieces during and after the burn. Collection of charcoal in the soil was limited to what could be picked up manually, small quantities of very fine charcoal remaining uncollected. After scraping and weighing of each stock of charcoal, a sample was kept of each class and type of material, ranging from approximately 100 g to 1.5 kg. Samples were placed in plastic bags and labeled. Samples were oven dried and dry weight was determined as for wood. Resolution of problems with dry weight determination is described in the appendix mentioned previously.

A linear regression was used to relate the direct and indirect methods for estimates of post-burn charcoal formation for wood >10 cm in diameter ($r^2=0.50$, $p < 0.05$, $n=54$):

$$Y = 0.63 + 0.79\ X$$

where:

Y = weight calculated from LIS
X = directly measured weight.

### 2.8.2. Charcoal Volumes

Volume of charcoal samples was determined only for those biomass classes >10 cm in diameter. Most of the charcoal stocks in the other classes contained a large amount of charcoal in the form of fine pieces or powder, making it difficult to measure their volumes by immersion.

For charcoal on pieces in the >10 cm diameter classes, a subsample of approximately 100 g was removed from each of the original samples. The subsamples were sifted in a plastic sieve to facilitate removal of any uncarbonized material. The charcoal from each subsample was then placed in a small plastic bag made of finely woven cloth (of known volume) through which the charcoal is not believed to pass. This was immersed in a 1000 ml-capacity graduated cylinder and its volume determined after subtraction of the volume of the cloth bag. After volume measurement, each subsample was dried in a homemade oven to avoid deterioration of the material.

The estimate of charcoal production was done from the difference in the volume (measured by LIS) of wood with charcoal and the volume without charcoal, of each ray segment in the area sampled by the LIS. To obtain an estimate of diameter for use in calculating the volume of wood for each log (i.e., exclusive of charcoal), an amount equal to the mean thickness of charcoal on the log was subtracted from the log's radius.

## 2.9. Standing Trees

The biomass in trees left standing in the clearings had to be estimated for each clearing as a whole, as the small area covered by the sample plots was insufficient to represent this component. No standing trees were located within the sample plots, and, had any of the plots included one or more such trees, the effect on the plot-based biomass estimate would have resulted in an overestimate.

A rough estimate of the biomass in standing trees was made from projected slides taken from the air during overflights of the plots. These were used to count standing trees and to estimate trunk heights to the first branch, as well as for estimates of the areas of the clearings. Tree diameters were not measured, but a grouping of trees into two classes ("normal" and "thin") allowed a rough approximation of volume based on standing trees seen near the sample plots. Biomass of standing trees was estimated as described in Table 1.

[Table 1 here]

## 2.10. Percentage of Biomass Consumed by the Burn

The percentage consumed was calculated considering the stock of biomass in each class before and after the burn, calculated from the data from direct measurement (destructive sampling) with the exception of the class of wood >10 cm in diameter. This was obtained from the mean of the percentages of biomass consumed in each ray segment by the indirect (volumetric) estimate by line intersect sampling (LIS).

The percentages consumed of two very small classes were considered to be equal to zero: vines >10 cm in diameter and "other" (palm fruits, etc.). For these two classes the biomass present in the post-burn destructive sampling plots was larger than that in the pre-burn destructive sampling plots. Because these classes are only infrequently encountered, it would be necessary to have a much greater number of repetitions or a larger plot size to adequately sample these highly variable classes.

## 2.11. Estimation of the Pre- and Post-burn Biomass

For forest in the study area, the pre-burn biomass in the >10 cm diameter wood class was calculated as a mean of the estimated biomass for this class prior to the burn in all plots, pre- and post-burn. For the pre-burn plots the direct (destructive) results were used, while the biomass prior to the burn in the post-burn plots was estimated by converting into weights the pre-burn volumetric (LIS) measurements in these plots. The indirect method was also used in the pre-burn ray segments where the timing of the burn made destructive sampling impossible.

The biomass stocks in the post-burn phase for wood >10 cm in diameter were estimated from the percentage consumed. This percentage was calculated by comparing the post-burn stock of the >10 cm diameter class present in the plots after the burn with the pre-burn (LIS) estimates of this class in the same plots.

## 3. Results

### 3.1. Biomass Stocks

### 3.1.1. Pre-burn Biomass

The "best estimate" of the mean total aboveground biomass was 263 t $ha^{-1}$. The stock of wood in the >10 cm diameter class (138 t $ha^{-1}$) included in this total was estimated in the pre-burn plots from the mean of the direct (destructive) measurements, and in the post-burn plots from the mean of the destructive measurements adjusted by the average percentage (over all plots) of wood lost as determined by LIS.

Direct (destructive) measurements were regressed against indirect (LIS) estimates of pre-burn wood dry weight for wood >10 cm in diameter. The linear equation obtained ($r^2=0.61$, $p <0.05$, $n=45$) was:

$$Y = 11.06 + 0.96 X$$

where:

Y = indirect (LIS) estimate of weight (t $ha^{-1}$)
X = direct (destructive) estimate of weight (t $ha^{-1}$).

The calculation of aboveground biomass in standing trees left in the clearing is shown in Table 1. An average of 5.6 t $ha^{-1}$ of biomass was left standing, but the amount left standing in each lot varied tremendously, ranging from 1.7 to 11.6 t $ha^{-1}$.

### 3.1.2. Post-burn Biomass

The estimate of the mean total stock of biomass in the post-burn phase was 150 t $ha^{-1}$. The stock for the class of fallen wood >10 cm in diameter was 109 t $ha^{-1}$, obtained indirectly using the percent consumed of the biomass in this class as measured with LIS.

A linear regression was used to relate the direct and indirect methods for post-burn measurements of wood >10 cm in diameter ($r^2=0.63$, $p<0.05$, $n=54$ ray segments):

$$Y = 7.78 + 1.26 X$$

where:

Y = indirect (LIS) biomass estimate (t $ha^{-1}$)
X = direct (destructive) biomass estimate (t $ha^{-1}$).

## 3.2. Charcoal

### 3.2.1. Indirect Estimation

Charcoal formation around the circumference of logs was unequal, with the thickness at the top, sides and bottom being significantly different (ANOVA, $p < 0.001$). Charcoal is thickest on the bottom part of the log, with a mean thickness of 0.39 cm (n=130); the top of the log had the thinnest charcoal, with a mean thickness of 0.23 cm (n=130), and the lateral measurements had thickness not significantly different from each other at the 0.05 level, both with means of 0.29 cm (n=130). The top and bottom thicknesses were significantly different from each other and from the lateral measurements at the 0.05 level (Newman-Keuls multiple range test). The mean charcoal volume measured by LIS on wood >10 cm in diameter was 3.65 $m^3$ $ha^{-1}$ (SD=4.93, n=54 ray segments). This corresponds to 1.72 t $ha^{-1}$, using the average density of 0.47 (SD=0.09, n=57 samples).

### 3.2.2. Direct Estimation

Direct measurements indicate a mean total dry weight of charcoal from all biomass stocks and from the soil of 2.2 t $ha^{-1}$ (SD=2.7, n=54 ray segments). Of this total, the class of wood >10 cm in diameter had a mean charcoal stock of 1.5 t $ha^{-1}$ (SD=2.2, n=54 ray segments), corresponding to 67% of the total stock of charcoal.

## 3.3. Percentage Consumed by Burn

As determined by LIS, 21% of the biomass was consumed for wood >10 cm in diameter. The pre-burn biomass volume of fallen wood (not including charcoal) in this diameter class was 273 $m^3$ $ha^{-1}$ and the post-burn volume was 215 $m^3$ $ha^{-1}$ (Figure 3). Of the total pre-burn carbon, 42% was presumably released (Table 2). If standing trees are excluded from the analysis, the portion released is 43%.

[Figure 3 and Table 2 here]

## 4. Discussion

Because burning efficiency varies greatly both in space and in time, and at a variety of scales, a well-designed sampling procedure is critical to success. Probably tens of measurements will be necessary to characterize the mean of this critical parameter. It is therefore important to develop improved low-effort methods to characterize biomass and biomass combustion in tropical forest environments. The experience gained in the present study is of strategic importance in directing our approach to further reducing the uncertainty in global emissions of greenhouse gases from tropical biomass burning.

The estimates reported in the current study contain substantial uncertainty. This stems from the limited precision of the balances and other equipment used in making the original measurements and, as mentioned earlier, from the necessity of eliminating some of the data collected due to a variety of mishaps and operational problems. We have no reason to believe that measurement errors and/or analysis procedures have biased the results in a systematic fashion, in either an upward or a downward direction. Although it is impossible to determine the amount of random error in the estimates, we believe that the level of uncertainty for aboveground biomass is in the range of tens of tons per hectare. Modest though this precision is, the results of the current study contribute to reducing the even larger ranges of uncertainty that are contained in many calculations of global emissions from tropical deforestation.

Belowground biomass averages 22.6% of total biomass for the available measurements from elsewhere in Amazonia (studies reviewed in Fearnside, 1994). This implies that the total dry weight biomass at the Altamira site corresponds to approximately 322 t $ha^{-1}$.

Little charcoal was formed by the burn. A charcoal formation rate lower than used in many global carbon models means that deforestation has more impact on greenhouse effect: because less of the carbon enters a long-term storage pool in charcoal, more goes into the atmosphere. Charcoal formed in the three 1986 burns we studied at Altamira (1.3% of pre-burn aboveground biomass carbon) is the lowest of the four existing measurements in burns of felled primary forest: 2.7% in Manaus in 1984 (Fearnside et al., 1993), 1.8% in Manaus in 1990 (Fearnside et al., nd), and 4.1% at Fazenda Nova Vida near Ariquemes, Rondônia (Graça, 1997; Graça et al., nd). The mean of the four existing studies, calculated as mean charcoal carbon formed as a percentage of mean pre-burn aboveground carbon, is 2.2%.

A certain amount of charcoal escapes measurement if it is formed inside hollow trees. There is also some omission of charcoal that becomes finely powdered and falls to the ground.

In line intersect sampling (LIS), stumps and vertical snags are not considered. In the case of our LIS estimates, this affected the results very little if at all, as the two major stumps encountered were both in post-burn plots, where destructive sampling made application of a correction factor for this biomass fraction unnecessary.

The estimates of biomass and burning efficiency include a correction for biomass left in uncut trees within the clearings. Virtually all trees left standing died before, during or shortly after the burn. This was confirmed on visits to the study plots in years subsequent to the burns. Uncut trees did not burn in the case of the clearings studied, but this is not always the case in Amazonian burns.

The average biomass left standing in the three lots was 5.6 t $ha^{-1}$, representing 2.1% of the pre-burn aboveground stock both in terms of biomass and carbon. This is probably somewhat higher than the average for small farmers such as the Transamazon Highway colonists. In one lot in particular (Gleba 15, lot 8), the colonist was fairly elderly and was clearing by himself using an ax rather than a chainsaw. The result was that he left more trees standing than did other colonists (see Table 1). The area of land that small farmers plant is often limited by the amount of family labor available for felling (Fearnside, 1980); a greater return can therefore result from incomplete felling of a larger area than from complete felling of a smaller one. The standing tree biomass found in the clearings studied here is undoubtedly higher than the average for deforestation in Brazilian Amazonia as a whole, where about 70% of the felling activity occurs on medium or large ranches rather than on small farms (Fearnside, 1993). As a general rule, clearing on larger properties is contracted out to third parties on a per-hectare basis, and a more thorough felling of the trees is demanded than that attained by small farmers clearing their own land. Lack of inspection by ranch owners sometimes allows contractors to leave some trees standing, but the standing biomass left by the elderly colonist included in our study (11.5 t $ha^{-1}$) would be rare on larger properties.

Burning efficiency is an important aspect of tropical burning for grenhouse gas emission estimates, as knowledge of this factor is needed for estimating the timing of the release and for trace gas composition. Trace gases such as methane ($CH_4$) and carbon monoxide (CO) have a greater impact per ton of carbon than does $CO_2$, and non-carbon trace gases such as nitrous oxide ($N_2O$) and compounds of nitrogen and oxygen ($NO_x$) released by burning also contribute to making the impact of each ton of carbon released through burning of deforested areas greater than the impact of a ton released through burning of fossil fuels, which releases substantially less trace gases relative to emissions of $CO_2$.

Burning efficiency is invariably less than 100%, but this does not mean that the unburned biomass can be ignored in carbon calculations, as has been the case in a number of carbon release estimates for tropical deforestation, including Brazil's official estimates of greenhouse gas releases (see Fearnside, 1996, 1997b). The logs left unburned (original forest remains) either rot or are consumed in subsequent burns when pasture or secondary forests are burned on the site, thus eventually releasing the carbon.

The measurements at Altamira imply a 42% reduction of aboveground carbon pools, substantially higher than the 27.6%

measured in an earlier study near Manaus (Fearnside et al., 1993). The size distribution of biomass pieces may explain about 80% of the difference in overall burning efficiency between the two sites. Altamira has more small-diameter material, especially vines and litter (including dead wood <5 cm in diameter) than Manaus (Figure 4-A). Smaller diameter pieces burn more thoroughly than larger ones (Figures 3 and 4-B). If biomass with the partitioning among diameter classes found at Manaus were burned with the burning efficiencies by size class at Altamira, the overall burning efficiency would be only 30%. In addition to this direct effect of the different diameter class compositions at Manaus and Altamira, the portion of the difference in the overall burning efficiencies observed at the two sites that is explained by higher burning efficiencies within each diameter class at Altamira could be partly a consequence of the greater quantities of small-diameter fuel at Altamira: the heat generated as the material in the smaller size classes burned could help consume a greater percentage of the >10 cm diameter wood that makes up most of the biomass.

At Altamira, the large percentage of aboveground carbon in vines (12.0%) is less typical of Amazonian forests than the lower percentage at Manaus (3.1%). The lower overall burning efficiency found at Manaus is therefore believed to be more typical of Amazonian burning in primary forests. The distribution of diameter classes also explains most of the difference with a burning efficiency of 34.6% measured in a 1994 burn at Fazenda Nova Vida, Rondônia (Graça, 1997; Graça et al., nd). Other studies of burning efficiency of felled primary forest have produced varied results: 28.3% at Manaus in 1990 (Fearnside et al., nd); 53.6% at Jacundá, Pará in 1990; 50.3% at Marabá, Pará in 1991; 42.8% at Santa Barbara, Rondônia in 1992 (Kauffman et al., 1995); 25.1% at Manaus in 1992 (Carvalho et al., 1995); and 21.9% at Tomé-Açú, Pará in 1993 (Araújo et al., 1997). The average burning efficiency of the 10 available studies, calculated as the change in the mean pre- and post-burn biomass C loading, is 39.3% (Fearnside, nd). High variability indicates the need for further studies in many localities, and for perfecting less laborious indirect methods. Both high biomass and low percentage of charcoal formation suggest significant potential contribution of forest burning to global climatic changes from $CO_2$ and trace gases.

[Figure 4 here]

## 5. Conclusions

The biomass estimates here confirm the presence of relatively high carbon stocks in Amazonian forests, adding to the weight of evidence suggesting substantial contribution of deforestation to greenhouse gas emissions. The results also show the high spatial variability of biomass, and the need for more measurements. Differences with a study conducted near Manaus in the amounts of vines and of woody biomass in small diameter classes indicates the variability of features that affect burning efficiency. Line intersect sampling (LIS) measurements were shown to be an important tool for burning efficiency measurements allowing changes to be detected despite the great spatial heterogeneity of the felled biomass.

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# FIGURE LEGENDS

Figure 1. Study site and plot locations.

Figure 2. Layout of plots at each sampling point (star).

Figure 3. Percentages of biomass stocks consumed by the burn. See text (section 2.2.1) for definitions of biomass types. The percentage consumed refers to the share of dry weight (i.e., not carbon) that disappears from the site.

Figure 4. Comparison of A) pre-burn partitioning of aboveground biomass and B) burning efficiency (loss of pre-burn carbon [%]) in Manaus (from Fearnside et al., 1993) and Altamira.

Table 1: Biomass in standing trees left in clearings.

| | Stars B & E<br>Gl. 15 Lot 9 | Stars A & F<br>Gl. 18 Lot 3 | Star C<br>Gl. 18 Lot 16 | Star D<br>Gl. 18 Lot 16 | Mean over all stars | Notes |
|---|---|---|---|---|---|---|
| Area of clearing (ha) | 6.0 | 6.4 | 2.4 | 1.6 | 4.8 | (a) |
| Number of "normal" trees left standing | 75 | 13 | 10 | 7 | 32 | (a) |
| Number of "thin" trees left standing | 16 | 9 | 8 | 1 | 10 | (a) |
| Average commercial height (all trees) (m) | 23 | 18 | 22 | 17 | 20 | (a) |
| Commercial volume of "normal" trees standing per ha ($m^3$) | 13.1 | 1.7 | 4.2 | 3.6 | 6.2 | (b) |
| Commercial volume of "thin" trees standing per ha ($m^3$) | 0.7 | 0.3 | 0.8 | 0.1 | 0.5 | (b) |
| Total commercial volume of standing trees per ha ($m^3$) | 13.8 | 2.0 | 5.0 | 3.7 | 6.7 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Commercial stemwood biomass of standing trees (t ha$^{-1}$) | 9.9 | 1.4 | 3.5 | 2.6 | 4.8 | (c) |
| Approximate biomass of crowns of standing trees (t ha$^{-1}$) | 2.4 | 0.3 | 0.9 | 0.6 | 1.2 | (d) |
| Approximate above-ground biomass of standing trees (t ha$^{-1}$) | 12.2 | 1.8 | 4.4 | 3.3 | 5.9 | (c) |

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(a) Based on slides taken with a hand-held camera during overflight of the plots.

(b) "Normal" trees are assumed to have a diameter at breast height (DBH, or diameter at 1.3 m) of 27 cm, this being based on trees seen near study plots.

"Thin" trees are assumed to have half the diameter of "normal" trees.

Commercial volume is the trunk volume (including stump) to the first branch, irrespective of species.

Volume is the volume of a cylinder with diameter equal to the DBH and height equal to the distance from the ground to the first branch, multiplied by the form factor. The value used for the form factor is 0.8092 based on 309 trees measured near Manaus by N. Higuchi et al. (unpubl. data; See Fearnside, 1992).

(c) Biomass is above-ground volume (commercial + slash) multiplied by basic density of 0.712 t $m^{-3}$. Basic density (oven dry weight/wet volume) is average for dense forests (Fearnside, 1997c).

(d) Measurements of 303 trees of harvestable size near Manaus by da Cruz and Machado (1986) indicate that, of the above-ground total, the crowns represent 19%, stumps 6% and the harvested boles 75%. The crowns represent 24% with respect to the portion below the first branch (stumps + harvestable boles).

Table 2: APPROXIMATE CARBON PARTIONING OF ABOVE-GROUND BIOMASS IN RAINFOREST BURNS IN ALTAMIRA-PARÁ

| FRACTION | PRE-BURN | | | POST-BURN | | | PARTI-TIONING |
|---|---|---|---|---|---|---|---|
| | Above-ground dry weight (t $ha^{-1}$) | Carbon content (%)[a] | Carbon stock (t $ha^{-1}$) | Above-ground dry weight (t $ha^{-1}$) | Carbon content (%)[a] | Carbon stock (t $ha^{-1}$) | Percent of total pre-burn carbon stock left in fraction |
| Wood > 10 cm | 137.8 | 49.3 | 67.9 | 108.5 | 49.9 | 54.1 | 41.7 |
| Wood 5-10 cm | 22.8 | 48.4 | 11.0 | 9.1 | 49.1 | 4.4 | 3.4 |
| Wood < 5 cm | 21.3 | 48.4 | 10.3 | 5.5 | 49.1 | 2.7 | 2.1 |
| Vines > 10 cm | 0.2 | 49.4 | 0.0 | 0.0 | 49.0 | 0.0 | 0.0 |
| Vines 5-10 cm | 3.3 | 49.4 | 1.6 | 0.7 | 49.0 | 0.3 | 0.3 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Vines < 5 cm | 28.7 | 49.4 | 14.2 | 6.9 | 49.0 | 3.4 | 2.6 |
| Litter, leaves and < 5 cm | 32.3 | 51.1 | 16.5 | 1.0 | 51.1[b] | 0.5 | 0.4 |
| Palm leaves and palms < 10 cm | 2.4 | 51.1[b] | 1.2 | 0.7 | 51.1[b] | 0.3 | 0.3 |
| Palm trunks (> 10 cm) | 8.2 | 49.3[c] | 4.0 | 9.3 | 49.9[d] | 4.6 | 3.6 |
| Standing trees | 5.6 | 49.3[c] | 2.8 | 5.6 | 49.3[c] | 2.8 | 2.1 |
| Other | 0.01 | 51.1[b] | 0.0 | 0.7 | 51.1[b] | 0.4 | 0.3 |
| Charcoal | 0.0 | 74.8 | 0.0 | 2.2 | 74.8 | 1.6 | 1.3 |
| TOTAL | 262.5 | | 129.6 | 150.1 | | 75.2 | 58.0 |
| Presumed release | | | | | | 54.4 | 42.0 |

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(a) Carbon content analyses from Manaus area (Fearnside et al., 1993).

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(b) Carbon content assumed equal to that of pre-burn "leaves."

(c) Carbon content assumed equal to that of pre-burn wood > 10 cm in diameter.

(d) Charcoal carbon content from Correa, 1988.

Fig. 1

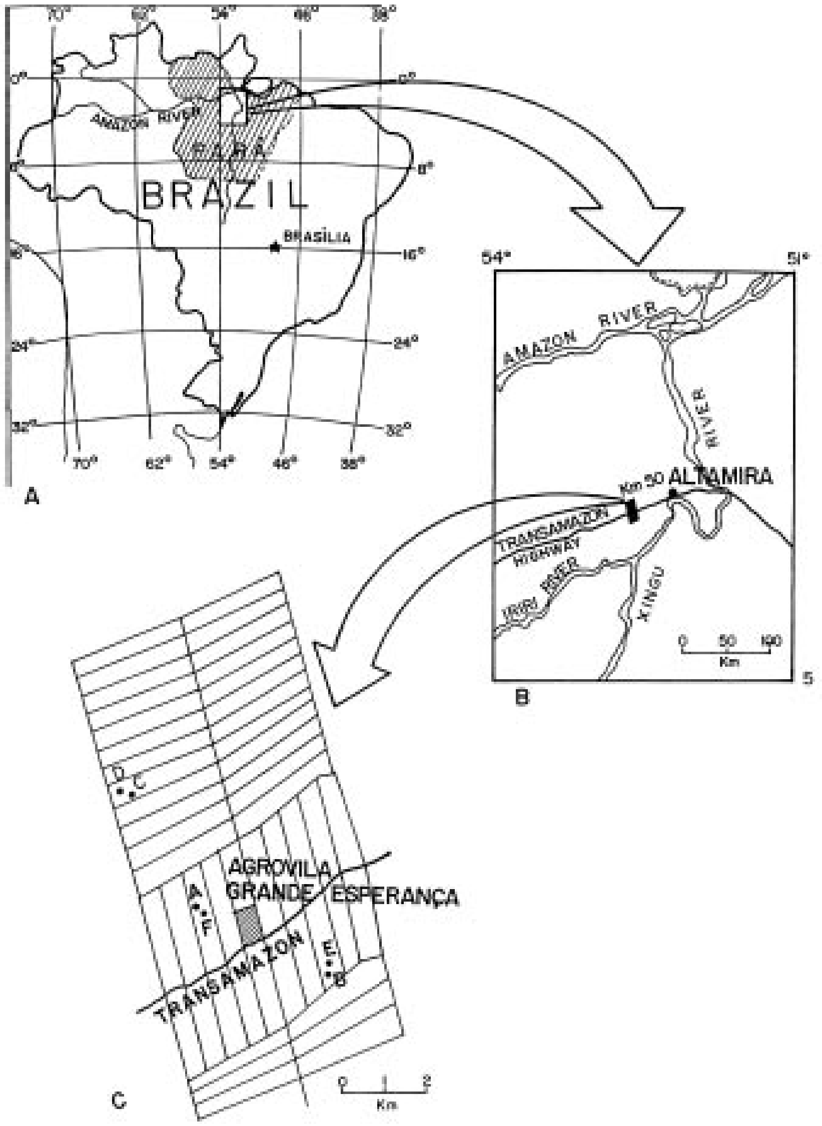

70°
62°
54°
46°
38°
0°
8°
16°
24°
32°
AMAZON RIVER
BRAZIL
BRASILIA
A
54°
51°
AMAZON RIVER
RIVER
Km 50
ALTAMIRA
TRANSAMAZON HIGHWAY
IRIRI RIVER
XINGU
0 50 100
Km
5
B
D
C
AGROVILA GRANDE ESPERANÇA
A
F
E
B
TRANSAMAZON
0 1 2
Km
C

Fig. 2

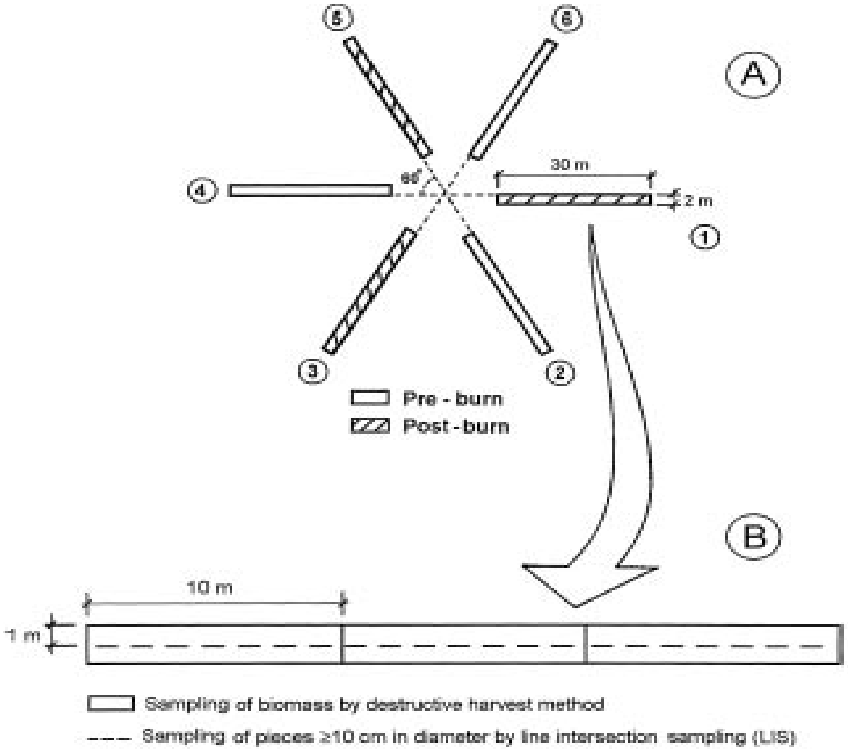

⑤
⑥
A
60°
30 m
④
2 m
①
③
②
Pre - burn
Post - burn
B
10 m
1 m
Sampling of biomass by destructive harvest method
Sampling of pieces ≥10 cm in diameter by line intersection sampling (LIS)

Fig. 3

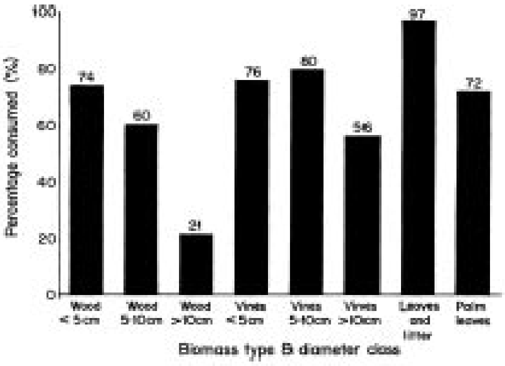
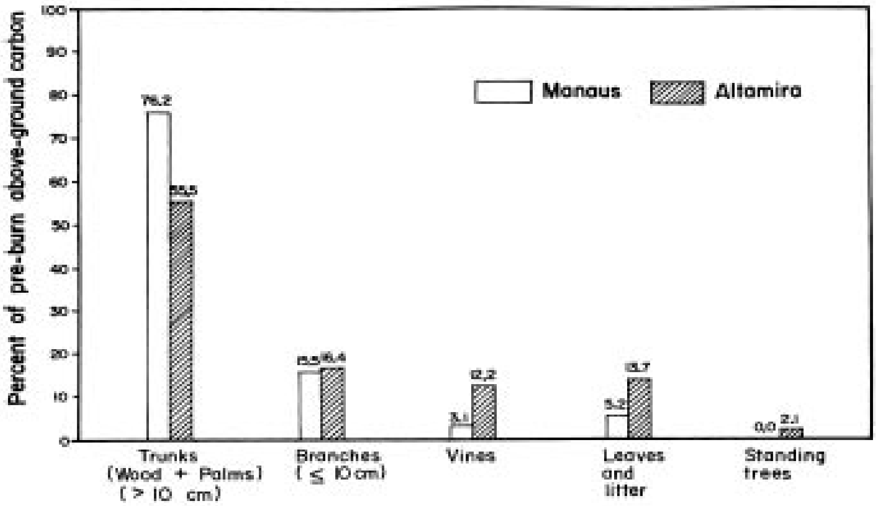
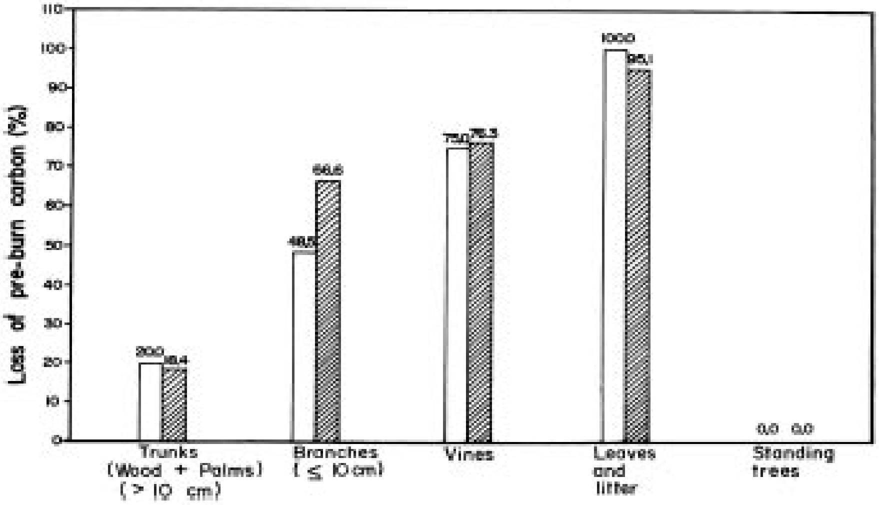

Percentage consumed (%)
100
80
60
40
20
0
74
60
21
76
80
56
97
72
Wood < 5cm
Wood 5-10cm
Wood >10cm
Vines < 5cm
Vines 5-10cm
Vines >10cm
Leaves and litter
Palm leaves
Biomass type & diameter class

Fig. 4



COMPARISON OF ALTAMIRA AND MANAUS

A.) Carbon partitioning



B.) Burning efficiency