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BURNING OF AMAZONIAN RAINFORESTS: BURNING EFFICIENCY AND CHARCOAL FORMATION IN FOREST CLEARED FOR CATTLE PASTURE NEAR MANAUS, BRAZIL

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Abstract

Twelve 60-m^2 plots were cut and weighed in a clearing at a cattle ranch near Manaus, Amazonas, Brazil. Above-ground dry weight biomass averaged 369 metric tons (megagrams = Mg) per hectare (Mg ha^{-1}) (SD=187). This corresponds to approximately 483 Mg ha^{-1} total biomass. Pre- and post-burn above-ground biomass loading was evaluated by cutting and weighing, and by line-intersect sampling (LIS) done along the axis of each quadrat. Because direct weighing of biomass disturbs the material being measured, the same quadrats cannot be weighed both before and after the burn. The high variability of the initial biomass present in the quadrats made use of volume data from the LIS more reliable for assessing change in the biomass of wood >10 cm in diameter; estimates of changes in other biomass components relied on data from direct weighing. Estimates of initial stocks of all components relied on direct measurements from the pre-burn quadrats; in the case of wood >10 cm in diameter this was supplemented with direct measurements from the post-burn quadrats adjusted for losses to burning as determined by LIS. The measurements in the present study imply a 28.3% reduction of above-ground carbon pools. This estimate of burning efficiency is in the same range obtained in other studies using the same method, but two other methods in use in Brazilian Amazonia produce consistently different results, one higher and the other lower than this one. Charcoal made up 1.7% of the dry weight of our remains in the post-burn destructive quadrats and 0.93% of the volume in the line-intersect sampling transects. Approximately 1.8% of the pre-burn above-ground carbon stock was converted to charcoal.

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

1. Introduction

Deforestation in Brazilian Amazonia is a significant contributor to global emissions of greenhouse gases (GHGs). Among the sources of GHG emissions, biomass burning is one for which calculations have the least foundation in field measurements. Previous measurements have been made of burning efficiency (Araújo et al., 1999; Carvalho, Jr. et al., 1995, 1998; Fearnside et al., 1993, 1999; Graça et al., 1999; Guild et al., 1998; Kauffman et al., 1995), and charcoal formation in burns of mature forest in Brazilian Amazonia (Fearnside et al., 1993, 1999; Graça et al., 1999). Although the number of measurements is still woefully small, the increase in available information allows estimation of the relationship between fuel dimensions and burning efficiency (the percentage of carbon released from the initial stock of carbon contained in the pre-burn above-ground biomass). Among other reasons for quantifying this relationship is its necessity in accounting for changes expected as a consequence of logging the forest prior to deforestation.

A wide variety of estimates exists for the magnitude of the contribution of tropical deforestation to global warming. The strength of the empirical basis for the estimates is even more varied. It is still common for the most rudimentary "back-of-the-envelope" calculations to play prominent roles in the policy debate surrounding global warming. Burning efficiency and charcoal formation are important factors in determining GHG emissions. These factors control how much release occurs through combustion and how much through decay—an important difference if one is estimating quantities of trace gases rather than simply carbon.

The present study was carried out in an area being cleared for cattle pasture in the Manaus Free Trade Zone's Agriculture and Ranching District, in the state of Amazonas (Fig. 1). Fazenda Dimona, a 10,000-ha ranch, was the site of the study; this is one of the four ranches where the National Institute for Research in the Amazon (INPA)/Smithsonian Institution (formerly INPA/World Wildlife Fund-US) Biological Dynamics of Forest Fragments Project is conducting a long-term study of changes in isolated reserves remaining as islands surrounded by pasture (Laurance and Bierregaard, Jr., 1997; Lovejoy and Bierregaard, Jr., 1990). Average annual rainfall at INPA's Model Basin, 14 km south of Fazenda Dimona, is 2052 mm (estimated from monthly means: Nov. 1979-Aug. 1984), but inter-annual variability is high. The clearing at Fazenda Dimona is at 2°19'24"S, 60°5'42"W, or about 1.6 km east of the 1984 clearing in which an earlier study of biomass and burning was conducted (Fearnside et al., 1993). Forest at the site is classified as Db (dense closed Amazonian lowland forest) in the vegetation typology used by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) (Brazil, IBGE and IBDF, 1988), and as Fda (tropical dense forest of the sub-region of low plateaus of Amazonia, lowlands with dissected topography) in the RADAMBRASIL typology (Brazil, Projeto RADAMBRASIL, 1978).

[Figure 1 here]

The Biological Dynamics of Forest Fragments project in which the study plots are located has an extraordinarily large data set on tree diameters and associated forest biomass. Over 137,000 diameter at breast height (DBH) measurements have been made on > 56,000 trees with DBH ≥ 10 cm; all of these trees have been mapped, botanically collected and identified to family, and most have been identified to species. In 65 1-ha plots in standing forest, the above-ground live biomass (including a correction for trees < 10 cm DBH) is 355.8±47.0 Mg ha^{-1} (Laurance et al., 1999), while for the subset of 36 plots located at least 100 m from the nearest forest edge it is 381.5±38.5 Mg ha^{-1} (Laurance et al., 1997). The area was quite inaccessible prior to the mid-1970s (with the exception of the historical occupation by indigenous peoples that applies to all Amazonian forests) and can be considered "primary" forest.

The study was done in a 17-ha clearing made for cattle pasture at Fazenda Dimona. The clearing is in an L-shaped strip along the southern and eastern sides of a 100-ha reserve (No. 2303). The felling was carried out by the Biological Dynamics of Forest Fragments project in order to isolate the reserve, and was done in early August 1990. The forest clearing was done using methods typical of Amazonian deforestation in general, beginning with underclearing (broca) using a brush hook (foice), followed by felling large trees using chainsaws (see Fearnside, 1990). Plots were set out after the felling was completed and the trees were lying on the ground. After being allowed to dry, the vegetation was burned on 19 September 1990.

Estimates of Amazon forest biomass vary tremendously. Because of the high biomass and vast area of dense upland forests in Amazonia, differences in values used for their biomass have a great effect on the conclusions drawn from calculations of release of carbon dioxide (CO_2) and other greenhouse gases. These controversies are reviewed elsewhere (Fearnside et al., 1993; Fearnside, 1994).

2. Methods

The great spatial heterogeneity in the fallen trunks makes burning efficiency determination impractical for large-diameter biomass components without very large sample sizes if efficiency is estimated by comparing destructive measurements (necessarily at different points) before and after the burn. The solution has been to base burning efficiency for this biomass component on indirect (LIS) measurements made on the same pieces of wood, measured before and after the burn at the same marked points. The burning efficiency estimate for the above-ground biomass as a whole is therefore derived from a combination of direct and indirect results.

Two "stars" of destructive quadrats were implanted, each consisting of six rays or quadrats of 2 × 30 m (Fig. 2). Locations of the stars within the clearing were chosen by generating the coordinates of the central point as random numbers, and extending the rays from the central point in predetermined directions. Half of the quadrats in each star were harvested before the burn, and half after. The pre- and post-burn rays alternate, so as to avoid any bias from the non-random spatial orientation of the felled trees (for ease in felling, chainsaw operators try to cut trees so that they fall roughly in parallel). The method is described in greater detail elsewhere (Fearnside et al., 1999; Graça et al., 1999). In each quadrat, a line-intersect sampling (LIS) transect was run along the midline of the quadrat, with measurements made for pieces >10 cm in diameter (Warren and Olsen, 1964). Diameters were measured at right angles to the axis of each piece (Van Wagner, 1968). Numbered aluminum tags were nailed to each piece at the point of measurement, allowing re-measurement in the same place and identification of the piece. Diameters were measured perpendicular to the axis of each piece--not following the transect line. We emphasize that these diameter measurements are not diameters at breast height (i.e., diameter at 1.3 m above the ground on a standing tree); the random location of the points at which the transect lines cross the prostrate trunks and branches of felled trees allows calculation of wood volume directly from the cross-sectional area of the intersection points, without use of allometric equations or form factors.

[Figure 2 here]

Within each quadrat, all biomass above ground level was cut with chainsaws, axes and machetes, and weighed using a series of spring balances, the largest being of 90-kg capacity accurate to ±1 kg. In the pre-burn quadrats, biomass was divided into ten fractions (pools): wood with diameter <5 cm, 5-10 cm and >10 cm; vines with diameter <5 cm, 5-10 cm and >10 cm; litter (including leaves that fall off the trees after felling); palms with diameter ≤10 cm and >10 cm; and "other" (bamboo and other grasses, palm fruits, etc.). The same pools were evaluated post-burn, plus additional categories for charcoal on the ground and charcoal still attached to unburned biomass. Subsamples of each fraction were collected in each quadrat for determination of water content for calculating dry weights.

Charcoal on the ground was collected manually from the entire area of the post-burn plots. Charcoal adhering to the biomass was scraped off with machetes. The same procedures used in the previous studies were applied (see Fearnside et al., 1993, 1999 for additional details of the collection procedure). The present charcoal production estimate excludes very finely powdered charcoal that cannot be collected manually from the ground and particulate elemental carbon released as soot in smoke.

Samples were dried in electric ovens to constant weight at 105°C. Subsamples were weighed at intervals to determine when constant weight had been attained.

Charcoal thickness was measured at four points equally spaced around the circumference of each piece: top, bottom, and two sides; in cases where a trunk was lying on the ground, the "bottom" measurement was made on one side as closely as possible to ground level, following the procedures applied previously (Fearnside et al., 1999).

The initial (pre-burn) biomass present in the area is estimated from the direct measurements of all components in the pre-burn quadrats. The great spatial heterogeneity of the wood >10 cm in diameter, however, makes it advisable to extend the sample size as much as possible for this biomass component. The sample size is doubled by using the volume of wood >10 cm in diameter present before the burn in the post-burn plots, as determined by LIS. The areas sampled for initial biomass are therefore 720 m^2 for wood >10 cm in diameter, and 360 m^2 for other biomass components.

3. Results

3.1. Biomass stocks

Pre-burn biomass of wood and palms >10 cm in diameter was estimated from all plots, with adjustments to LIS measurements in post-burn plots as described above, while other components were estimated from direct measurements in pre-burn plots (Table 1). The mean total above-ground biomass dry weight was 369±187 megagrams (Mg) (= metric tons) ha^{-1} before the burn. The class of wood >10 cm in diameter totaled 270±121 Mg ha^{-1} and represented the greatest portion of the above-ground stock (73.1%). The fractions of wood <5 cm and wood 5-10 cm in diameter (composed mostly of branches) together totaled 55±32 Mg ha^{-1} and represented 14.9% of the total stock of above-ground biomass; vines totaled 11±19 Mg ha^{-1} and represented 2.9%; palms contributed 3.5 Mg ha^{-1} and represented 0.9%; litter (including leaves and twigs that had fallen off the trees after felling) contributed 30±13 Mg ha^{-1} and represented 8.1%.

[Table 1 here]

Total biomass remaining above ground after the burn was 258±134 Mg ha^{-1} (Table 2). The biomass of wood >10 cm in diameter was 223±99 Mg ha^{-1} and represented 86.4% of the total remaining biomass above ground. The fractions for wood <5 cm and wood 5-10 cm in diameter (composed mostly of branches) together totaled 18±16 Mg ha^{-1}, representing 7.0% of the total stock of biomass above ground; vines totaled 1.7±3.6 Mg ha^{-1} and represented 0.7%; palms contributed 1.7 Mg ha^{-1} and represented 0.7%; litter (including leaves and twigs falling off trees after felling) contributed 9.6±9.1 Mg ha^{-1} and represented 3.7%, and charcoal contributed 4.3±5.9 Mg ha^{-1} and represented 1.7%.

[Table 2 here]

Above-ground biomass before and after burning for each fraction are shown in Table 2. The size of the pieces greatly influences the percentage burned: 17.5% of the >10-cm diameter wood being burned versus 79.8% of the <5-cm diameter wood. Of the above-ground biomass present before the burn, 8.3% was <5 cm, 6.6% 5-10 cm and 73.2% >10 cm in diameter. No significant difference was found between results for biomass determination using the LIS and the direct method for wood >10 cm in diameter (t-test, p=0.47; n=6).

Approximate total dry weight biomass can be estimated using the fraction of the total biomass in roots found in existing studies that include below-ground biomass. Using a root/shoot ratio of 0.31 (derived from three studies reviewed in Fearnside, 1994) as the estimate for below-ground biomass results in an estimate of total dry weight biomass of 483 Mg ha^{-1} at Fazenda Dimona. Average wood density for the >10 cm diameter class was 0.81 g cm^{-3} (oven-dry weight/volume at time of collection, n=18, SD=0.12).

3.2. Influence of slope on stock of wood >10 cm in diameter

By chance one of the stars (P) was located on steeply sloping terrain, with almost half (48%) of the total length of the rays having slopes ≥55%, with some slopes up to 68%. The other star (F) was on level ground. No significant difference was found in the biomass of wood >10 cm in diameter present in the two stars (p=0.81, n=6). The steep slope of the terrain at point (star) P did not influence the result for pre-burn biomass in the class of wood >10 cm in diameter when compared with point F on flat land. The biomass contained in the post-burn plots (rays) was converted to pre-burn biomass using the percentage changes from the burn obtained from the LIS for these plots. The means for biomass of >10 cm in diameter in the two sets of plots were not significantly different (t-test, p=0.812, n=6). The mean for biomass of wood >10 cm in diameter on flat terrain was 277±118 Mg ha^{-1}, while on the steeply sloping terrain it was 263±85 Mg ha^{-1}.

3.3. Comparison between the direct and LIS methods

The values for mean biomass for wood >10 cm in diameter after the burn derived by the two methods did not differ significantly (t-test, p=0.474, n=6). The post-burn mean biomass for wood >10 cm in diameter by the direct method was 215±86 Mg ha^{-1} (Table 1), while that estimated from LIS was 259±111 Mg ha^{-1}.

3.4. Charcoal formation

The total stock of charcoal formed after the burn as determined by the direct method was 4.3±5.9 Mg ha^{-1}. Of this, 1.2±1.8 Mg ha^{-1} of charcoal was lying on the ground and the remaining 3.1±4.1 Mg ha^{-1} was clinging to the above-ground biomass. The class of wood >10 cm in diameter contributed 71.0% (2.2±2.7 Mg ha^{-1}) to the total of charcoal clinging to the biomass. Using the indirect method (LIS), the estimated stock of charcoal clinging to the biomass for wood >10 cm in diameter was 1.5±0.7 Mg ha^{-1}. The estimated mean charcoal stocks clinging to the biomass for wood >10 cm in diameter did not differ significantly between the direct and indirect methods (t-test, p=0.11, n=6).

3.5. Stock of carbon in the biomass

Biomass stocks were converted to carbon (Table 3) using the percentage of carbon in the pre- and post-burn biomass from Fearnside et al. (1993). Carbon content of charcoal is assumed to be 74.8%--the mean for charcoal manufactured from primary forest woods in the Manaus region (Corrêa, 1988, p. 99). Carbon partitioning among different compartments is calculated in Table 3. Total stock of carbon in above-ground biomass before the burn was 182 t C ha^{-1}. After the burn the stock of carbon was reduced to 130 t C ha^{-1}, presumably releasing 51 Mg ha^{-1} of carbon into the atmosphere. Of the carbon in pre-burn biomass, 1.8% is converted to charcoal. The means of pre- and post-burn biomass measurements imply a release of 28.3% of the pre-burn carbon stock (Table 3).

[Table 3 here]

Although we did not analyze carbon in the ashes from this study, we know that their carbon content is very low based on other studies (C concentration = 6.6%, SE=0.5, n=6; see Graça et al., 1999). Ashes therefore can be expected to contribute very little to the total stock of post-burn carbon.

3.6. Burning efficiency and biomass consumption

Overall burning efficiency was 28.3% (Table 3). Biomass fractions most consumed by the burn were vines >10 cm in diameter and vines <5 cm in diameter, losing 92.0% and 86.7% of their weight, respectively. The class of wood >10 cm in diameter was the one that burned least, with only 17.5% of its biomass being consumed by fire.

Burning efficiency and water content of wood, which accounts for 160 t C ha^{-1} of the 182 t C ha^{-1} total pre-burn carbon stock, or 87.9%, follows a regular pattern. As diameter increases, the percentage of water content at the time of the fire increases and the burning efficiency decreases (Table 4). One would expect that differences in the burning efficiency among materials of the same dimensions would be explained by the intrinsic water content of each type of plant tissue. Classes with higher water contents should have lower burning efficiencies. However, we found that some fractions of the less important types with higher pre-burn water contents were more completely burned than others with lower water contents (Table 4). The class of wood <5 cm in diameter had a 79.8% burning efficiency and a mean water content of 30.3%, while vines in the same diameter class had a burning efficiency of 86.7% and a water content of 71.8%. The high variability in the sampling may explain this result for small fractions such as vines, which represent only 2.4% of the pre-burn carbon stock. Categories of biomass with smaller amounts present generally have greater variability (e.g. Table 2).

[Table 4 here]

4. Discussion

The results show high variability in biomass over short distances. The small area of the study plots logically results in high levels of variability. In addition, variability between quadrats can be expected to be higher for plots in an already felled forest, as in the present study, than for plots in the same area with the forest still standing, as in studies where the estimates are done from volume estimates of standing trees, or where felling is done experimentally. For plots of equal size, higher variability is expected in already felled areas because the process of felling leads to greater clumping.

High variability indicates a need for many measurements and careful sampling design in order to gain adequate estimates of biomass for the region as a whole. Biomass studies in the general area of the study site are compared in Table 5. All of these studies are in the same forest type (Db) as classified by the Brazilian Institute for Environment and Renewable Natural Resources (IBAMA) (Brazil, IBDF and IBGE, 1988). The largest data-set for the area immediately surrounding the study is based on diameter measurements of trees ≥10 cm diameter at breast height (DBH) in 65 1-ha plots of standing forest (Laurance et al., 1999). When adjusted for vines and dead biomass, this indicates a mean of 384 Mg ha^{-1} of above-ground biomass, quite close to our value of 369 Mg ha^{-1}. For the same forest type throughout the state of Amazonas, the mean above-ground biomass averages 332 Mg ha^{-1}, based on forest volume surveys conducted by Brazil's Projeto RADAMBRASIL (1978) in the same forest type (Fearnside, 1994). Indirect methods based on forest volumes are needed to obtain reliable means for large areas, although estimates such as those in the present study are needed to adjust the volume-based studies for other components such as vines and palms.

[Table 5 here]

The relative contributions that different classes of material make to emissions will determine how these results can be applied to other types of forests in the region. Although the larger-diameter classes represent the largest part of the pre-burn biomass, the small proportion of these classes that burns reduces their relative importance in the carbon emitted by combustion (Fig. 3). The percentage of material in the >10 cm diameter class varies among sites. The present study at Fazenda Dimona found wood >10 cm in diameter to represent 73.2% of the pre-burn above-ground biomass, which agrees well with the 76.1% we found in our previous study on the same ranch (Fearnside et al., 1993). By contrast, wood >10 cm in diameter represented 62.4% of the biomass at Fazenda Nova Vida (Ariquemes), Rondônia (Graça et al., 1999) and 52.5% at Altamira, Pará (Fearnside et al., 1999). These latter sites had substantially more of the emission contributed by the small-diameter classes, especially at Altamira where vines were more abundant than at the other sites (Fig. 3).

[Fig. 3 here]

Within the > 10-cm diameter wood class, the distribution of volume among diameter ranges could affect the burning efficiency of this class. Were the biomass dominated by a few very large individuals, the burning efficiency could be expected to be lower than if trees of modest diameter make up most of the biomass. While some very large individuals occur in the forest, our study plots did not contain any of these (the maximum diameter was 38.0 cm). For the post-burn plots (from which burning efficiency for the > 10-cm diameter wood class is derived) the distribution of volume among diameter ranges for the pre-burn measurements is shown in Figure 4.

[Fig. 4 here]

Our estimate of burning efficiency at Fazenda Dimona (28.3%) is in the range of other estimates obtained by this method (Method 1 in Table 6) in other primary forest burns in Amazonia. Two other methodologies have been used in the region, with results that appear to differ from ours for methodological reasons. One (Method 2 in Table 6) has generally produced higher values for burning efficiency. This method used a LIS similar to ours, with the important difference that only the two end points of each transect were marked, not the point on each piece where the measurement was made. Destructive sampling was not used (except for litter, live seedlings and resprouts), instead estimating all size classes using LIS, with shorter transects for the smaller-diameter classes. The estimates of Kauffman et al. (1995) each has a total transect length of 352 m for pieces ≥7.6 cm in diameter, about the same as the total of 360 m in the present study but with double the length for which we have both pre- and post-burn transects.

[Table 6 here]

The third method (Method 3 in Table 6) has produced consistently lower values. This method used an observation (method, sample size and variability not specified) that no more than 3 mm (Araújo et al., 1999) or 5 mm (Carvalho, Jr. et al., 1995) was removed from the diameter of each piece for trunks >5 cm and branches >10 cm in diameter. This reduction in diameter was then applied to the volume of material in each of these categories, resulting in very low burning efficiencies for these fractions. In the most recent study (Carvalho, Jr. et al., 1998), the diameter reduction was measured separately for each trunk or branch in the sample quadrats, as well as the length along the piece to which the reduction applied. This method indicates minimal amounts of burning in biomass fractions for which burning efficiency was estimated with this procedure: 0.4% for trunks of trees >30 cm diameter at breast height (DBH), 4.4% for trunks of trees 5-30 cm DBH, and 4.4% for branches >10 cm in diameter (Carvalho, Jr. et al., 1998). These values are at least an order of magnitude lower than our results for material >10 cm in diameter (Table 4). On the other hand, burning efficiencies for the remaining (smaller-diameter) fractions may be biased in the opposite direction. These were estimated by direct weighing of the same material before and after the burn, but cutting and piling the material in bonfire-like heaps (see photographs in Araújo, 1995, pp. 186-189) probably led to over-estimates of the burning efficiencies for these fractions.

It should be emphasized that conclusions on the effect of methodology are necessarily limited by the fact that burn quality varies greatly from one site to the next and from one year to the next, depending on meteorological parameters, timing of the burn, and characteristics of the vegetation (Fearnside, 1986, 1989). Nevertheless, the clustering of results obtained by different methods suggests a methodological effect (Fig. 5). Our method (Method 1 in Fig. 4) produces a mean value for percent burning efficiency ($\bar{x}=33.7 \pm 6.9$) significantly lower ($p<0.001$) than Method 2 ($\bar{x}=49.8 \pm 6.2$) and higher ($p<0.05$) than Method 3 ($\bar{x}=21.9 \pm 2.8$).

[Figure 5 here]

Although the explanation for differences in results associated with the different methodologies remains unknown, we are confident that our LIS procedure’s re-measurement of diameters at precisely marked locations on each piece greatly reduces error in determination of burning efficiency for the >10-cm diameter class that contributes most to carbon emissions (Fig. 3), thereby greatly reducing the uncertainty of our overall result as compared to the other two methods. Our direct-method estimates for combustion efficiency of the smaller size categories, although highly variable due to the natural heterogeneity of the fuel load and of the burning process, have no known biases either up or down. This probably makes them more reliable than direct methods that use burning in disturbed material (i.e., Carvalho, Jr. et al., 1995, 1998) that would have a high bias. On the other hand, the LIS method applied by Kauffman et al. (1995) for material in this size class may produce more reliable results for combustion efficiency of this fraction than does our more labor-intensive direct weighing approach. A comparison of the two methods in the same burn would be needed to determine which approach is most efficient for the small-diameter portion of the material.

Our percentage of charcoal formation (1.8% of pre-burn above-ground carbon) is in the same range as those found in our other studies of primary forest burns: 1.3% at Altamira, Pará (Fearnside et al., 1999), 2.9% at Ariquemes, Rondônia (Graça et al., 1999), and 2.7% at Fazenda Dimona, Amazonas (Fearnside et al., 1993). The absolute amount of charcoal dry weight formed in the burn studied here (4.3 Mg ha^{-1}) is also similar to that found in the above studies, which found, respectively, 2.2 Mg ha^{-1} at Altamira, 6.4 Mg ha^{-1} at

Ariquemes, and 4.7 Mg ha^{-1} at Fazenda Dimona. Globally, an estimated 49 × 10^6 t C is converted to charcoal annually by biomass burning in tropical deforestation and in clearing of secondary forests (including shifting cultivation), considering clearing rates for the 1981-1990 period (Fearnside, nd). This reduces annual net committed emissions of 2.4 × 10^9 t C by only 2% (Fearnside, nd). However, charcoal is important as one of the only ways that carbon is transferred to long-term pools in black carbon and can have important effects on atmospheric composition over geological time scales (e.g. Kuhlbusch, 1998).

5. Conclusions

The dense forests of Central Amazonia have high biomass, but spatial variability is great. Burning efficiency (percent of the pre-burn above-ground carbon stock released in the burn) depends strongly on the diameter of the material, smaller-diameter pieces burning more completely. While burning efficiency varies among burns, knowledge of the size composition of the material allows a substantial reduction of the uncertainty in predicting the amount of the total above-ground biomass consumed in a burn. The burning efficiency of 28.3% determined for the burn studied is in the range of values found for other burns estimated using the same method, but two other methods in use in Brazilian Amazonia have produced consistently different results, one higher and one lower than those obtained with the method used here. The study’s finding that 1.8% of pre-burn above-ground carbon is converted to charcoal confirms low rates of charcoal formation in Amazonian burns.

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Figure captions

Fig. 1. Location of the study area.

Fig. 2. Layout of plots.

Fig. 3. Pre-burn distribution of biomass among diameter classes and contributions to carbon of each class in four studies of burning in felled primary forest in Amazonia: (A) Dimona 1990 (this study), (B) Dimona 1984 (Fearnside et al., 1993), (C) Ariquemes 1994 (Graça et al., 1999), and (D) Altamira 1986 (Fearnside et al., 1999).

Fig. 4. Distribution of volume by diameter range in the > 10-cm diameter wood class for post-burn plots.

Fig. 5. Burning efficiency in Brazilian Amazonia found by different methods. Method 1: this study, Fearnside et al. (1993, 1999), Graça et al. (1999); Method 2: Kauffman et al. (1995), Guild et al. (1998); Method 3: Araújo et al. (1999), Carvalho, Jr. et al. (1995, 1998).

Table 1
Initial biomass stocks at Fazenda Dimona (Manaus) 1990

Plot[a]	Plot type	Pre-burn measurements			Post-burn measurements		
		Wood >10 cm diameter (Mg ha^{-1})	Other components (Mg ha^{-1})	Total	Wood >10 cm diameter (Mg ha^{-1})	Other components (Mg ha^{-1})	Total
F2	Pre-burn	201.25	81.53	282.77			
F4	Pre-burn	311.38	110.00	421.38			
F6	Pre-burn	356.49	117.69	474.19			
P2	Pre-burn	403.13	116.52	519.65			
P4	Pre-burn	178.65	95.78	274.44			
P6	Pre-burn	225.97	74.85	300.82			
F1	Post-burn	140.24[b]			113.15	28.68	141.83
F3	Post-burn	455.67[b]			379.15	47.82	426.97
F5	Post-burn	197.81[b]			162.74	28.25	190.99
P1	Post-burn	214.11[b]			170.06	21.71	191.77
P3	Post-burn	329.62[b]			261.35	38.43	299.78
P5	Post-burn	224.23[b]			202.51	26.83	229.34
	Mean	269.88	98.40	378.87[c]	214.83	31.95	246.78
	SD	94.53	16.71	98.42	86.00	8.65	93.75
	n	12	6	6	6	6	6

a Plots 60 m^2 (2 × 30 m).

b Post-burn wood >10 cm in diameter estimated from direct measurement made after the burn, adjusted by the percent of loss determined by LIS to each plot.

c Pre-burn total differs from 369.3±186.9 Mg ha^{-1} derived in Table 2 because pre-burn biomass of palms >10 cm in diameter used in Table 2 is back calculated from post-burn biomass using LIS estimates of losses (see Table 2, note b).

Table 2
Above-ground biomass dry weight before and after burn

Fraction	Pre-burn biomass (Mg ha^{-1} ± SD)	Post-burn biomass (Mg ha^{-1} ± SD)
Wood <5 cm	30.5±15.0	6.2±3.8
Wood 5-10 cm	24.5±16.9	11.8±11.8
Wood >10 cm[a]	269.9±120.5	222.7±99.4
Vines <5 cm	4.4±4.8	0.6±0.7
Vines 5-10 cm	3.2±4.4	0.8±1.8
Vines >10 cm	3.2±9.7	0.3±1.1
Litter	30.0±12.9	9.6±9.1
Palms ≤10 cm	2.2±2.7	0.6±0.8
Palms >10 cm[b]	1.3	1.1
Charcoal	-	4.3±5.9
Total	369.3±186.9	257.9±134.4

a Pre-burn biomass for this class was calculated from the mean from the pre-burn and post-burn plots, correcting the post-burn results for the percentage burned found by LIS for each plot. Post-burn biomass was estimated indirectly using the mean percentage consumed in post-burn plots based on LIS applied to pre-burn biomass in these plots.

b Only one palm >10 cm in diameter was present in LIS (the data used here); direct measurements for this category indicated 0.5±2.1 Mg ha^{-1} in pre-burn plots and 2.2±5.8 Mg ha^{-1} in post-burn plots.

Table 3

Above-ground carbon stock before and after the burn

Fraction	Pre-burn		Post-burn		Carbon partitioning (% of total pre-burn C left in fraction)
	Carbon content (%)	Carbon stock (Mg ha^{-1})	Carbon content (%)	Carbon stock (Mg ha^{-1})	
Wood <5 cm	48.4	14.8	49.1	3.0	1.7
Wood 5-10 cm	48.4	11.9	49.1	5.8	3.2
Wood >10 cm	49.3	133.0	49.9	111.1	61.2
Vines <5 cm	49.4	2.2	49.0	0.3	0.2
Vines 5-10 cm	49.4	1.6	49.0	0.4	0.2
Vines >10 cm	49.4	1.6	49.0	0.1	0.1
Litter	51.1[a]	15.3	51.1	4.9	2.7
Palms ≤10 cm	51.1	1.1	51.1	0.3	0.2
Palms >10 cm	49.3[b]	0.2	49.9[b]	1.1	0.6
Charcoal			74.8[c]	3.2	1.8
Total		181.7		130.2	71.7
Presumed release				51.4	28.3

a Carbon content assumed equal to that of pre-burn "leaves."

b Carbon content assumed equal to that of wood >10 cm in diameter.

c Charcoal carbon from Corrêa (1988).

Table 4

Percentage of biomass consumed by the fire and water content in plant tissues before the burn

Fraction (diameter size class)	Consumed (%)	Pre-burn water content (%)
Wood <5 cm	79.8	30.3
Wood 5-10 cm	52.1	41.4
Wood >10 cm*	17.5	46.0
Vines <5 cm	86.7	71.8
Vines 5-10 cm	74.6	127.1
Vines >10 cm	92.0	132.4
Litter	68.0	97.9
Palms ≤10 cm	75.0	276.4
Palms >10 cm*	13.6*	108.4

* Percentage consumed of wood and palms >10 cm in diameter determined by LIS.

Table 5
Above-ground biomass estimates in the Manaus area

Location with respect to this study	Above-ground biomass reported (Mg ha^{-1})	Missing components	Above-ground biomass[a] (Mg ha^{-1})	Reference	Comment[b]
--	369±189	None	369±189	This study	Fazenda Dimona
1.6 km W	265	None	265	Fearnside et al., 1993	Fazenda Dimona

Adjacent reserves at Fazenda Dimona and in two other ranches up to 15 km E	356±47	Dead above-ground biomass, vines	384[c]	Laurance et al., 1999	PDBFF reserves
14 km S	424.9	None	424.9	Carvalho, Jr. et al., 1995	INPA silviculture experimental station
14 km SSE	275	None	275	McWilliam et al., 1993	EMBRAPA experimental station
50 km SW	531.8	None	531.8	Klinge et al., 1974	Reserva Egler
Mean for this forest type in the state of Amazonas	332	None	332	Fearnside, 1994	

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a Dry weight of all above-ground live and dead biomass, including palms, vines, epiphytes, leaves, understory and litter.

b PDBFF = Biological Dynamics of Forest Fragments Project; INPA = National Instititute for Research in the Amazon; EMBRAPA = Brazilian Enterprise for Agriculture and Ranching Research.

c Vines approximately 8 Mg ha^{-1} (Laurance et al., nd); dead above-ground biomass 20 Mg ha^{-1} (Chambers, 1998, p. 58).

Table 6
Types of burning efficiency studies in primary forest burns

Method	Major features of procedure	Study	Location	Burning efficiency reported (%)	Comments
1	Line-intercept sampling for pieces > 10 cm diameter (with marked measurement points on each piece); destructive sampling for smaller size classes and litter.	This study	Fazenda Dimona, Amazonas	28.3	
		Fearnside et al., 1993	Fazenda Dimona, Amazonas	27.6	Destructive quadrats in 10 × 10-m format; separate post-burn LIS.
		Fearnside et al., 1999	Altamira, Pará	41.9	Mean of 3 burns.
		Graça et al., 1999	Ariquemes, Rondônia	36.8	
2	Line-intercept sampling for all diameter classes (without marked measurement points on each piece). Destructive sampling for litter, live seedlings and resprouts.	Kauffman et al., 1995	Jacundá, Pará	51.5	
		Kauffman et al., 1995	Marabá, Pará	51.3	
		Kauffman et al., 1995	Santa Barbara, Rondônia	40.5	
		Kauffman et al., 1995	Jamarí, Rondônia	56.1	
		Guild et al., 1998	Site 1, Rondônia	47	

		Guild et al., 1998	Site 2, Rondônia	54	
3	Estimate of diameter reduction in mm (method and sampling unspecified) extrapolated to all volume with diameter above specified minimum. Smaller material with direct weighing of same pre- and post-burn samples.	Araújo et al., 1999	Tomé-Açu, Pará	20.1	Diameter reduction of 3 mm for trunks > 5 cm diameter and branches > 10 cm diameter.
		Carvalho et al., 1995	Manaus, Amazonas	25.1	Diameter reduction of 5 mm for trunks > 5 cm diameter and branches > 10 cm diameter.
		Carvalho et al., 1998	Manaus, Amazonas	20.5	Separate diameter reduction measurements for each piece + measurement of length to which it applies.

Fig. 1

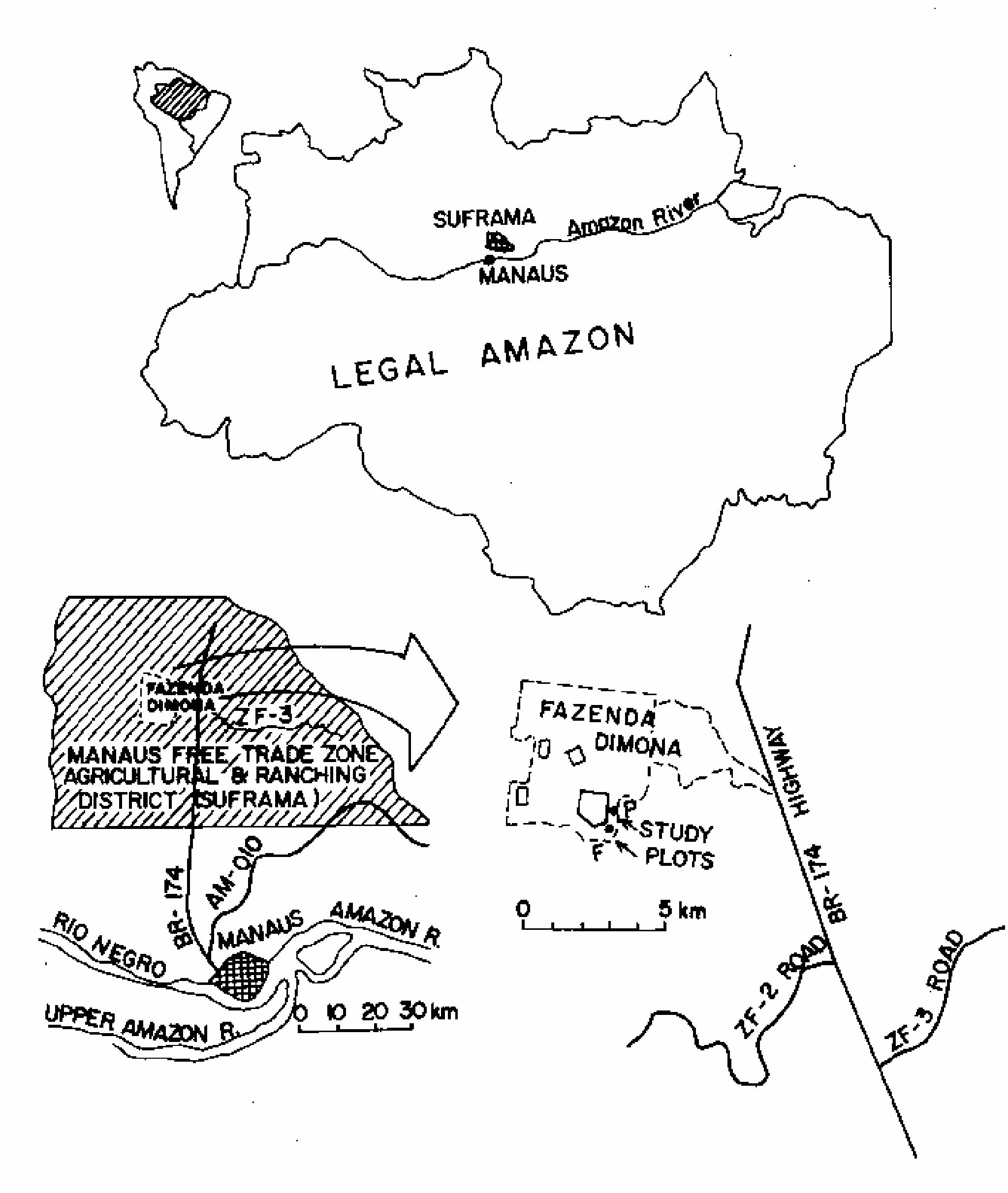
SUFRAMA
Amazon River
MANAUS
LEGAL AMAZON
FAZENDA DIMONA
ZF-3
MANAUS FREE TRADE ZONE AGRICULTURAL & RANCHING DISTRICT (SUFRAMA)
BR-174
AM-010
MANAUS
AMAZON R.
RIO NEGRO
UPPER AMAZON R.
0 10 20 30 km
FAZENDA DIMONA
P
STUDY PLOTS
F
0 5 km
HIGHWAY BR-174
ZF-2 ROAD
ZF-3 ROAD

Fig. 2

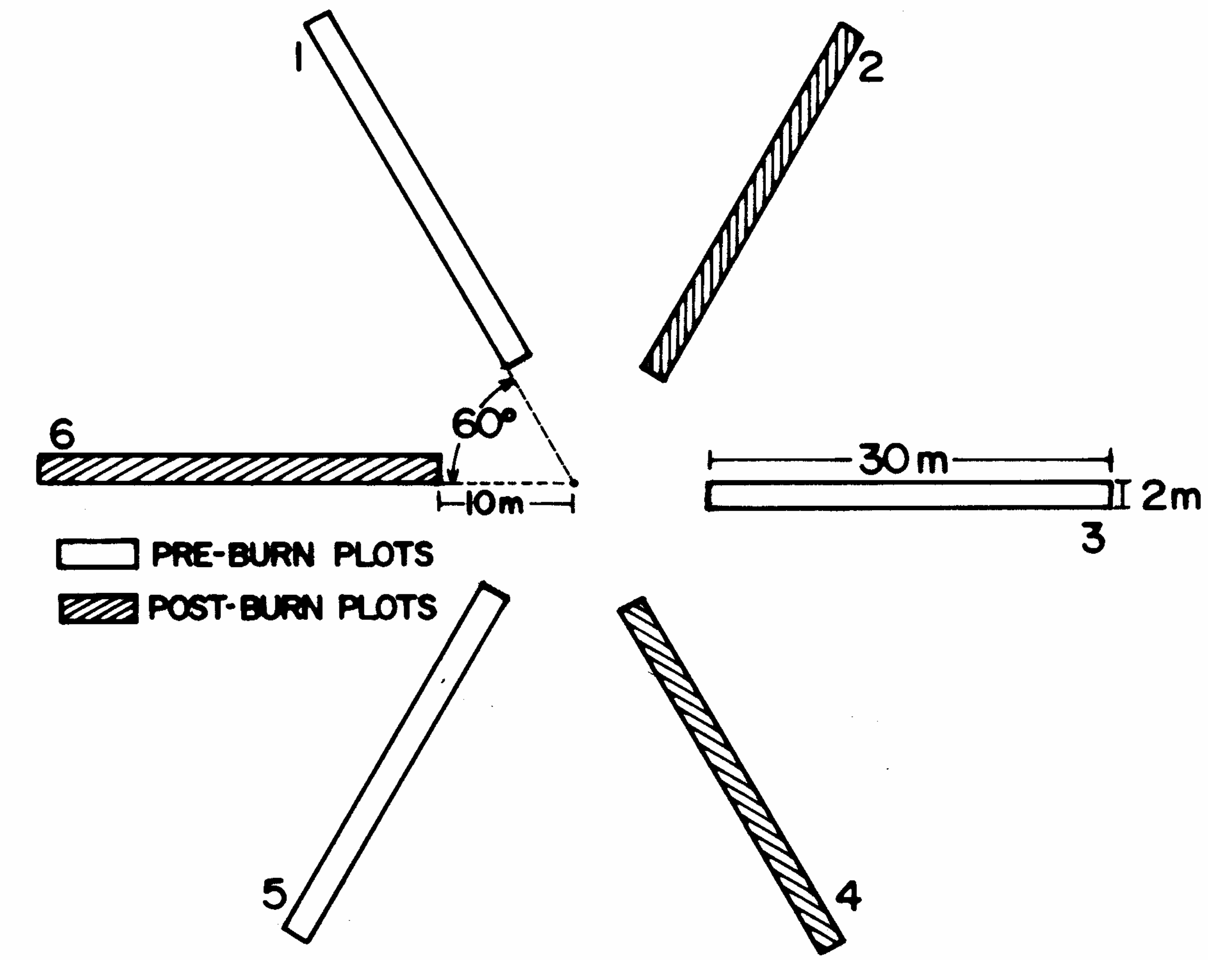

Fig. 3

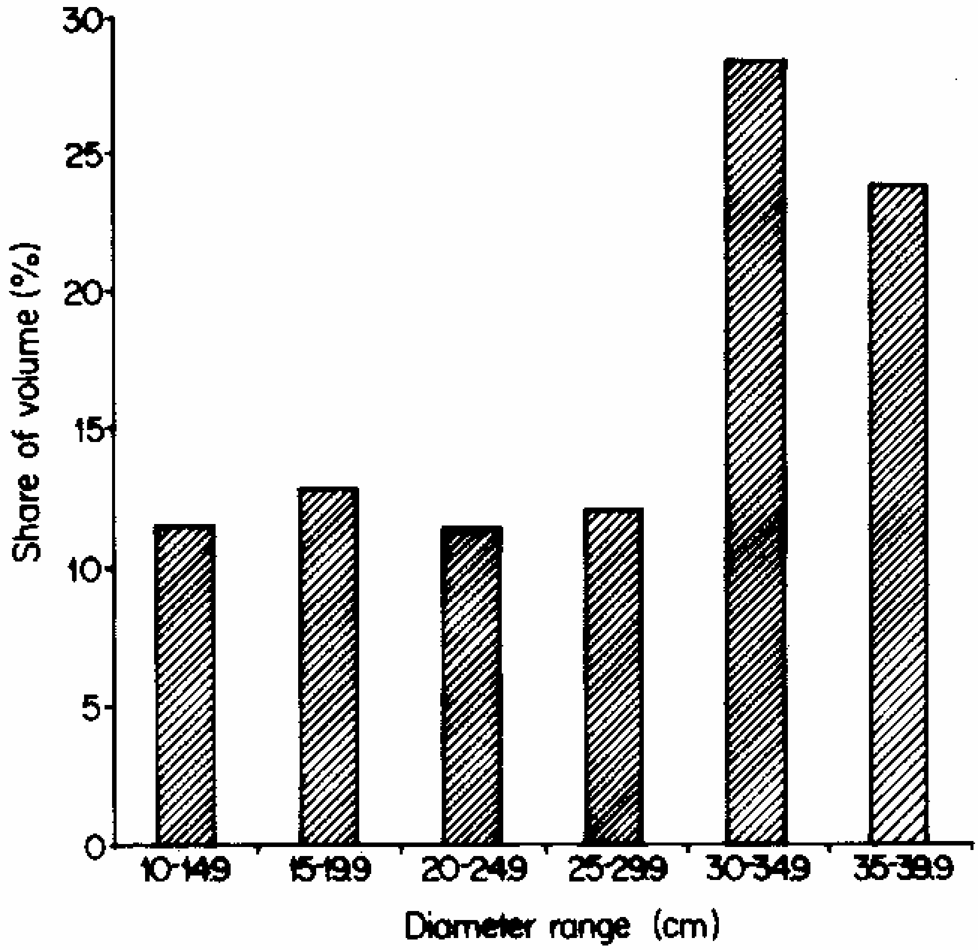
30
25
20
15
10
5
0
Share of volume (%)
10-14.9
15-19.9
20-24.9
25-29.9
30-34.9
35-38.9
Diameter range (cm)

Fig. 4

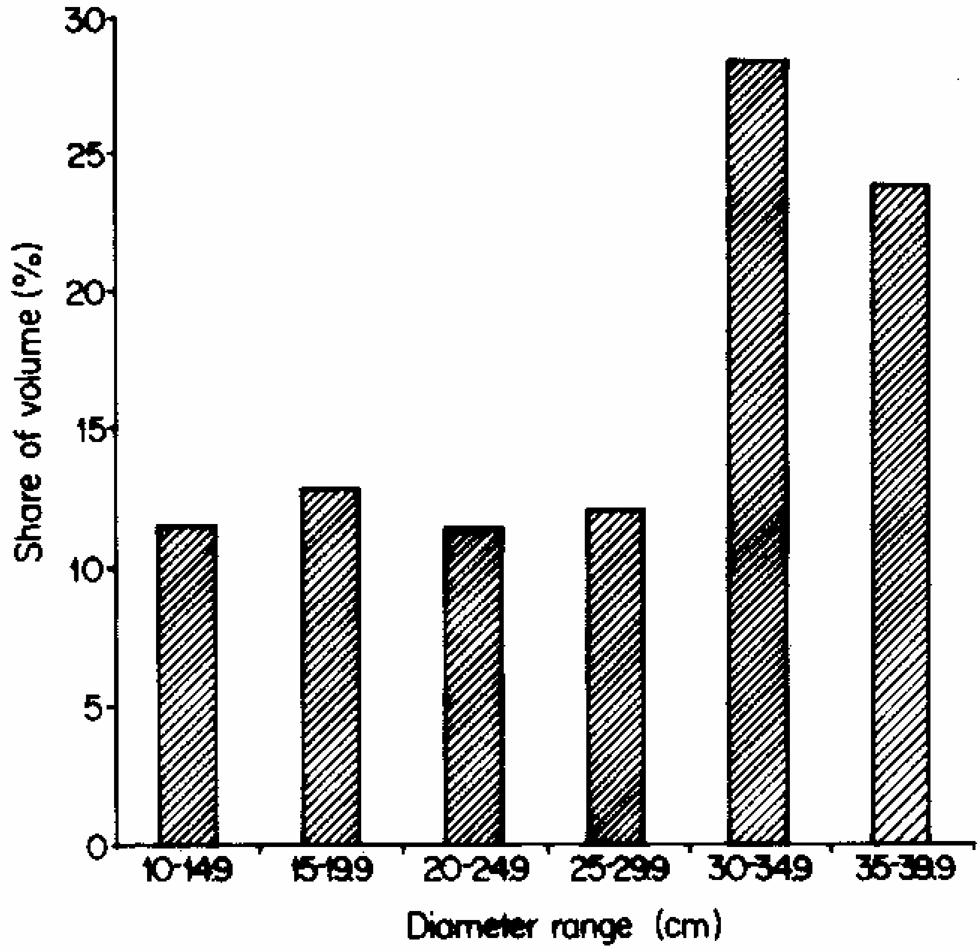
30
25
20
15
10
5
0
Share of volume (%)
10-14.9
15-19.9
20-24.9
25-29.9
30-34.9
35-38.9
Diameter range (cm)

Fig. 5