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RAINFOREST BURNING AND THE GLOBAL CARBON BUDGET: BIOMASS, COMBUSTION EFFICIENCY AND CHARCOAL FORMATION IN THE BRAZILIAN AMAZON

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ABSTRACT

Biomass present before and after burning was measured in forest cleared for pasture in a cattle ranch (Fazenda Dimona) near Manaus, Amazonas, Brazil. Aboveground dry weight biomass loading averaged 265 t ha^{-1} (standard deviation (SD) = 110, n = 6 quadrats) at Fazenda Dimona, which corresponds to approximately 311 t ha^{-1} total dry weight biomass. A five-category visual classification at 200 points showed highly variable burn quality. Postburn aboveground biomass loading was evaluated by cutting and weighing of 100 m^2 quadrats and by line intersect sampling. Quadrats had a mean dry weight of 187 t ha^{-1} (SD = 69, n = 10), a 29.3% reduction from the preburn mean in the same clearing. Line intersect estimates in 1.65 km of transects indicated that 265 m^3 ha^{-1} (approximately 164 t ha^{-1} of aboveground dry matter) survived burning. Using carbon contents measured for different biomass components (all around 50% carbon), and assuming a carbon content of 74.8% for charcoal (from other studies near Manaus), the destructive measurements imply a 27.6% reduction of aboveground carbon pools. Charcoal made up 2.5% of the dry weight of the remains in the postburn destructive quadrats and 2.8% of the volume in the line intersect transects. Thus approximately 2.7% of the preburn aboveground carbon stock was converted to charcoal, substantially less than is generally assumed in global carbon models. The findings confirm high values for biomass in Central Amazonia. High variability indicates the need for further studies in many localities, and for making maximum use of less laborious indirect methods of biomass estimation. While indirect methods are essential for regional estimates of average biomass, only direct weighing such as that reported here can yield information on combustion efficiency and charcoal formation. Both high biomass and low percentage of charcoal formation suggest the significant potential contribution of forest burning to global climate changes from CO_2 and trace gases.

INTRODUCTION

Clearing and burning of tropical forests releases large quantities of carbon dioxide, trace gases and aerosols (R.A. Houghton 1990a,b). Increases in atmospheric CO_2 and CH_4 contribute to the greenhouse effect, expected to warm global climate significantly over the coming decades (e.g. J.T. Houghton et al., 1990, 1992).

Current best estimates for clearing rates of primary forest (including flooding for hydroelectric dams) are 22.0 X 10^3 km^2 yr^{-1} for the 1978-1988 period, 19.0 X 10^3 km^2 yr^{-1} for 1988-1989, 13.8 X 10^3 km^2 yr^{-1} for 1989-1990, and 11.1 X 10^3 km^2 yr^{-1} for 1990-1991 (Fearnside et al., nd). Deforestation rates, together with information on the biomass of forest, the replacement vegetation, and the fate of carbon during burning and other transformations, can be used to calculate net committed emissions. "Committed emissions" refers to the weights of gases released from the land use change--including the releases from the decay of unburned material from the original forest and the uptake by regrowing vegetation on the areas deforested in a given year, but not including historical effects prior to the year of the estimate. Using the 1990 clearing rate in each of the region's nine states and the distribution of forest types among the states, carbon releases from the top 20 cm of soil, and a mosaic of replacement vegetation types assuming the equilibrium proportions implied by current land use transformation behavior, clearing in Brazilian Amazonia (exclusive of clearing in scrub savanna (cerrado) and in secondary forest) contributed the following weights of gases in 1990 as net committed emissions in a conservative (low trace gas) scenario: 855 X 10^6 t of CO_2, 2.2 X 10^6 t of CH_4, 24.9 X 10^6 t of CO and 0.27 X 10^6 t of N_2O (Fearnside, nd, updated from Fearnside, 1992a).

The contribution of deforestation to atmospheric increases in greenhouse gases has generated a lively academic debate. Much of the controversy of the past decade is due to the scarcity of data on carbon storage and release from tropical forests. For example, Woodwell et al. (1978) calculated that the terrestrial biota could be releasing between 2 and 13 G tons of carbon annually, and thereafter refined their calculations to yield estimates of 1.8-4.7 G tons (Woodwell et al., 1983). A number of studies point to substantial contributions from tropical forest burning (e.g. R.A. Houghton et al., 1983, 1985).

Seiler and Crutzen (1980: 241) arrived at the lower range of ±2 G tons for annual carbon release through biomass burning in the terrestrial biosphere. A substantial carbon sink in charcoal was a major factor in this result: the charcoal production rate (0.5-1.7 ?t C yr^{-1}) is 13-85% of the magnitude of the gross carbon flux to the atmosphere from CO_2 released by biomass burning (2-4

?t C yr^{-1}), or 37%, using the midpoints of these ranges. Charcoal formation has not been measured in the tropics, where over 70% of the earth's biomass burning presently occurs (Seiler and Crutzen, 1980: 232), and where the potential amount of burning is even greater should deforestation continue to increase rapidly. The value for charcoal formation was based on "qualitative observations" made in a ponderosa pine (Pinus ponderosa) stand in Colorado after a forest fire (Seiler and Crutzen, 1980: 236). Seiler and Crutzen (1980: 237) state that "since no good quantitative data are available from any ecosystem, we guess that elemental carbon represents 20-30% of the total aboveground unburned carbon." This was extended to the tropics on the strength of "pictures of freshly cleared fields" (Seiler and Crutzen, 1980: 236). Seiler and Crutzen's (1980) pioneering study has filled an important gap in understanding the carbon problem: For lack of a better value, their visual estimate has been, prior to the results reported here, the most commonly used parameter for charcoal in global carbon modeling (e.g. Goudriaan and Ketner, 1984). More recent work by Crutzen and Andreae (1990) has used a value of 5% for charcoal formation with respect to preburn aboveground biomass carbon (exposed carbon), based on a preliminary version of the measurement reported in this paper (the preliminary value of 3.6% was higher than the present one of 2.7% due to assumption of a higher value for the carbon content of the charcoal), and on a value of 5.4% derived from a study of prescribed burning in pine forest in Florida (Comery, 1981). The paucity of quantitative data for charcoal formation, and the poor representativeness of fires in temperate coniferous forests as indicators of results for tropical forest burning for ranching and agriculture show the urgent need for measurements.

On a regional or global scale, an equilibrium is eventually established between the carbon in atmospheric CO_2 and that in the vegetation replacing the forest. When forest is cut, a pulse of CO_2 is released to the atmosphere; regrowth of vegetation puts some released carbon back into storage. Since the average biomass of replacement vegetation is lower than that of forest, the net result of forest conversion is to transfer carbon from the biosphere to the atmosphere. Subsequent burnings of pasture or secondary forest have a relatively minor effect on carbon balance (although they do contribute methane).

Reburning may affect transfer of charcoal to slow-cycling pools in either direction: by oxidizing charcoal formed in the initial burning of primary forest, or by creating new charcoal. Processes removing some of the charcoal from exposure to burning include burial in the soil and transport by wind or water to deposition sites in ocean sediments (see Sanford et al., 1985 on soil charcoal pools and Suman, 1984 for sediment burial rates). Over a time scale of centuries, these sinks slowly accumulate carbon. These burial processes would have little effect on the massive pulse of carbon released to the atmosphere over the next few decades should Amazonian deforestation proceed unabated (R.A. Houghton et al., 1983).

Burning also releases trace gases such as N_2O, CO, CH_4, CH_3Cl, and NO (Andreae et al., 1988, Crutzen et al., 1979, 1985). Increases in the atmospheric load of these gases contribute to global warming and dominate the dry season photochemistry of the lower latitudes (Dickinson and Cicerone, 1986; Ramanathan et al., 1985, Thompson and Cicerone, 1986). Releases of gases from burning in tropical forest areas are poorly quantified.

Estimates of Amazon forest biomass vary tremendously. Because of the high biomass and vast area of dense upland forests of Amazonia, the differences in the values used for their biomass have a great effect on the conclusions drawn from calculations of release of CO_2 and other greenhouse gases. Estimates of total (above- and below-ground) dry weight biomass range from the 765 t ha^{-1} value of Whittaker and Likens (1973) for "tropical rainforest" to a value of 155.1 t ha^{-1} calculated by Brown and Lugo (1984) for "tropical American undisturbed productive broadleafed forests."

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 (Figures 1-2). Fazenda Dimona, a 10,000 ha ranch, was the site of the study; it is one of 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 (Lovejoy and Bierregaard, 1990). Average annual rainfall at INPA's "model basin," 28 km south of Fazenda Dimona, is 2052 mm (estimated from monthly means: Nov. 1979-Aug. 1984), but inter-annual variability is high. Fazenda Dimona is approximately 85 km north of the port of Manaus on the BR-174 (Manaus-Caracaraí) highway, or 68 km north of the 0-km mark for that highway. The clearing is at 2°19'24"S latitude, 60°5'42"W longitude. The 200-ha clearing was burned on 23 October 1984. Burn quality was variable but considered satisfactory by the ranch managers.

METHODS

PREPARATIONS

We surveyed topography and the locations of the sample stations along transect lines. Each station was marked with a 1-m iron rod that was topped with brightly colored paint and numbered to permit accurate relocation postburn. Secondary trails were cut perpendicular to each main transect. Each secondary transect was sampled at five pairs of primary and secondary points. Primary points were located along the cut trails at locations chosen haphazardly. A secondary point was placed off the trail, 5 m due north of each primary point. Soil samples were taken at each primary point before and after the burn. The steepest slope at each point was measured and recorded.

DESTRUCTIVE QUADRAT SAMPLING

Biomass was weighed in six 10 m X 10 m quadrats before the burn and ten after the burn. Quadrats were placed 20 meters to the west of primary points chosen at random on the secondary trails. In one case, the quadrat location selected using this procedure fell on the firebreak for one of the Biological Dynamics of Forest Fragments Project reserves, and so was displaced 15 m from the randomly chosen point.

Within each quadrat, all biomass above ground level was cut with chain saws, axes, and machetes, and weighed using a 90-kg capacity spring balance accurate to ±1 kg. In the preburn quadrats, biomass was divided into four fractions (pools): trunks (operationally defined as pieces with diameters >10 cm), branches (≤10 cm diameter), vines, and leaves and detritus. The same pools were evaluated postburn, 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, taking all black material visible to the eye in a close examination of the ground from the vantage of a squatting or crawling position. While some finely powdered charcoal is undoubtedly left behind by this procedure, the amount is believed to be small. Charcoal was also separated from all soil samples (before and after the burn) in the laboratory, using a fine brush (but no optical magnification).

For charcoal attached to the biomass fractions, char was scraped off the wood of trunks, branches, and vines. This was done in the field immediately after harvesting each quadrat. Since char grades into unburned wood in a continuum, a consistent operational definition must be applied. Char was removed using a blunt machete, striking each piece at a 45° angle with a "medium" amount of force. This was sufficient to remove char that was definitely black in color, while leaving the brownish-colored partially charred wood.

DRY WEIGHTS

Samples were dried in a forced air oven to constant weight at 110° C. Subsamples were weighed to determine when constant weight had been attained.

LINE INTERSECT TRANSECTS

Line intersect transects (Warren and Olsen, 1964) were run following the burn. In order to reduce any potential bias arising from the direction of tree boles lying on the ground, approximately equal lengths of transect were run at right angles to each other (van Wagner, 1968). Because of the oblong form of the clearing, these transects were divided into one extending over the long axis of the clearing and two shorter transects crossing in the shorter direction. Transect segments of 50 m were used, alternating with unsampled stretches of 50 m. The sampled stretches totaled 1.65 km. The decision rules of Warren and Olsen (1964) were used for inclusion of pieces intersected by the transect line. Using tree calipers, the diameters of the ovals representing the plane of intersection projected from the line were measured, rather than diameters at right angles to the axis of each piece; the data were later transformed to represent circular sections (Note that direct measurement of the circular diameter is recommended instead).

The thickness of charcoal was measured on all pieces that had been charred by the fire. Measurements were made 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 (Note that random points around the circumference are recommended instead). For each measurement, a cut was made with a light blow of a machete perpendicular to the axis of the piece of wood. The thickness of the black layer of charcoal was then measured with a clear plastic ruler calibrated in millimeters.

RESULTS

The day after the burn, a rough visual evaluation of burn quality was made at each of the 200 sampling points, classing the burns into five categories: "excellent" (at least some trunks burned to ash), "good" (burned vines and thick branches), "medium" (burned leaves and thin branches), "poor" (only leaves burned), and "none" (not even dry leaves on the ground burned). The distribution of qualities is shown in Figure 3. Wide variability is evident. While 67% of the points were classed as excellent or good, 33% had burns classed as medium, poor, or none.

Mean preburn aboveground biomass dry weight from the destructive quadrats was 265 t ha^{-1} (SD = 110, n = 6). Total dry weight biomass can be estimated using the fraction of total biomass in roots found in the three existing studies in Brazilian Amazonia where belowground biomass was measured: Klinge _et al_. (1975; see also Klinge, 1973a, b, c), working at INPA's Reserva Egler, located about 50 km southwest of the Fazenda Dimona site, found the belowground component to represent 23.9% of the total biomass (live + dead); Russell (1983: 29), found 12.6% at Jari, Pará, and Nepstad (1989) found 7.3% at Paragominas, Pará. All of these are probably underestimates of belowground biomass due to exclusion of the underground bole directly beneath each tree. Using the mean of 15.1% from the existing studies as the estimate for belowground biomass in our destructive quadrats yields an estimated total dry weight biomass of 311 t ha^{-1}.

Aboveground biomass after burning averaged 187.1 t ha^{-1} (SD=69, n=10 quadrats). Figure 4 gives the dry weights of postburn remains in the destructive quadrats. Figure 5 presents volumes of postburn remains as determined from line intersect transects. Figure 6 gives the unburned percentage of the biomass in each fraction, measured in the destructive quadrats. The size of the pieces greatly influences the percentage burned: 20.9% of the trunks being burned versus 100% of the leaves.

Carbon partitioning among different compartments is calculated in Table 1. 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: 99). Of the carbon in preburn biomass, 2.7% is converted to charcoal.

DISCUSSION

BIOMASS

The results show the very high variability in biomass on the scale of 10 X 10 m quadrats. The variability between quadrats can be expected to be higher for plots laid down on an already felled forest, as in the present study, than for plots of the same area in standing forest in studies where the felling is done experimentally (laying out plots in standing forest is possible for preburn biomass studies, such as that as by Klinge _et al_., 1975). Higher variability is expected in already felled areas because the process of felling leads to greater clumping.

Data from direct weighing of biomass are rare in Brazilian Amazonia. The methods, and consequently the reliability, of the studies vary tremendously. In addition to differences in plot size and design, number of plots, and the use of regressions based on weighing of individual trees, the studies differ in the attention paid to measuring wood density and water content. These factors, especially water content, are highly variable, making them important limitations on the reliability of results.

Klinge et al. (1975), for example, estimated approximate dry weights using a constant fraction of wet weight, whereas observations in the present study and elsewhere do not support the assumption that all tissues have the same water content.

The results of biomass studies are frequently not comparable because different components are included. For example, in addition to the question of whether or not underground biomass is included, some studies exclude nonwood biomass (principally leaves), litter (either fine, gross, or both), and standing dead biomass. Some even include soil organic matter as a form of dead biomass. Studies are summarized in Table 2; in order to permit comparisons, the table includes approximations of fractions not measured by the authors of each study (based on ratios derived from the other studies included in the table).

For comparison, indirect estimates by Brown and Lugo (1984, 1992a, b), Brown et al. (1989) and Fearnside (1991, 1992a, b, nd) are also shown in Table 2. The early volume-based estimate of Brown and Lugo (1984) stands out as being much lower than almost all other estimates, either direct or indirect, including the more recent calculations of these same authors.

The Brown and Lugo (1984) estimate has been important because of its use in global carbon calculations, including the 1992 estimates by the Intergovernmental Panel on Climate Change (IPCC). The IPCC's 1992 supplementary report (Watson et al., 1992: 33) opted not to revise the land-use change emission estimate of 1.6 Gt C yr^{-1} derived in the 1990 scientific assessment (Watson et al., 1990: 17) as the midpoint of a range of values for deforestation emissions in 1980 reported by Detwiler and Hall (1988) and by Houghton et al. (1985, 1987, 1988) (see Watson et al., 1990: 11). The studies that produced these emissions calculations all used the forest biomass estimates of Brown and Lugo (1984). Brown and Lugo's (1984) estimate was based on timber volumes in trees over 25-cm diameter at breast height (DBH) inventoried in various parts of Brazilian Amazonia by the Food and Agriculture Organization of the United Nations (FAO). However, examination of data in these surveys reveals mean total biomass of 226 t ha^{-1} (SD = 63) in 16 localities reported in five volumes of the FAO study (Heinsdijk, 1957, 1958a, b, c; Glerum, 1960), the first four of which were among the five volumes used by Brown and Lugo (1984). The above mean was calculated using the constants applied by Brown and Lugo (1984) for estimating total volume from the timber data and Brown and Lugo's (1984: 1291) mean wood density of 0.62 for tropical America to estimate dry weight biomass (Note that Brown et al. [1989] subsequently revised their estimate of density upward by 11% to 0.69). Only 1 of the 16 localities has a biomass value as low as Brown and Lugo's (1984) 155.1 t ha^{-1}. (See Fearnside, 1986a, 1987 for data and discussion).

The discrepancy between the results of direct measurements and volume-based estimates decreased when Brown and Lugo (1984) revised their biomass values upward by 28-47%, mainly the result of an improved correction for the small diameter biomass components not directly measured in the original surveys of forest volume carried out by FAO. A substantial further upward adjustment is necessary for factors omitted from the Brown et al. (1989) estimate, including roots, palms, vines, stems <10 cm DBH, and dead biomass. The authors calculate a mean aboveground live biomass of 169.68 t ha^{-1} for undisturbed forests in tropical America (Brown et al., 1989: 898), which is equivalent to 201.7 t ha^{-1} of total live biomass if a conversion factor of 1.19 is applied (based on studies in Table 2), or 196.8 t ha^{-1} if calculated with the factor of 1.16 used by Brown et al. (1989: 898). Inclusion of dead biomass would bring the total to 215.6 t ha^{-1} (Table 2). Applications of the Brown et al. (1989) estimate to global carbon calculations (e.g. Houghton, 1989, 1991) have not included adjustments for the omitted biomass fractions, which, taken together with adjustments for form factor and other considerations, increase the total biomass present by about 65% (Table 2 and Fearnside, 1992b). On the other hand, it should be noted that the effect is offset in these particular calculations because they used an estimate of deforestation (Myers, 1989) that overestimates the rate in Brazil by a factor of 2 (see Fearnside, 1990).

Brown and Lugo (1992b) have recently derived an estimate of 162 t ha^{-1}, subsequently revised to 227 t ha^{-1} (Brown and Lugo, 1992a), as the average aboveground live biomass of dense forests in Brazilian Amazonia, based on forest volume data from RADAMBRASIL Project inventories (Brazil, Projeto RADAMBRASIL, 1973-1983). A variety of factors not considered by Brown and Lugo indicate the need for upward adjustment of this estimate (Fearnside, 1992b; see Brown and Lugo, 1992c, Fearnside, 1993). On the other side, Sombroek (1992) believes that Brown and Lugo's (1992a) estimate should be scaled down because of nonforest vegetation types excluded from the RADAMBRASIL surveys and because the survey teams' choices of plot locations within the sampled vegetation may have avoided patches with low biomass. The exclusion of nonforest vegetation is not relevant to biomass estimates confined to forest (as opposed to the full 5 X 10^6 km^2 Legal Amazon region of Brazil). Any bias in the choice of sample plots, however, would indeed affect these results as well as others (e.g. Fearnside, 1992a, nd) based on RADAMBRASIL survey data.

The current best estimate for average total biomass (including dead and belowground components) in primary forests of Brazilian Amazonia is 385 t ha^{-1} for all forests present and 364 t ha^{-1} for areas cleared in 1990 (Fearnside, nd, updated from

Fearnside, 1992a). These estimates are derived from published wood volume data from 2892 ha of forest inventory surveys distributed throughout the region.

Estimates of average biomass for geographical areas and vegetation types are only practical using indirect methods such as calculation from inventories of forest volumes. However, only direct weighing of biomass, such as the measurements reported here, can yield information on combustion efficiency and charcoal formation.

COMBUSTION EFFICIENCY AND CHARCOAL

The means of preburn and postburn biomass measurements from the destructive plots at Fazenda Dimona indicate a reduction in the aboveground carbon stock from 130.2 t ha^{-1} to 94.3 t ha^{-1}, implying a release of 27.6% of the preburn carbon stock (Table 1). However, the high variability between plots (coefficients of variation approximately 40%) precludes confidence in the preburn and postburn biomass estimates sufficient to distinguish them at the 5% level with the 16-plot sample of the current study at Fazenda Dimona. The observed means and variances for biomass indicate that approximately 22 plots of the same design would be needed, distributed equally between the two treatments (following Snedecor and Cochran, 1967: 111-114). Nevertheless, the current study's finding of 27.6% combustion efficiency (in terms of carbon) has a much firmer basis than values commonly used in global carbon calculations.

The values obtained from our analyses of the carbon content of biomass in the different compartments, both before and after the burn, are all quite close to the value of 0.50 used in calculations by Brown and Lugo (1984) based on a mean of 0.51 for tropical American woods. The value of 0.45, frequently used in global carbon calculations, is not supported by these results; use of the 0.45 value for carbon content would result in calculated emissions about 10% lower than those reported here.

Our charcoal formation rate is low compared with Seiler and Crutzen's (1980) estimate. Seiler and Crutzen's (1980: 237) charcoal carbon value (20-30% of aboveground postburn carbon) corresponds to 15-23% of the aboveground preburn carbon using the 25% combustion efficiency they assumed (p. 219). Our finding that 2.7% of the preburn aboveground carbon was converted to charcoal is only 12-18% as high. As a percentage of "transformed carbon," or carbon either released or converted to charcoal, our estimate for charcoal is 9.0% (while the Seiler and Crutzen, 1980 value corresponds to 38-48%). However, burn quality varies greatly between fires (Fearnside, 1989), and we only have data from one fire. More measurements are needed to assure that the estimated char rate approaches the population mean.

The present charcoal production estimate excludes particulate elemental carbon released as soot in smoke. This is also the case for the Seiler and Crutzen (1980) estimate. A study in Panama (Suman, 1984) suggests that the quantity released this way is small: only 5% of the charcoal produced annually in a coastal watershed reached sediments in the adjacent Gulf of Panama, and of the sediment charcoal, only 3% was transported by wind. However, the possibility remains that much of the aeolian-transported carbon was deposited in deep ocean and hence escaped measurement.

The tremendous variability within one burn is apparent. Burn quality has been rated in slash-and-burn agricultural fields on Brazil's Transamazon Highway (Fearnside, 1986b, 1989), indicating that variability is very great from one farmer to the next and from one year to the next. This variability is a major factor affecting crop yields and the carrying capacity of the land for supporting a human population.

CONCLUSIONS

The dense forests of Central Amazonia have high biomass. However, there is very great spatial variability in biomass, making studies in many more localities necessary for adequate estimates of biomass for the region. Burn quality varies greatly, affecting the release of greenhouse gases and the formation of long-term carbon pools in charcoal.

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FIGURE LEGENDS

Figure 1 -- Location of study site.

Figure 2 -- Fazenda Dimona plot and transect locations.

Figure 3 -- Burn quality at Fazenda Dimona from visual evaluation: Excellent = burned at least some trunks to ash; Good = burned vines and thick branches; Medium = burned leaves and thin branches; Poor = burned only leaves; None = nothing burned, including dry leaves on ground.

Figure 4 -- Dry weights of post-burn remains from destructive quadrats.

Figure 5 -- Volumes of post-burn remains from line intercept transects.

Figure 6 -- Unburned percentage of biomass fractions in destructive quadrats.

(TABLE 2 NOTES)

(a) Metric tons (t) ha^{-1} dry weight. Numbers in italics are as measured by original authors. Numbers without italics are calculated using proportions derived from other studies in the table, unless otherwise noted.

(b) Total biomass value includes volume-based data for line-intercept transects for pieces >10 cm in diameter.

(c) Calculated biomass components use the same proportions adopted in the cited study, except for below-ground biomass which is derived as in note a.

(d) Excludes 250 t ha^{-1} of soil organic matter included by Klinge et al. (1975: 117).

(e) Calculated as in note a. Brown et al. (1984) use a ratio of 0.16, resulting in a calculated total live biomass of 196.8 t ha^{-1}.

(f) Above-ground portion same as Fearnside (1992b).

Table 1: APPROXIMATE CARBON PARTIONING OF ABOVE-GROUND BIOMASS IN A RAINFOREST BURN

Fazenda Dimona, Manaus 1984

FRACTION	PRE-BURN			POST-BURN			PARTITIONING
	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 left in fraction
Trunks	201.3	49.3	99.2	159.2	49.9	79.4	61.0
Branches	41.8	48.4	20.2	21.2	49.1	10.4	8.0
Vines	8.1	49.4	4.0	2.0	49.0	1.0	0.8
Leaves	13.4	51.1	6.8	0.0	--	0.0	0.0
Charcoal	0.0	--	0.0	4.7	74.8(b)	3.5	2.7
TOTAL	264.6		130.2	187.2		94.3	72.5
Presumed release						35.9	27.5

(a) Carbon content analyses: number of observations (each a mean of two replicates, with the exception of two samples), with standard deviations, for pre-burn vegetation at Fazenda Dimona: trunks=5 (0.54), branches=5 (1.08), vines=2 (range=48.5 -- 50.3), leaves=5 (0.67); for post-burn vegetation: trunks=9 (0.61), branches=7 (0.89), vines=5 (1.94).

(b) Charcoal carbon content from Correa (1988).

TABLE 2:BIOMASS ESTIMATES IN TERRA FIRME FORESTS IN BRAZILIAN AMAZONIA

Forest type	Location	Above Ground				Below ground	Total live	Total (live+ dead)	Reference	Note
		Live	Fine litter	Other dead	Total					
DIRECT MEASUREMENTS										
Lowland broadleaf dense forest	Manaus, Amazonas (Fazenda Dimona)	241	6	17	265	46	287	311	This study (destructive quadrats)	(a)
High forest, steep slopes-type a	Tucuruí, Pará	555	12	40	607	106	661	713	Revilla Cardenas et al., 1982	(b)
High forest, steep slopes-type b	Tucuruí, Pará	162	8	12	182	31	193	213	Revilla Cardenas et al., 1982	(b)
High dense forest-a	Tucuruí, Pará	610	12	44	666	116	726	782	Revilla Cardenas et al., 1982	(b)
High dense forest-b	Tucuruí, Pará	155	17	11	183	30	185	213	Revilla Cardenas et al., 1982	(b)
Medium high forest-a	Tucuruí, Pará	303	15	22	340	58	361	398	Revilla Cardenas et al., 1982	(b)
Medium high forest-b	Tucuruí, Pará	168	8	12	188	32	200	220	Revilla Cardenas et al., 1982	(b)
Lowland broadleaf dense forest	Manaus (Reserva Egler)	357 (+-) 18.8	7.2	25.8	390 (+-) 18.8	122.5 (+-) 7.7	479.5 (+-) 26.5	512.5 (+-) 26.5	Klinge et al., 1975; Klinge and Rodrigues, 1973	(c)
Submontane broadleaf dense forest	Jari, Pará	425.9	5.7	6.2	437.7	103.5	529.4	541.3	Russell, 1983: 44	(b)
Submontane broadleaf open forest	Samuel Dam, Rondônia	303 (+-) 60	13	11	328	58.2	361.2	386	Martinelli et al., 1988	(b)
Dense riparian forest	Belo Monte Dam, Pará	186.1	8.3	11.2	206	36.5	222.6	242	Revilla Cardenas, 1987: 51	
Dense riparian forest	Babaquara Dam, Pará	297.4	10.5	12.3	320	56.8	354.2	377	Revilla Cardenas, 1988: 76	
Dense upland forest	Babaquara Dam, Pará	198.3	12.3	8.9	219	39.0	237.2	258	Revilla Cardenas, 1988: 77	
Dense upland forest	Samuel Dam, Rondônia	387.9	13.6	1.7	403	71.6	459.4	475	Revilla Cardenas, 1986: 39	
Open upland forest	Belo Monte Dam, Pará	126.1	9.5	7.5	143	25.4	151.4	168	Revilla Cardenas, 1987: 34	
"Mata de baixio" (open upland forest on poorly-drained terrain)	Samuel Dam, Rondônia	362.5	5.4	5.5	373	66.3	428.7	440	Revilla Cardenas, 1986: 39	
INDIRECT ESTIMATES										
Undisturbed productive broadleafed forests	Tropical America	133.7	5.9	5.0	144.7	21.4	155.1	166.0	Lugo and Brown, 1984	(d)
Undisturbed productive broadleafed forests"	Tropical America	169.68	7.5	6.4	183.6	32.1	201.7	215.6	Brown et al., 1989	
All forests present	Brazilian Amazon	172.1	3.5	12.4	188.0	59.0	231.1	247	Fearnside, 1991	
Forests cleared in 1988	Brazilian Amazon	147.0	3.0	10.6	160.6	50.4	197.4	211	Fearnside, 1991	
Dense forests (RADAMBRASIL data)	Brazilian Amazon	268	11.9	10.1	289.9	50.6	318.6	340.6	Brown and Lugo, 1992a	

Dense forests (FAO data)	Brazilian Amazon	*162*	7.2	6.1	175.3	30.6	192.6	205.9	Brown and Lugo, 1992a	
Dense forests (RADAMBRASIL data)	Brazilian Amazon	*289*	12.8	10.9	312.7	54.6	343.6	367.2	Brown and Lugo, 1992b	
Dense forests (FAO data)	Brazilian Amazon	*227*	10.0	8.5	245.6	42.9	269.9	288.5	Brown and Lugo, 1992b	
Non-dense forests (RADAMBRASIL data)	Brazilian Amazon	*239*	10.6	9.0	258.6	45.1	284.1	303.7	Brown and Lugo, 1992b	
Dense forests present	Brazilian Amazon	142.3	6.3	5.4	271.8	48.2	190.5	*320*	Fearnside, 1992a	
Non-dense forests present	Brazilian Amazon	100.5	4.4	3.8	191.9	34.1	134.6	*226*	Fearnside, 1992a	
All forests present	Brazilian Amazon	121.0	5.3	4.6	231.0	41.0	162.0	*272*	Fearnside, 1992a	
Dense forests present	Brazilian Amazon	319.9	11.4	16.1	347.4	61.7	381.9	*409*	Fearnside, nd	(e)
Non-dense forests present	Brazilian Amazon	281.3	10.1	14.1	305.4	54.3	335.8	*360*	Fearnside, nd	(e)
All forests present	Brazilian Amazon	301.1	10.8	15.1	326.9	58.1	359.4	*385*	Fearnside, nd	(e)
Dense forests cleared in 1990	Brazilian Amazon	321.3	11.5	16.1	348.9	62.0	383.5	*411*	Fearnside, nd	(e)
Non-dense forests cleared in 1990	Brazilian Amazon	263.6	9.4	13.2	286.2	50.9	314.7	*337*	Fearnside, nd	(e)
All forests cleared in 1990	Brazilian Amazon	284.5	10.2	14.3	308.9	54.9	339.6	*364*	Fearnside, nd	(e)

Measurements are in tons per hectare dry wieght. Numbers in italics are as measured by the original authors. Numbers not in italics are calculated using proportions derived from other cited studies, unless otherwise noted. FAO is the Food and Agriculture Organization of the United Nations.

(a) Metric tons (t) ha^{-1} dry weight. Numbers in italics are as measured by original authors. Numbers without italics are calculated using proportions derived from other studies in the table, unless otherwise noted.

(b) Total biomass value includes volume-based data for line-intercept transects for pieces >10 cm in diameter.

(c) Calculated biomass components use the same proportions adopted in the cited study, except for below-ground biomass which is derived as in note a.

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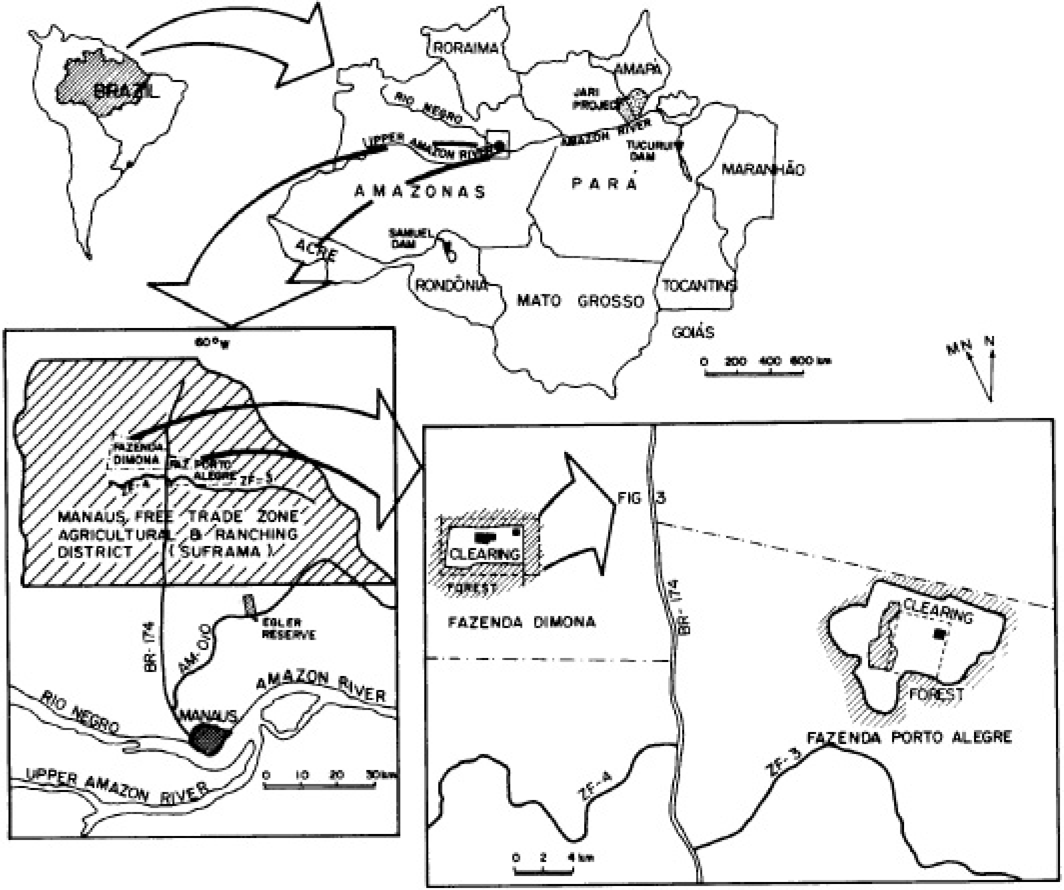
(f) Above-ground portion same as Fearnside (1992b).


BRAZIL
RORAIMA
AMAPÁ
RIO NEGRO
JARI PROJECT
UPPER AMAZON RIVER
AMAZON RIVER
TUCURUÍ DAM
MARANHÃO
AMAZONAS
PARÁ
SAMUEL DAM
ACRE
RONDÔNIA
MATO GROSSO
TOCANTINS
GOIÁS
0 200 400 600 km
MN
N
60°W
FAZENDA DIMONA
FAZ. PORTO ALEGRE
ZF-4
ZF-3
MANAUS FREE TRADE ZONE AGRICULTURAL & RANCHING DISTRICT (SUFRAMA)
BR-174
AM-010
EGLER RESERVE
AMAZON RIVER
RIO NEGRO
MANAUS
UPPER AMAZON RIVER
0 10 20 30 km
FIG 3
CLEARING
FOREST
FAZENDA DIMONA
BR-174
CLEARING
FOREST
FAZENDA PORTO ALEGRE
ZF-4
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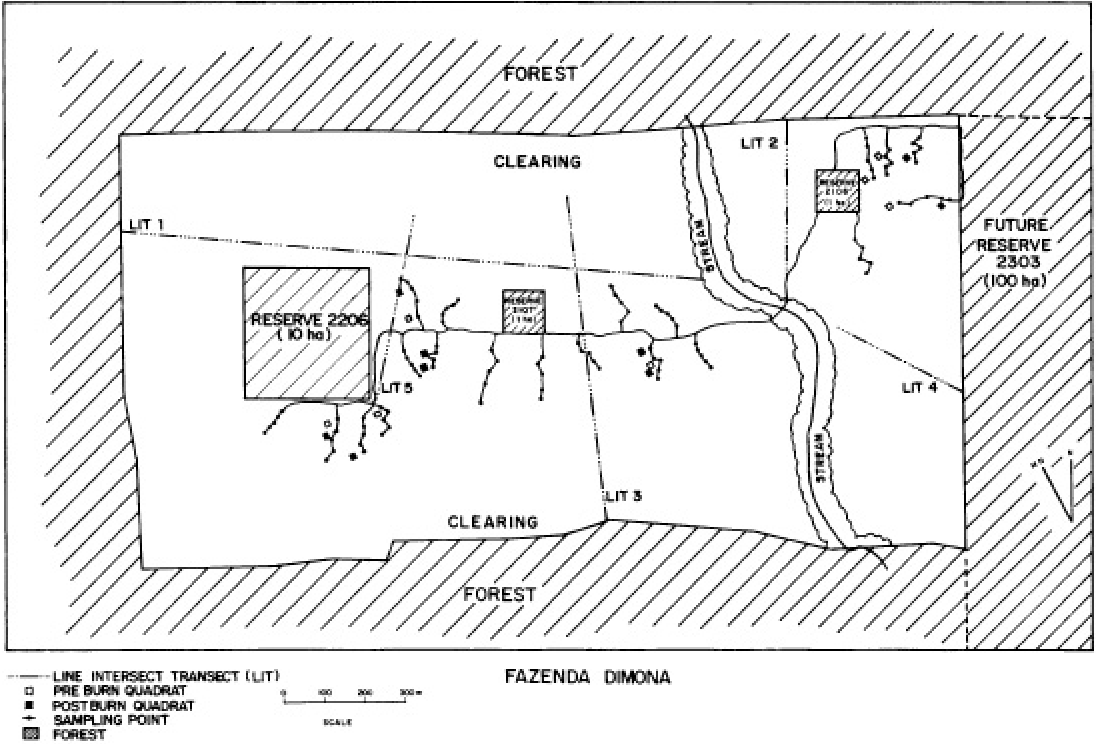
0 2 4 km


FOREST
CLEARING
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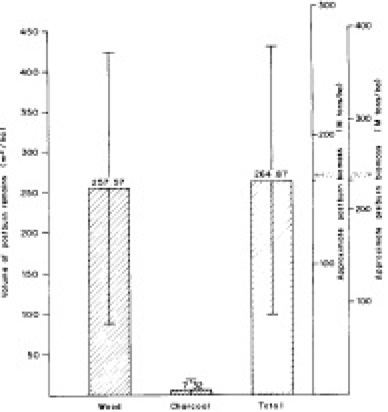
LIT 3
LIT 4
LIT 5
STREAM
STREAM
RESERVE 2206
(10 ha)
FUTURE
RESERVE
2303
(100 ha)
CLEARING
FOREST
FAZENDA DIMONA
LINE INTERSECT TRANSECT (LIT)
□ PRE BURN QUADRAT
■ POSTBURN QUADRAT
+ SAMPLING POINT
▨ FOREST
0
100
200
300 m
SCALE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350
300
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264.87
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Charcoal
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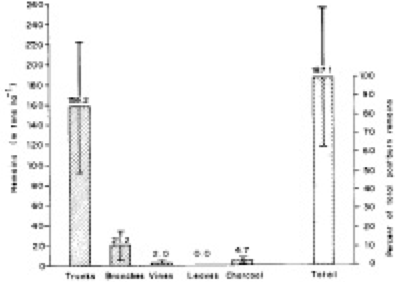
300
200
100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4.7
187.1
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70
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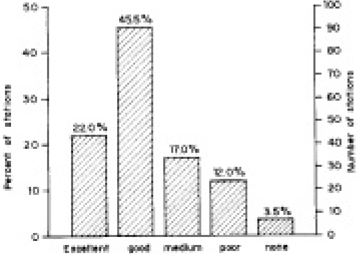
Trunks
Branches
Vines
Leaves
Charcoal
Total



Percent of stations
Number of stations
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40
30
20
10
0
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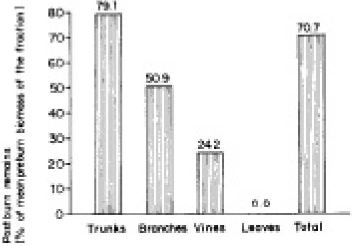
80
70
60
50
40
30
20
10
0
22.0%
45.5%
17.0%
12.0%
3.5%
Excellent
good
medium
poor
none


Postburn remains
[% of mean preburn biomass of the fraction]
80
70
60
50
40
30
20
10
0
79.1
50.9
24.2
0.6
70.7
Trunks
Branches
Vines
Leaves
Total