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BURNING OF AMAZONIAN FOREST IN ARIQUEMES, RONDÔNIA, BRAZIL: BIOMASS, CHARCOAL FORMATION AND BURNING EFFICIENCY

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ABSTRACT

Transformations from biomass burning were evaluated for a forest at Fazenda Nova Vida, Ariquemes, Rondônia, Brazil. The above-ground biomass dry weight before the burn was estimated at 313.3 Mg/ha, and the corresponding carbon stock was estimated at 142.3. After the burn this stock was reduced by 34.6% (burning efficiency). This implies a transfer of 49.2 t C/ha to the atmosphere. The quantity of carbon in the charcoal and ash formed in the burn corresponded to only 3% of the total above-ground carbon stock present before the burn. The direct (destructive) and indirect (line-intercept sampling) methods of estimating biomass and charcoal after the burn were compared and had a correlation coefficient of 0.91. The distribution of initial biomass among the classes of plant material explained most of the differences among values for burning efficiencies found in Amazonia. The forest studied is typical of wide areas of Brazilian Amazonia that are undergoing deforestation; the high biomass found adds to the growing body of evidence indicating a great potential for carbon emissions to the atmosphere from deforestation.

Key words: Amazonia, deforestation, tropical forest, biomass, burning efficiency, carbon, charcoal.

I.) INTRODUCTION

The Brazilian Legal Amazon is approximately 5 X 10^6 km^2 in area, of which approximately 4 X 10^6 km^2 was originally covered by forests. The cummulative area of forests cleared by 1996 was estimated at 517,069 km^2 (Brazil, INPE, 1998), or 12.9% or the originally forested area. One of the principal causes of deforestation in Amazonian forest has been the conversion of natural primary forests to cattle pastures, the main land use in deforested areas (Fearnside, 1996a). Slashing and burning is the most widely used practice in conversion of forests to pasture. This change in land use causes marked changes in forest biomass and consequently in the stock of carbon.

Emissions of CO_2 and other gases are of worldwide concern because of their contribution to global warming. Estimates of carbon flux in the tropics provoked by land-use changes are derived from models in which parameters for forest biomass and its fate after deforestation are key inputs. In the case of Amazonia, estimates of forest biomass are a source of controversy, and current estimates still contain substantial uncertainty (Fearnside, 1994; I.F. Brown et al., 1995). Another source of uncertainty is linked to the parameters that will affect the fate of the carbon contained in the biomass.

Burning efficiency and formation of charcoal are important factors in the fate of carbon after burning the biomass because they control the amount of carbon that will be released by combustion and that will occur through decomposition. When the forest is cut and burned for agricultural use, part of the original biomass carbon is released immediately to the atmosphere as CO_2, a second part remains as charcoal and a third part remains unburned, but will release carbon over a period of several years when it is oxidized either in subsequent burns or through decomposition (Fearnside, 1992a, 1996b, 1997a; Houghton, 1990; Seiler and Crutzen, 1980).

Early calculations of the contribution of biomass burning to the global carbon problem were obliged (by lack of data from the tropics) to adopt values derived from coniferous forests in temperate regions for some of these parameters. Wong (1978) used a value of 75% for burning efficiency in the tropics based on data from an experimental burn in a stand of Douglas fir (Pseudotsuga taxifolia) in a temperate forest. In their pioneering work on biomass burning, Seiler and Crutzen (1980: 219) "guessed" a value of 25% for the tropics based on published photographs of shifting cultivation fields. Goudriaan and Ketner (1984: 178-179) present values for burning efficiency for leaves (95%), branches (90%), and stems (30%), which they apparently derived by combining their own guesses for percentages of unburned biomass with those of Seiler and Crutzen (1980) for charcoal formation. Because Goudriaan and Ketner (1984: 178) assumed an unexpectedly high percentage (30%) of the total biomass in leaves, their estimate corresponds to an overall burning efficiency of 69%. Bogdonoff et al. (1985: 347) used Seiler and Crutzen's (1984) value of 25%.

Burning efficiency values in other studies of burns in Amazonia have ranged from 22 to 56% (Fearnside et al., 1993; Kauffman et al., 1995; Araújo, 1995) in terms of carbon released to the atmosphere in gases. However, these estimates are still insufficient for the vast extent and variety of forests that exist in Amazonia, especially for forests in areas most affected by recent deforestation, such as on the southeast edge of the Amazon Basin (Fearnside, 1997b).

The formation of charcoal from burning forest biomass is another parameter that has been little studied in the tropics. Seiler and Crutzen (1980) suggested that 20-30% of the total above-ground biomass left after the burn was charcoal. This value corresponds to 15-23% of the carbon in the above-ground biomass present before the burn, thus indicating that this compartment contributes significantly to the long-term carbon pool. However, these data were extrapolated from qualitative observations in a Ponderosa pine (Pinus ponderosa) forest in Colorado, U.S.A. In a more recent study, Crutzen and Andreae (1990) used a value of 5% for charcoal, based on a preliminary value of 3.6% from a study by Fearnside et al. (1993) and a value of 5.4% derived from a study of controlled burning in a coniferous forest in Florida, U.S.A. Fearnside et al. (1993) revised the preliminary value of 3.6% to a value of 2.7% (based on a lower value for the carbon content of the charcoal) to estimate the percentage of carbon in the pre-burn above-ground biomass that is converted to charcoal in a primary forest near Manaus.

Formation of ash is another result of biomass burning. Ash are rarely mentioned in studies of carbon emissions, possibly because they represent only a small part of the total carbon stock present after the burn. However, ash are critical to studies of nutrient cycling because they cause important alterations in the chemical properties of the soil (Ewel et al. 1981; Smyth and Bastos, 1984; Hernani et al., 1987; Gonçalves and Moro, 1995). However, quantification and analysis of the nutrient content of ash is also rare. Dantas and Matos (1981) state that production of ash depends mainly on the biomass of the vegetation and the type of burn. The production of ash is, in large part, responsible for changes in pH and for increased availability of nutrients in soils of recently burned areas (Brinkmann and Nascimento, 1973). Production of ash has an important role in shifting cultivation, having been considered by many authors to be responsible for the temporary improvement in soil fertility in the site to be cultivated (Brinkmann and Nascimento, 1973; Sánchez, 1976; Jordan, 1987; Jordan,1991).

The paucity of data on these parameters for burns in tropical forests indicates the urgent need for more measurements in the tropics, where the potential for burning is still enormous (Fearnside et al., 1993). This is essential if estimates of greenhouse gas emissions are to become more reliable. The present study aims to estimate the stock of carbon in an Amazonian forest in Rondônia and its potential to emit carbon to the atmosphere through initial burning and other processes such as decay. To attain these objectives, an experiment was carried out in Ariquemes, Rondônia to accompany the transformations in carbon stocks resulting from burning the forest. The study required quantifying the total above-ground biomass before and after the burn, estimating burning efficiency and formation of charcoal and ash by burning primary forest, and analyzing carbon content in the different compartments in above-ground biomass with a view to accompanying possible changes in their stocks before and after cutting and burning the forest.

II.) MATERIAL AND METHODS

A.) Study Site

The study was conducted at Fazenda Nova Vida (10°10'5"S, 60° 49'27"W) located approximately 250 km southeast of the city of Porto Velho on the BR-364 Highway, in the município (county) of Ariquemes, Rondônia (Figure 1). This cattle ranch has a total area of 22,000 ha. The local climate is classified as Ami in the Köppen system, with high annual rainfall and a short well-defined dry season lasting from June to August. The mean annual precipitation is 2200 mm and the mean annual temperature is 25.6°C (Bastos and Diniz, 1982).

[Figure 1 here]

The vegetation is characterized as open tropical forest, with a large number of palms (Brazil, Projeto RADAMBRASIL, 1978; Pires and Prance, 1985). Nelson (1992) described this forest type as generally having a flatter canopy than dense forest, with fewer emergent trees and a mean height of 25 m or less. The understory is open with greater distances between trees and a greater penetration of light. Seen from above, the larger palms stand out when present, giving rise to the term "open forest with palms." According to Pires and Prance (1985), the most common palms are _Orbignya barbosiana_ (babaçu), _Oenocarpus_ spp. (bacaba), _Jessenia bataua_ (patauá), _Euterpe precatoria_ (açaí da mata), and _Maximiliana regia_ (inajá).

The soil in the study area was classified by Moraes _et al_. (1996) as a latosolic red-yellow podzolic soil in the Brazilian system, or a kandiuldult (Ultisol) in the U.S. soil taxonomy. An area of approximately 3.5 ha of primary forest was felled for the purpose of the study. Felling began on 15 June and ended 26 June 1995. The forest was cut using methods traditionally employed by ranchers in the region. The trees were cut with a chainsaw, which has replaced the ax in recent colonization areas in Amazonia. After felling the forest, the biomass was left in place to dry for 98 days. Some trees remained standing after the felling.

The burn in the experimental area was carried out by workers on the ranch on 10 September, using traditional Amazonian methods. The fire was lit using a flaming strip of rubber from a tire attached to the end of a stick. The fire was started at the edges of the clearing so the flames would meet in the middle of the clearing and maximize the effect of burning. The burning started at 13:00 h, the hottest time of the day (36°C), and lasted for three hours. At 16:00 h the flames had already gone out, the remaining burning being of the smoldering type.

Two methods were used to evaluate the transformations in the biomass provoked by burning: direct or destructive harvesting and indirect or line-intersect sampling (transects). In the area sampled where the forest was felled, biomass for wood $\geq$10 cm diameter was estimated from the mean of the stocks in plots (rays) before the burn measured with the destructive method, and complemented with means from plots left for the post-burn phase measured with the indirect method (line-intersect sampling, or LIS). The other biomass components were calculated using only the direct method.

B.) Destructive harvesting (direct) method

The destructive harvesting (direct) method consisted of weighing all biomass in the completely felled area. The transformations of biomass caused by the burn, such as the amount of carbon released, the amount of charcoal formed and the burning efficiency, were analyzed comparing stocks of carbon in the biomass before and after the burn.

Two "stars" were implanted with plots (rays) for destructive harvest (Fig. 2). Each star consisted of six plots or rays measuring 2 × 30 m. The rays emanated from a common center at angles of 60° and began 10 m from the center point. The plots used in the post-burn stage had their corners marked with iron reinforcing bars that were resistant to burning so that they could be located after the fire. Half of the plots in each star were harvested before the burn and the other half after it. The rays alternated between pre- and post-burn harvest in order to avoid any bias due to the systematic spatial orientation of the felled trees. This methodology was originally conceived by Jennifer Robinson.

[Figure 2 here]

Biomass was weighed in each plot. All above-ground biomass was cut with a chainsaw and machetes, and weighed using a spring balance with 90-kg capacity accurate to ±1 kg. After weighing, the biomass was put back into the plots in order to minimize the effect of piles of fuel in the area to be burned, which might influence the burn quality. The biomass in the pre-burn phase was divided into eleven classes, according to the type of plant material and the diameter of the sampled pieces: a) wood <5 cm diameter; b) wood between 5 and 10 cm diameter (woody material composed of branches and stems of saplings); c) wood ≥10 cm diameter (consisting of branches and trunks of trees); d) vines (lianas) <5 cm diameter; e) vines between 5 and 10 cm diameter; f) vines ≥10 cm diameter; g) fine litter (composed of fine litter from the forest plus leaves that had fallen from tree crowns--the "green" leaves could not be collected separately because the leaves begin to abscise soon after felling); h) palms <10 cm diameter; i) palms ≥10 cm diameter; j) palm leaves; and k) rotten trunks >10 cm diameter.

In addition to these, the post-burn phase also included classes for charcoal and ash deposited on the soil surface and charcoal attached to the partially charred biomass in the same classes as those used for pre-burn biomass. The charcoal on the soil was collected manually. In this procedure, fragments were collected that were visible on careful examination of the ground. A 5-mm mesh sieve was used to separate the charcoal from the ash deposits. A certain amount of charcoal of very small dimensions could not be separated; however we believe that this value is proportionately very small. The charcoal attached to the biomass fractions (trunks, branches and vines) was scraped off with machetes. The charred parts were removed by applying machete blows with moderate force to each piece, enough to remove the charred part that is black in color but leaving behind the partially charred brown-colored wood.

The procedures used in the destructive method for collecting samples in the field and for determining the physical and chemical characteristics of the biomass are described in the following paragraphs. The samples of biomass and of charcoal were taken from the plant material in the sub-plots (2 × 10 m) into which the rays (2 × 30 m) of each "star" were divided. For each class of biomass and charcoal one sample was separated, weighed in the field, placed in plastic bags and labeled with information on the type of material, sub-plot and diameter class. These samples were taken haphazardly from the piles of material that had been weighed in the sub-plots; samples were taken for each type of plant material and diameter class, with the exception of the wood ≥10 cm diameter class, for which a disk was taken from each piece.

On the day following the burn, a sampling of the ash was done in the post-burn rays. The ash samples were carefully collected manually using a plastic shovel and a paintbrush, and placed in plastic bags, avoiding any contamination with clay aggregates, charcoal or other plant fragments (pieces of leaves, twigs, etc.). The ash were collected in an area measuring 0.10 × 10 m (1 m^2) in each subplot at a randomly chosen location but avoiding the central axis of the ray. Ash collection was done before beginning the process of cutting and weighing biomass in the plots.

To determine the moisture content, all plant samples and products of the burn were dried at 60°C in electric ovens with forced air ventilation. Samples were considered completely dry when their weights became constant after periodic weighings. The water content (percentage) was calculated on a dry-weight basis (using dry weight as the denominator).

Basic density (oven dry weight of the sample/wet volume of the sample) was calculated by the immersion method, based on the change in the apparent weight of the samples as described by Trugilho et al. (1987). This is also known as the hydrostatic balance method, based on the Archimedes principle, where the apparent loss of weight of a body immersed in a liquid is equal to the weight of the liquid displaced (the density of water is assumed to be one). Basic density was determined separately for samples of wood ≥10 cm diameter, samples of charcoal adhering to wood ≥10 cm diameter, and bark.

The percentage of bark in the ≥10 cm diameter class was estimated by separating all bark present on the disks sampled from trunks and branches in this biomass class. The percentage of bark was determined dividing the weight of all bark contained in the samples by the total weight (bark + wood) of the samples, and expressed as a percentage by multiplying the result by 100. The percentage of bark was calculated for each stage before and after burning, since bark was consumed in the fire. Quantification of the percentage of bark was necessary in order to estimate the quantity of bark in the biomass stocks estimated by the indirect methods.

The samples, previously dried, were first completely ground into "toothpick" form, with the exception of samples of wood with ≥10 cm diameter, from which a wedge-shaped subsample was taken, representing 1/8 of the disk collected in the field, separating the bark to be analyzed separately. The ground plant material was homogenized and a subsample was removed for milling in a Wiley-type ball mill with a 1-mm mesh opening. After the milling process, chemical analyses were performed.

C.) Line-Intersect Sampling

The line-intersect sampling (LIS) methodology adopted was developed by Van Wagner (1968) to estimate the volume of wood in felled areas. In the present study, the method was applied before and after the burn to estimate the volume of all pieces of wood with $\geq$10 cm diameter. The same method was used to estimate charcoal formation. This made it possible to calculate the percentage of biomass consumed by the burn for each biomass class.

The volume of wood was estimated using Equation 1.

$$V = \frac{\pi^2 \sum d^2}{8L} \qquad \text{(Eq. 1)}$$

where:

V = volume of wood per unit of area (m^3/ha)
d = diameter of the piece (m)
L = length of the sampling transect (m).

In plots used for destructive sampling in the post-burn phase, line-intersect sampling transects were implanted after felling along the central axis of each ray, both before and after the burn. The decision rules described by Van Wagner (1968) were used for inclusion of pieces intersected by the sampling line.

The circumference of each piece of wood was measured at right angles to the axis of the piece. Numbered aluminum tags were nailed to each piece at the point of measurement. The measurements were taken at ten randomly chosen points around the circumference of each piece. For each measurement, an incision was made perpendicular to the axis of the piece of wood using a machete. The thickness of the charcoal layer formed on the piece was then measured using a transparent plastic ruler calibrated in millimeters.

The quantity of charcoal clinging to the pieces of wood (trunks and branches) with $\geq$10 cm diameter was calculated subtracting the total volume of wood estimated after the burn in each plot (each 2 × 30 m ray of a "star") from the volume of wood without charcoal. The volume of wood without charcoal was calculated by subtracting the diameter of each piece of wood from the thickness of the charcoal layer. The volume of charcoal was converted to mass by multiplying by the density measured in the charcoal samples.

D.) Consumption of biomass for wood $\geq$10 cm diameter

The percentage consumed was calculated from the difference in biomass in the pre- and post-burn phases, converting the volume of wood $\geq$10 cm diameter to weight. Wood and bark were calculated separately for each plot.

E.) Biomass of trees left standing in the clearing

The trees left standing were estimated indirectly by allometric inference. Equation 2 was used to estimate the trees with intact crowns. This is based on the equation developed by I.F. Brown _et al_. (1995) to estimate biomass of open forest in the Samuel Ecological Reserve in Rondônia, modified in accord with the density of wood in the samples in the $\geq$10 cm diameter class.

$$B = 0.0384\ D^2\ H \qquad \text{(Eq. 2)}$$

Where:

B = biomass (kg/tree)
D = diameter at breast height (cm at 1.3 m height)
H = total height (m).

Equation 3 was used to estimate the biomass of trees with damaged crowns (or without crowns). This equation includes a form factor, or the ratio of the volume of the commercial trunk or bole to the volume of a cylinder with diameter equal to the diameter at breast height (DBH) and height equal to the commercial height (the distance from the ground to the first branch). The value used, 0.78, was derived by Fearnside (1992b: 22) using form factors by diameter class calculated by Niro Higuchi (personal communication, 1992) based on 309 trees measured near Manaus, Amazonas and the distribution of bole volume into different DBH classes at the same Manaus site (Coic _et al_., 1991). The value used is applicable only to estimates based on commercial (as opposed to total) height and for a minimum DBH of 10 cm. The corresponding value for use with RADAMBRASIL data (Brazil, Projeto RADAMBRASIL, 1973-1983), which has a lower DBH limit of 31.8 cm, is 0.81 (Fearnside, 1992b). Equation 3 also uses basal area, which refers to the cross-sectional area at breast height.

$$B = A\ H\ S\ F \qquad \text{(Eq. 3)}$$

Where:

B = trunk biomass (kg dry weight per trunk)
A = basal area (m^2)
H = commercial height (m)
S = Basic density (kg/m^3)
F = Form factor (0.78)

F.) Carbon content of biomass and charcoal

Carbon content of biomass, ash and charcoal samples were determined by the "dry" method using a LECO carbon analyzer (Model CR-412). Samples were put in a furnace at 1350ºC in pure oxygen, thus oxidizing the material completely to CO_2. The gases produced were dehumidified in $Mg(ClO_4)_2$ before passing through infrared detection cells. The cells also measured CO_2 in the gas, and the apparatus converted the values to percent carbon.

The values produced for carbon content of charcoal by this method refer to the total content of carbon (not only elemental carbon) in the sample. What appears visually as charcoal contains, in fact, some carbon in organic form, which can be expected to decay at a much more rapid rate than the elemental ("black") carbon. Kuhlbusch and Crutzen (1995) have estimated that 52-63% of the carbon contained in charcoal such as this is in elemental form, assuming that carbon that resists oxidation at temperatures up to 340ºC is elemental carbon. However, the amount of carbon remaining unoxidized is highly sensitive to temperature: if 300°C were used as the standard instead of 340ºC, the amount classified as elemental carbon would approximately double (Kuhlbusch and Crutzen, 1995).

III.) RESULTS

A.) Above-ground biomass

The total stock of above-ground biomass in the felled area was 313.3 Mg/ha, including trees left standing (6.8 Mg/ha). Considering only the fuel left lying on the ground, the class of wood ≥10 cm diameter had a biomass of 191.3 Mg/ha and represented 62.4% of total above-ground felled biomass (Table 1). Wood in the <5 and 5-10 cm diameter classes together represented 15.6%; vines represented 11.6%; fine litter represented 7.9%; palms represented 7.0%; and rotten wood ≥10 cm diameter represented only 3.2%.

[Table 1 here]

The mean stock of total above-ground biomass after the burn was 196.6 Mg/ha (Table 2), not including trees left standing. The estimate of biomass after the burn represented approximately 64.5% of the initial above-ground biomass. As can be seen in Table 2, wood ≥10 cm diameter (79.3%) was the fuel that contributed most to the total stock of biomass remaining above ground. The other compartments together represented only 20.7% of the total remaining above-ground biomass.

[Table 2 here]

The measurements obtained for biomass in the class of wood ≥10 cm diameter after the burn, for the same plots, by the direct and indirect methods (153.7 and 164.8 Mg/ha, respectively) did not differ significantly (t test, $p > 0.05$). The results of the two methods were closely correlated ($r = 0.91$, $n=17$).

[Figure 3 here]

B.) Formation of charcoal and ash

The total stock of charcoal after the burn was 6.4 Mg/ha and the stock of ash was 5.7 Mg/ha (Table 2). These two compartments represented 6.2% of the total stock of material left after the burn. The formation of charcoal clinging to pieces of wood ≥10 cm diameter was estimated by both the indirect (LIS) and direct (destructive) methods. The charcoal stock estimated by the indirect method for this fraction was 4.5 Mg/ha. This estimate was obtained from the mean apparent density of charcoal of 0.43 (SD = 0.11, n=16) used to convert the volume of charcoal to mass (Mg/ha).

The estimate by the direct method for the stock of charcoal clinging to the pieces (scraped off in the plots) in the fraction of wood $\geq$10 cm diameter was 3.1 Mg/ha, which represented 48.5% of the total stock of charcoal measured in the plots after the burn. The means estimated by both methods did not differ significantly (t test, $p > 0.05$). The stock (mass) found in the sub-plots (2 × 10 m), as estimated by the direct and indirect methods, were closely correlated ($r = 0.91$, n=13). In the present study, calculations of carbon stocks were based on charcoal stocks measured by the direct method.

C.) Carbon content of biomass and charcoal

The carbon content (% C) of the different biomass fractions before and after the burn are presented in Table 3. Carbon content of charcoal samples is also presented. All values refer to total carbon (i.e., carbon in any form).

[Table 3 here]

D.) Burning efficiency and carbon release

The percentage values for burning biomass (only woody material, not including charcoal) show that wood $\geq$10 cm diameter was the biomass category most resistant to the action of fire, which consumed only 18.5% of the original mass (Fig. 3). In contrast, fine branches, vines, fine litter and palm leaves had their masses drastically reduced by the burn. The class of wood <5 cm diameter had its mass reduced by 91.7%.

[Figure 3 here]

The class of palms <10 cm diameter had a slight increase in its biomass stock after the burn; the percentage consumed was therefore considered to be zero. The distribution of this class is highly irregular, being found in only two sub-plots (2 × 10 m). A much greater number of repetitions or larger plots would be necessary to adequately sample this small and highly variable class.

The approximate distribution of carbon in the above-ground biomass and the amount of carbon released by the burn are presented in Table 4. Of 142.3 t C/ha in above-ground biomass (exposed to the burn), 49.2 t C/ha was released to the atmosphere; that is, burning efficiency was 34.6%.

[Table 4 here]

IV.) DISCUSSION

A.) Above-ground biomass

The total stock of above-ground biomass of 313.3 Mg/ha found here is within the range of values found for open forest at other localities in Amazonia. I.F. Brown et al. (1995) estimated the above-ground biomass at 325 Mg/ha (not including vines, understory and palms) for this same type of forest in the Samuel Ecological Reserve in Rondônia. Kauffman et al. (1995) estimated total above-ground biomass to be 290.2 Mg/ha and 361.2 Mg/ha for Jamari and Santa Barbara, Rondônia, respectively. It is common in Amazonia to find high variability in estimates of biomass, even for a single forest type (Houghton, 1994; Martinelli et al., 1994). The high floristic and structural heterogeneity of tropical forests can contribute to high variability in forest biomass among sites. Biomass estimation in Amazonian forests is still a controversial subject (Fearnside, 1992b, 1993; S. Brown and Lugo, 1992a,b; I.F. Brown et al., 1995).

In Ariquemes, biomass of components other than trunks and branches contributed 21.4% of the total above-ground biomass after felling (including trees left standing). This percentage, obviously, varies depending on the structure of the forest under study. In Manaus, Amazonas, for a dense forest with few palms and vines, this value was 8.1% (Fearnside et al., 1993). These forests (which have relatively low percentages of their biomass in components other than trunks and branches) represent 53% of the total forest cover of the Legal Amazon; almost half of the forest cover is composed of non-dense forests such as the one at Ariquemes (Graça, 1997).

Although the presence of palms in Amazonian forests is common, they are frequently excluded from forest surveys because they are considered to lack economic importance for lumber. Fearnside (1992b) pointed out that the abundance of palms varies greatly in Amazonian forests, ranging from 0.3% to 6.7% of the total above-ground biomass. At our study site in Ariquemes, 33 palms ≥10 cm diameter were found, with a basal area of 1.6 m^2/ha. The percentage contribution of palm biomass (7.0%) relative to the total above-ground biomass was very close to the 6.7% found by Fearnside et al. (nd) in Altamira, Pará. These locations coincide with parts of Amazonia with high densities of babaçu palms mentioned by Nelson (1992). However, in Ariquemes, the biomass of babaçu leaves exceeded by 30% the value found for palm trunks. This reflects the high frequency of young individuals of babaçu, which in this phase are trunkless but have a significant mass of leaves. The high spatial variability of the trunks also explains this difference. Leaves of the babaçu class occurred in all 18 sub-plots (2 × 10 m) sampled in this phase, whereas trunks were only found in six of the sub-plots.

One important factor in this calculation of pre-burn biomass is the estimation of biomass of trees left standing in the clearing, a factor not always considered in burning studies. In cleared areas, it is common for some trees that are commercially valuable or are protected by law (e.g., Brazil nut, Bertholletia excelsa) to be intentionally left standing (Kauffman et al., 1995).

In Ariquemes, eight trees were left standing in a felled area of approximately 3.5 ha. Of these, five had intact crowns and the other three were without crowns. The biomass of these trees was estimated at 6.8 Mg/ha.

B.) Formation of charcoal and ash

Quantifying the charcoal in burns in Amazonia has rarely been attempted. Only two studies (Fearnside et al., 1993, nd) on burning primary forest in Amazonia explicitly mention the quantity of charcoal. These studies estimated 4.7 Mg/ha in a burn near Manaus, Amazonas (Fearnside et al., 1993), and 2.2 Mg/ha in Altamira, Pará (Fearnside et al., nd). The value found in Ariquemes was higher than these two.

The quantity of ash found (5.7 Mg/ha, excluding charcoal that could be separated manually) is lower than values found in the literature for primary forests in Amazonia. Dantas and Matos (1981) found 17.2 Mg/ha at Capitão Poço, Pará; Smyth and Bastos (1984) found 9.2 Mg/ha near Manaus, Amazonas, and Kauffman et al. (1995) found 8.8 Mg/ha at Jacundá, Pará, 10.9 Mg/ha at Marabá, Pará, 9.4 Mg/ha at Santa Barbara, Rondônia and 7.2 Mg/ha at Jamari, Rondônia. The lower value found at Ariquemes could have been due to rain (8 mm) that fell the day preceding collection.

C.) Carbon content of biomass and charcoal

Carbon content of wood fractions (Table 3) is only slightly higher than the value of 45% that has often been used in converting biomass to carbon values in global carbon balance studies. For example, wood in the ≥10 cm diameter fraction before the burn had a mean C content of 46.0%. The mean for all pre-burn biomass, weighted by the dry weight of each fraction present, was 45.4%, while the corresponding weighted mean for post-burn biomass was 45.7%. This result indicates that considerable variation among locations exists in the percent carbon content of primary forest. Fearnside et al. (1993) found a mean carbon content of 49.3% for trunks ≥ 10 cm near Manaus; Higuchi and Carvalho (1994) found 48.5% at the base and 48.2% at the top near Manaus; Guimarães (1993: 51) found 46.7% near Altamira, Pará, Kauffman et al. (1995: 401) found 50.1% for trunks >7.6 cm in Marabá and Jacundá, Pará, and Jamari and Santa Barbara, Rondônia, and Araújo (1995: 59) found 45.6% near Tomé-Açu, Pará (for pre-burn trunks >10 cm in diameter).

D.) Burning efficiency and carbon release

In general, the same tendency regarding consumption of these components was found in other studies on burning in forests in areas subject to slash-and-burn practices in Amazonia (Fearnside et al., 1993; Araújo, 1995; Kauffman et al., 1995). However, the percentage of above-ground biomass burned can vary greatly depending on the amount of burnable material that is piled up and chemical composition of this material present in the felled area, as well as on climatic conditions at the time of burning (Jordan, 1985; Kauffman et al., 1988).

Burning efficiency in Amazonian burns is highly variable. Fearnside et al. (1993) estimated burning efficiency at 27.5% near Manaus, while Araújo, (1995) estimated 22% near Tomé-Açu, Pará. The highest values were found by Kauffman et al. (1995), who found a mean burning efficiency (which they term a "combustion coefficient") of 50% as compared to the total stock of carbon present before the burn in Pará and Rondônia. Kauffman et al. (1995) argued that this value is higher than the value (around 25%) used in studies on net emissions of carbon to the atmosphere from burns in tropical forests, adopted by Fearnside (1992a) and Crutzen and Andreae (1990). Kauffman et al. (1995) also stated that the lower values for burning efficiency were probably not representative of areas subject to deforestation and burning, such as those in Pará and Rondônia. Thus, release of carbon to the atmosphere via decomposition could be overestimated. However, the value found in the present study is also lower (30% lower) than the mean value of 50% found by Kauffman et al. (1995). The initial distribution of biomass components before the burn can partially explain this difference.

Wood ≥10 cm diameter (including rotten wood) represented 66% of the total above-ground biomass felled before the burn. After the burn, this percentage increased to 84% with respect to the total remaining biomass (excluding charcoal and ash). This demonstrates that the smaller-diameter fractions can have a great influence on the final result for burning efficiency. Fearnside et al. (nd) report that the initial distribution of biomass among fractions explains, in large part, the differences found in burning efficiency among burns. This partitioning is one of the characteristics of variability that could affect burning efficiency. For example, in the present study, which found a burning efficiency of 34.6%, the fraction of wood ≥10 cm diameter represented 61% of total above-ground biomass before the burn, while in Manaus (Fearnside et al., 1993), where trunks >10 cm diameter represented 76% of total above-ground biomass, the value for burning efficiency was lower (27.5%). However, the percentage of biomass consumed for the fraction of wood ≥10 cm diameter in Manaus (20.9%) was only marginally higher than the 18.5% found in Ariquemes.

The importance of size class partitioning for burning efficiency means that better estimates of a regional mean for burning efficiency could be derived by quantifying the size class distribution of felled vegetation in different forest types. The distribution of material among the size classes could then be used in conjunction with size-specific burning efficiency information (such as that from the present study) to derive regional means. Size class distributions could be further related to DBH distributions in order to allow existing forest surveys (such as RADAMBRASIL data) to be extrapolated to the region for weighted burning efficiency estimates. Adjustments can also be done for the effect of logging (see Fearnside, 1997a). Additional studies of burning would help to strengthen the basis for these extrapolations.

In addition to variability in the distribution of biomass size fractions, high variability in burning efficiency in Amazonia is undoubtedly increased by year-to-year variation in weather parameters during the short time of year when burning is practiced. Fearnside (1989), evaluating burn quality in agricultural areas on the Transamazon Highway estimated variation in burn quality from one year to the next and among colonists in one colonization area. Variability in burn quality was shown to be a key factor affecting agricultural production and, consequently, carrying capacity for human populations in areas of recent colonization in Amazonia.

At our study site in Ariquemes, approximately 62% of the carbon remained in the system in the form of biomass surviving the burn. This stock of carbon can still be released to the atmosphere over the coming decades, either by slow decomposition of the wood (mainly by microorganisms and termites), or by the successive reburning of pasture or secondary vegetation for agricultural purposes (Fearnside, 1992a, 1996b, 1997a; Houghton, 1994). The other 3% remained in the form of charcoal and ash.

Charcoal is considered to be a virtually permanent carbon stock. In Amazonian soils under 'primary' forest it is common to find charcoal with ages up to 6000 years (Bassini and Becker, 1990; Gomes, 1995; Sanford et al., 1985). Seiler and Crutzen (1980) considered charcoal formation to be an important sink for carbon in burns in tropical forests, contributing approximately 20-30% of the total stock of carbon in the remaining biomass (15-23% of above-ground pre-burn carbon, if calculated using the 25% burning efficiency these authors assumed). Crutzen and Andreae (1990) used a value of 5% for charcoal formation for total above-ground biomass present before the burn. This value is higher than the 3% found in the present study with respect to the total stock of above-ground biomass carbon before the burn. The percentage values found up to now for charcoal formation in Amazonian burns have been quite small. The quantity of carbon contained in the ash was also small (0.4 Mg/ha of carbon), contributing 0.3% of the carbon with respect to the total pre-burn stock of carbon. The mean carbon content of the ash was 6.6% (SD = 1.1, n=6).

The total carbon stock found before the burn of 142.3 Mg/ha was reduced to 93.1 Mg/ha by the action of the fire. This means that at the time of burning, 49.2 t C/ha was emitted to the atmosphere. It is probable that a small quantity of carbon is left in the system in graphitic form (soot), but this quantity is believed to be insignificant. Also not quantified (but believed negligible), was carbon present in fine charcoal on the ground, which escaped manual collection, although part of this powdered charcoal was included in the ash samples.

Figure 4 summarizes the transformations in the carbon stocks in above-ground biomass before and immediately after the burning of forest. Of the 142.3 t C/ha above-ground stock present before the burn, 35% was released to the atmosphere (burning efficiency), 62% remained on the ground unburned, and 3% was left as charcoal and ash.

[Figure 4 here]

V.) CONCLUSIONS

The high biomass of the forest studied near Ariquemes, Rondônia (313.3 Mg/ha) confirms the findings of other studies and indicates the great potential importance of forest loss as a source of carbon emissions to the atmosphere.

Burning efficiency at this site (34.6%) is close to several existing estimates made in other burns in the region, but significantly lower than some others. These differences may stem from differences in measurement methodologies, as well as the natural variability of Amazonian burns. High structural variability of the forest is, to a great extent, responsible for the different burning efficiencies observed in Amazonia. Burning of forest results in little reduction of biomass in the class of wood $\geq$10 cm diameter (such as trunks and thick branches), which represents most of the above-ground biomass. Obtaining a representative mean for the region will require both a greater number of burning studies from other locations. In our study, line-intersect sampling proved to be quite efficient, indicating that indirect methods could be useful in easing the difficult fieldwork of weighing plant biomass in future studies. In order to derive estimates of regional means, studies are needed to quantify diameter distributions of pieces (fuel fractions) in felled vegetation of different forest types.

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Figure legends

Figure 1. Location of Fazenda Nova Vida, Ariquemes, Rondônia, Brazil.

Figure 2. Layout of experimental plots.

Figure 3. Percentages of biomass stocks consumed by the burn for each biomass fraction.

Figure 4. Fate of biomass above-ground carbon before and after burning

Table 1. Biomass stock on the ground (pre-burn) in each compartment and its percentage in relation to total biomass

Class[a]	Biomass stock	Coefficient of variation	Relative distribution
cm	Mg/ha (mean ± SE)	%	%
Wood <5	26.5 ± 3.8	68.1	8.6
Wood 5-10	21.4 ± 3.4	75.1	7.0
Wood ≥10[b]	191.3 ± 24.8	44.9	62.4
Vines <5	10.0 ± 2.7	132.5	3.2
Vines 5-10	1.9 ± 0.5	128.6	0.6
Litter	24.1 ± 2.4	47.7	7.9
Palms <10	0.3 ± 0.1	163.6	0.1
Palms ≥10	8.6 ± 2.6	147.1	2.8
Palm leaves	12.7 ± 3.4	129.0	4.1
Rotten wood >10	9.7 ± 4.9	244.9	3.2
Total	306.5 ±48.6		100

[a] Without considering biomass of trees left standing after clearing

[b] Calculated from the 12 pre- and post-burn rays of the “stars” for the direct and indirect methods. The other components were directly measured, as the mean for 6 rays.

Table 2. Remaining above-ground biomass stock (post-burn) in each biomass class

Class[a]	Biomass stock[b]	Coefficient of variation	Relative distribution
cm	Mg/ha (mean ± SE)	%	%
Wood <5	2.2 ± 0.4	45.5	1.1
Wood 5-10	12.4 ± 1.7	34.7	6.3
Wood ≥10[c]	155.9		79.3
Vines <5	1.1 ± 0.3	63.6	0.6
Vines 5-10	1.8 ± 0.6	83.3	0.9
litter	1.0 ± 0.5	120.0	0.5
Palms <10	0.9 ± 0.6	150.0	0.5
Palms ≥10	7.1 ± 3.1	107.0	3.6
Palm leaves	2.0 ± 1.9	235	1.0
Rotten wood >10	0.1 ± 0.1	400	0.05
Charcoal	6.4 ± 2.7	104.2	3.3
Ash	5.7 ± 1.0	42.5	2.9
Total	196.6		100

[a] Does not include trees left standing pre-burning.

[b] Averages correspond to the six sampling rays (2 × 30 m) of the "star" of the post-burn phase for the direct method.

[c] Biomass of wood ≥10 cm diameter was estimated by the percentage of mass consumed by the burn, considering the wood only, excluding any attached charcoal.

Table 3. Carbon content of biomass and charcoal at Fazenda Nova Vida, Rondônia

Biomass fraction by diameter class	Pre-burn			Post-burn		
	Mean	Standard deviation	n	Mean	Standard deviation	n
cm	%			%		
Wood <5	44.4	2.1	18	44.5	1.8	16
Wood 5-10	44.6	1.6	18	45.7	2.6	16
Wood ≥10[a]	46.0	-	-	46.5	-	-
Vines <5	44.9	1.8	17	44.7	3.7	11
Vines 5-10	42.9	1.4	8	44.0	1.6	9
Vines ≥10	absent			absent		
Palms <10	41.5	-	2	46.4	-	2
Palms ≥10	46.3	1.9	6	45.5	1.1	7
Palm leaves	44.1	3.5	18	44.4	1.2	5
Litter and leaves	42.8	3.5	18	39.5	6.0	8
Rotten wood ≥10	46.4	-	2	35.4	-	1
Charcoal	absent			64.6	6.3	172
Ash	absent			6.6	1.7	6
Standing trees[b]	46.0	-	-	46.0	-	-

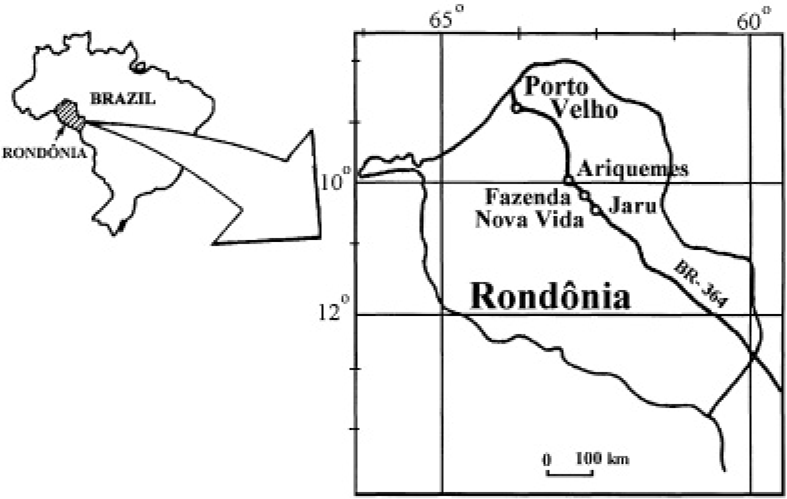
[a] Pre-burn carbon content is a weighted mean of bark and wood: carbon content of bark was 41.7%(n=18; SD=2.8) and of wood was 46.4(n=18; SD=2.1); the dry weight of the ≥ 10 cm diameter class was composed of 8% bark and 92% wood. The post-burn mean is similarly weighted: the mean of carbon content of bark was 41.1%(n=18; SD=3.1) and wood was 46.8(n=18; SD=2.0); the dry weight the ≥ 10 cm diameter class was composed of 5% bark and 95% wood.

[b] Percent carbon for standing trees was assumed the same as the fraction for pre-burn wood ≥10 cm diameter.

Table 4. Distribution of above-ground biomass carbon and carbon released at Fazenda Nova Vida, Rondônia

Biomass fraction by diameter class	Pre-burn		Post-burn		Total pre-burn carbon left in fraction
	Biomass	Carbon	Biomass	Carbon	
cm	Mg/ha	Mg/ha	Mg/ha	Mg/ha	%
Wood <5	26.50	11.8	2.2	1.0	0.7
Wood 5-10	21.40	9.5	12.5	5.7	4.0
Wood ≥10[a]	191.3	88.0	155.9	72.5	51.0
Vines <5	10.0	4.5	1.1	0.5	0.3
Vines 5-10	1.9	0.8	1.8	0.8	0.5
Vines ≥10	absent	absent	absent	absent	0.0
Palms <10	0.3	0.1	0.9	0.4	0.3
Palms ≥10	8.6	4.0	7.1	3.2	2.3
Palm leaves	12.7	5.6	2.0	0.9	0.6
Litter and leaves	24.1	10.3	1.0	0.4	0.3
Rotten wood ≥10	9.7	4.5	0.2	0.1	0.0
Charcoal	absent	absent	6.4	4.1	2.9
Ash	absent	absent	5.7	0.4	0.3
Standing trees	6.8	3.1	6.8	3.1	2.2
Total	313.3	142.3	203.6	93.1	65.4
Carbon released				49.2	34.6

[a] Biomass fraction for wood ≥10 cm post-burn was estimated from the burning efficiency found by the indirect method (LIS).



BRAZIL
RONDÔNIA
65°
60°
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Porto Velho
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Fazenda Nova Vida
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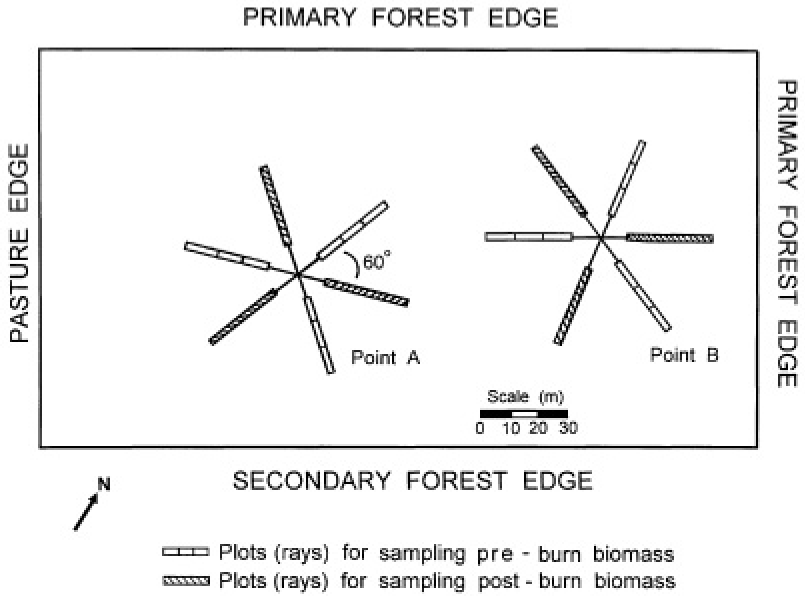
PRIMARY FOREST EDGE
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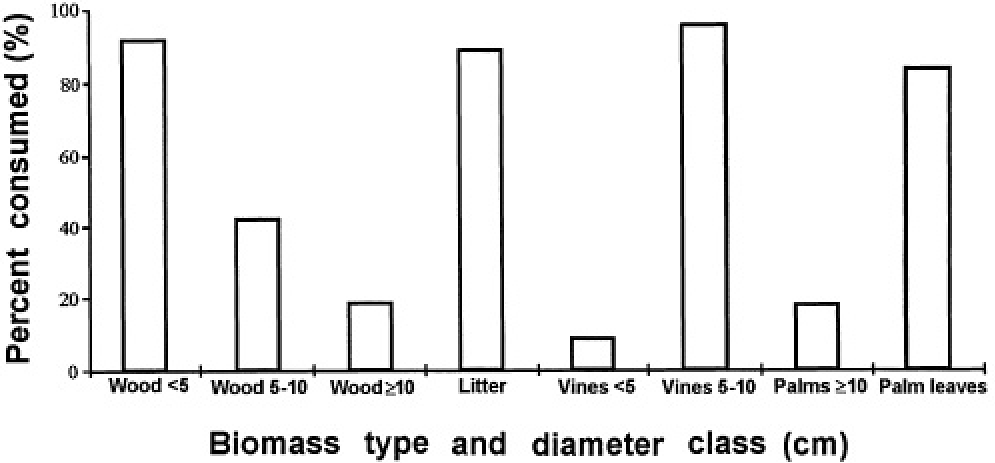
Plots (rays) for sampling pre - burn biomass
Plots (rays) for sampling post - burn biomass



Percent consumed (%)
100
80
60
40
20
0
Wood <5
Wood 5-10
Wood ≥10
Litter
Vines <5
Vines 5-10
Palms ≥10
Palm leaves
Biomass type and diameter class (cm)