The text that follows is a PREPRINT.

Please cite as:

Fearnside, P.M., R.I. Barbosa, and P.M.L.A. Graça. nd. Burning of Secondary Forest in Amazonia: Biomass, Burning Efficiency and Charcoal Formation during Land Preparation for Agriculture in Apiaú, Roraima, Brazil. *Forest Ecology and Management* (in press).

ISSN: 0378-1127

Burning of secondary forest in Amazonia: Biomass, burning efficiency and charcoal formation during land preparation for agriculture in Apiaú, Roraima, Brazil

Philip M. Fearnside*
Reinaldo Imbrozio Barbosa**
Paulo Maurício Lima de Alencastro Graça*

* Department of Ecology
National Institute for Research in the Amazon (INPA)
Caixa Postal 478
69011-970 Manaus-Amazonas
BRAZIL
Fax: +55 - 92 – 3642-8909
E-mail: pmfearn@inpa.gov.br

** Nucleus for Research in Roraima
National Institute for Research in the Amazon (INPA)
Caixa Postal 96
69301-970 Boa Vista-Roraima
BRAZIL
Fax: +55 - 95 - 3623-9433

1 Feb. 2007

Abstract

In a burn of five-year-old secondary forest cleared for agriculture in Roraima, Brazil, carbon partitioning was measured for above-ground portions of both secondary forest (regrowth) and the remains of original forest, felled and burned six years previously. Above-ground dry weight biomass averaged 43.0 ± 6.5 Mg (megagrams = metric tons) per hectare (Mg ha^{-1}) for secondary forest and 105.8 ± 23.7 Mg ha^{-1} for original forest remains. Pre- and post-burn above-ground biomass loadings were estimated by cutting and weighing six 60-m^2 plots and by line-intersect sampling (LIS) done along the axis of each post-burn plot (three transects), plus two supplementary LIS transects. High variability of initial biomass made LIS more reliable for assessing change in material >10 cm in diameter; quantities for diameter classes <10 cm relied on direct weighing. Above-ground carbon pools were reduced by 67.8% in secondary forest and 32.0% in original forest remains. Burning released 28.8 Mg C ha^{-1} (original forest remains plus secondary forest biomass), or 41.6% of the pre-burn total carbon stock in biomass. The remainder of the carbon either remained as residual biomass (39.2 Mg C ha^{-1} or 56.5% of pre-burn C) or as charcoal and ashes (1.4 Mg C ha^{-1} or 2.0%). Carbon stock in charcoal increased from 0.50 Mg C ha^{-1} to 1.07 Mg C ha^{-1}, a net gain of 0.57 Mg C ha^{-1}, or 0.8% of the pre-burn above-ground carbon stock. The net gain of charcoal carbon was composed of 0.21 Mg C ha^{-1} from secondary forest biomass and 0.36 Mg C ha^{-1} from original forest remains; 1.1% of the above-ground secondary forest carbon was converted to charcoal, while the corresponding percentage for original forest remains was 0.7%. Ashes contained an additional 0.29 Mg C ha^{-1}, of which 0.11 Mg C ha^{-1} can be attributed to secondary forest biomass and 0.18 Mg C ha^{-1} to original forest remains. If the carbon in ashes is assumed to be finely powdered charcoal, this stock adds 0.21% to the charcoal formation percentage for secondary forest and 0.36% to that for original forest remains. The overall charcoal-formation percentage was 1.6%, or 2.0% if ashes are included. Charcoal-formation percentages in this study are lower than those sometimes assumed in global carbon models; nevertheless, charcoal can represent an important sink of atmospheric carbon over long time scales.

Keywords: Biomass burning; Carbon dioxide; Deforestation; Global warming; Greenhouse gases; Secondary forest

1. Introduction

Conversion of mature tropical forests to agricultural landscapes releases carbon dioxide (CO_2) and other gases to the atmosphere that contribute to global warming through the greenhouse effect. One source of controversy in evaluating the net effect of tropical deforestation is the extent to which carbon releases from the original clearing are attenuated by removal of carbon from the atmosphere through regrowth of secondary forests on the deforested sites (Achard et al., 2002, Brown and Lugo, 1990; Fearnside, 1996a, 1997; Fearnside and Guimarães, 1996; Fearnside and Laurance, 2004; Houghton et al., 2000). The amount of carbon stored in the secondary forests and released at the time secondary forests are burned depends both on the biomass accumulation and the completeness of the burns.

Fixing of carbon in secondary forests is temporary, the age of the stands when re-cleared being important in determining the proportion of the total cycle (including use periods as agriculture or as pasture) that is spent under secondary forest. Charcoal formed in the burn provides one of the only routes for carbon to be removed from the cycle, such that it cannot readily recombine with oxygen to form carbon dioxide. On the other hand, while burning of the secondary forest biomass releases no more carbon dioxide than was removed from the atmosphere as the secondary forest grew, this burning also releases methane (CH_4) and other trace gases that do not enter photosynthetic reactions. Burning of secondary forest biomass therefore makes a net contribution to the atmospheric buildup of these non-CO_2 combustion products. Globally, burning of tropical secondary forests is estimated to release (under low and high trace-gas emissions scenarios), 3.1-3.7 $\times$ 10^6 Mg CH_4, 73-92 $\times$ 10^6 Mg CO, 0.2-1.6 $\times$ 10^6 Mg N_2O and 2.4 $\times$ 10^6 Mg NO_x (Fearnside, 2000). Using the 100-year global warming potentials adopted for the 2008-2012 first commitment period of the Kyoto Protocol (Schimel et al., 1996, p. 121), these trace-gas emissions are equivalent to 34-156 $\times$ 10^6 Mg C annually.

The fate of the biomass remaining from the original forest is also important in calculating the rate at which carbon is released from the portion of the original forest biomass that did not burn at the time of initial clearing, much of which will decay. While combustion in primary forest burns has received more attention (e.g., Araújo et al., 1999; Carvalho Jr. et al., 1995, 1998; Fearnside et al., 1993, 1999, 2001; Graça et al., 1999; Guild et al., 1998; Kauffman et al., 1995), very few measurements have been made on secondary forest burns in Brazilian Amazonia (Guimarães, 1993; Hughes et al., 2000). The present study reports on a secondary forest burn in Roraima, in northern Brazil. These data will contribute to reducing the uncertainty in calculation of the net contribution to global climate change made by

secondary forest burning (as in shifting cultivation).

2. Methods

2.1. Study area

Colônia do Apiaú is a government-sponsored colonization project located in the county (*município*) of Mucajaí, state of Roraima, Brazil. The headquarters of the colonization project is at Vila Apiaú (2^{o}34'N, 61^{o}18'W), which lies 112 km by road southwest of the city of Boa Vista, the state capital (Fig. 1). The area is part of a Rapid Settlement Project (*Projeto de Assentamento Rápido*: PAR), an area in which settlement began in November 1981, initially in 23,608 ha. The present area is approximately double that occupied by the 60-100-ha lots of the original project, as the settlement scheme has expanded through distribution of additional lots. The area is bounded by the Apiaú and Mucajaí rivers to the north and northeast and by a range of hills (the Serra de Mucajaí) to the south. The climate is classified as "Ami" in the Köppen system--a rainy tropical climate with a marked dry season (December to March) (Barbosa, 1997). Mean annual rainfall is approximately 2000 mm and mean relative humidity is 87% (Lameira and Coimbra, 1988). The altitude ranges from 100 to 180 m (excepting the hills). Additional information on the site is available elsewhere (Barbosa and Fearnside, 1996a,b). Apiaú has become renowned as the main focus of the Great Roraima Fire that burned an estimated 11,394-13,928 km^2 of standing upland forest over the December 1997-March 1998 period (Barbosa and Fearnside, 1999).

[Figure 1 here]

In the April 1991 secondary forest burn that is the subject of the present study, burn quality was considered to be good by the farmer, who planted maize and manioc on the site. The secondary forest was cut in late February and early March and the cut biomass was burned on 14 April (at 2:00 pm), after four consecutive days without rain. The farmer conducted the burn and selected its time and date without interference from the research team. The area burned totaled approximately 1 ha. The original forest had been felled and burned in 1985, after which the area was planted in annual crops. The principal tree species in the felled original forest was *Hymenolobium complicatum* (angelim ferro), which has hard wood with basic density of approximately 0.800 g cm^{-3} and is resistant to both decomposition and fire. Secondary forest (mainly *Cecropia* spp.) was allowed to grow on the site beginning in 1986, and was five years old at the time it was cut and burned.

2.2. Preparations and destructive sampling

The study used a modified version of the methodology

employed in studies of burning efficiency and charcoal formation in mature forest burns at Manaus (Amazonas), Altamira (Pará) and Ariquemes (Rondônia) (Fearnside et al., 1993, 1999, 2001; Graça et al., 1999). In the present study, plots were laid out in a star-shaped design, each with six rays of 4 × 15 m (double the width and half the length used in our primary forest studies, made necessary by the small area of the clearing and its L-shaped format). Each plot was divided into sub-plots of 4 × 5 m (Fig. 2). The star-shaped plot design avoids bias from non-random orientation of the fallen trunks, which often are deliberately cut to fall in parallel (i.e., to fall outwards into the clearing as cutting proceeds into a stand of trees).

[Figure 2 here]

Within each plot, all biomass above ground level was cut with chainsaws, axes and machetes, and weighed using a series of spring balances, chosen depending on the weight of the load. Balances ranged in capacity from 50 g (± 1 g) up to 90 kg (± 1 kg). In both the pre- and post-burn plots, biomass and charcoal were divided into categories referring to secondary forest and remains of the former primary forest; material in these two categories was further divided into the following fractions or pools: wood with diameter <5 cm, 5-10 cm, and >10 cm; vines; palms; and "other" (bamboo and other grasses, palm leaves, etc.), plus additional categories for charcoal on the ground, charcoal still attached to unburned biomass (both original forest remains and secondary forest biomass), and ashes. Litter and leaves were considered as a separate group, being composed of fine detritus originating both from the secondary forest biomass and from the remains of the original forest. Not all of the above categories had any material present for each type of biomass origin (secondary forest or original forest remains) and time of collection with respect to the burn (before or after). Sub-samples of each fraction (0.16-1.13 kg, depending on the diameter class) were collected in each plot for determination of water content for calculating dry weights.

All wood pieces were divided into sub-categories as "rotten" or "sound" (i.e., not rotten). Rottenness was determined from the look and feel of the wood. Density and moisture content were determined separately for the two sub-categories. Presence or absence of charcoal was noted for material in all diameter classes.

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. Some finely powdered charcoal is undoubtedly left behind by this procedure. For charcoal attached to the biomass fractions, char was scraped off the wood of trunks, branches, and vines using machetes (see Fearnside et al., 1999).

2.3. Line-intersect sampling (LIS)

Line-intersect sampling (LIS) transects (Warren and Olsen, 1964) were run along the central axis of each plot (plus two supplementary transects of the same length, with randomly chosen directions). Measurements of cross-sectional diameter were made for all pieces with diameters >10 cm that intersected the line; two measurements were made at right angles to the axis of each piece (Van Wagner, 1968). Only wood and palms from the original forest were included in the sample (secondary forest wood was excluded, even though it was measured).

The thickness of charcoal was measured on all pieces that had been charred by the fire. Measurements were made at four points 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 (NB: 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.

Aluminum tags were affixed to the pieces with nails to allow identification of the same pieces after the fire.

2.4. Dry weight

All samples were dried in an electric oven at 80^{o} C to constant weight.

2.5. Carbon content

Carbon content was calculated based on values obtained for the same fractions in another study in the same settlement area (Barbosa and Fearnside, 1996b). In both cases, samples were ground and analyzed for carbon content by the “dry” method, which converts the carbon in the plant mixture into CO_2 by combustion at 1100^{o} C. The gas released is sent to a cell containing sodium hydroxide with standardized electrical conductivity. Carbon content of the material is calculated from the difference between the conductivity of the standard solution and that of the carbonated solution. Carbon content was determined at the Center for Nuclear Energy in Agricultura (CENA), University of São Paulo, Piracicaba, São Paulo, Brazil.

2.6. Burning efficiency

Burning efficiency, or the percentage of the carbon stock that disappears as a result of burning (presumed volatilized), was determined by a combination of the direct (destructive) and

indirect (LIS) methods. Direct measurements compare nearby but different plots, as the same plots cannot be used for successive destructive measurements: the same biomass pieces cannot be weighed before and after the burn because the process of cutting and weighing the pieces would disturb their placement and their burning characteristics. The amount of biomass present varies greatly over small distances, especially for material >10 cm in diameter. Given these facts, the most effective means of estimating the change in carbon stock is to estimate the stocks of small-diameter material directly in the destructive plots (the change, for these components, being determined by differences between the pre- and post-burn stocks), and to use LIS measurements at marked locations on the >10 cm diameter biomass pieces to measure the *change* in volume (and carbon stock) for the large-diameter categories.

2.7 Wood Density

Density (dry weight/humid volume) of wood >10 cm in diameter of original forest remains was calculated based on the Arquimedes Principle (displacement of volume by immersion in water). This was done by transforming the volume result obtained from the LIS into biomass for all pieces with diameter >10 cm. Since variability is high and the number of pieces collected is small relative to the sampling universe, we calculated the mean for the basic density of “sound” and “rotten” pieces by lumping the densities for each of the sampling units collected in both phases of the burn (pre and post), keeping the two wood qualities separate (“sound” and “rotten”).

3. Results

Density (pre- and post-burn) of sound wood >10 cm in diameter of original forest remains is higher (mean = 0.803 ± 0.122 g cm^{-3}; n = 5) than that of rotten wood (mean = 0.774 ± 0.217 g cm^{-3}; n = 19) in absolute terms. Note that the small sample sizes, particularly for sound wood, imply considerable uncertainty in this result.

The total above-ground biomass dry weight, considering the combined results of direct measurements and indirect estimates for the class of wood >10 cm in diameter, was 148.9 ± 18.7 Mg ha^{-1} in the pre-burn phase and 86.7 Mg ± 17.4 ha^{-1} in the post-burn phase; a reduction of 41.8% (Table 1). Of the total pre-burn biomass, 105.8 Mg ha^{-1} (71.1%) was composed of original forest components, and 43.0 Mg ha^{-1} (28.9%) of secondary forest components. These figures include an apportionment of other components like litter, ashes and charcoal (on the ground and in the wood), totaling 7.1% (10.6 Mg ha^{-1}) of the pre-burn biomass. After the burn, 41.2% (1.77 Mg ha^{-1}) of the total mass (secondary forest plus forest remains) of these components was ash, 39.2% (1.69 Mg ha^{-1}) charcoal and 19.6% (0.84 Mg ha^{-1}) litter.

[Table 1 here]

Wood pieces <5 cm (17.85 Mg ha^{-1} sound + 0.26 Mg ha^{-1} rotten) in diameter represented 42.1% of the secondary forest biomass. This fraction's susceptibility to fire is reflected in its high burning efficiency (>80%). For biomass of the remaining forest, the most abundant component was wood in diameter >10 cm, with 96.5 Mg ha^{-1}, or 91.2%, before the burn and 69.3 Mg ha^{-1}, or 94.4%, after the burn. In the pre-burn phase, 99.2% of the wood >10 cm in diameter from the secondary forest and 49.0% of the forest remains in this diameter class were categorized as sound, while in the post-burn phase these values were 100% and 46.7%, respectively.

The stock of carbon in above-ground secondary forest biomass before the burn was 18.6 ± 3.7 Mg C ha^{-1}, including all litter (Table 2). After the burn, the carbon stock in secondary forest was reduced to 6.0 ± 1.4 Mg C ha^{-1}, or 32.2% of the initial amount. The original forest remains had a pre-burn stock of 50.8 ± 2.7 Mg C ha^{-1}, representing 73.3% of the total pre-burn above-ground carbon stock (Table 2). Carbon release from the original forest remains was 16.3 Mg C ha^{-1}, or 23.4% of the initial stock. Secondary forest and original forest remains together had a stock of 69.4 ± 3.0 Mg C ha^{-1} and released 28.8 Mg C ha^{-1}, or 41.6% of the initial stock (Table 2).

[Table 2 here]

The dry weight of charcoal present before the burn totaled 0.80 Mg ha^{-1} (only original forest remains), while that present after the burn totaled 1.69 Mg ha^{-1} (forest remains plus secondary forest) indicating a net increase of 0.89 Mg ha^{-1} (Table 1). In terms of carbon, the charcoal stock increased from 0.50 to 1.07 Mg C ha^{-1}, or 0.57 Mg C ha^{-1} (Table 2). The net gain represents 0.8% of the total pre-burn above-ground carbon. The net gain of charcoal carbon is composed of 0.21 Mg C ha^{-1} from secondary forest biomass and 0.36 Mg C ha^{-1} from original forest remains; 1.1% of the above-ground secondary forest carbon was converted to charcoal, while the corresponding percentage for original forest remains was 0.7%.

Ashes, which were not present before the burn, represented a gain of 0.29 ± 0.32 Mg C ha^{-1}, or 0.42% of the pre-burn carbon stock (Table 2), considering that they contain 16.1% carbon (Barbosa and Fearnside, 1996b). The ashes can be apportioned between the two types of biomass burned based on the proportion of the estimated carbon emission represented by each (exclusive of common components); 0.11 Mg C ha^{-1} can be attributed to the secondary forest biomass and 0.18 Mg C ha^{-1} to the original forest remains. If the carbon in ashes is assumed to be finely powdered charcoal, it adds 0.21% to the charcoal formation

percentage for secondary forest and 0.36% to that for original forest remains. The overall charcoal formation percentage was 1.6%, or 2.0% if ashes are included.

Most of the carbon in the pre-burn biomass was in the original forest remains (50.3 Mg C ha^{-1} or 72.5%), as was also the case for the post-burn (33.5 Mg C ha^{-1} or 82.7%) (Fig. 3). The percentage represented by secondary forest fell from 21.4% (pre-burn) to 13.1% (post-burn), while the percentage in charcoal and ashes increased from 0.7% (pre-burn) to 3.3% (post-burn).

[Figure 3 here]

The percentage of carbon presumed released from the secondary forest carbon pool (67.8%) is more than double the percentage released from the original forest remains (32.0%) (Table 2 and Fig. 4). The total amount of carbon released by the burn, considering the sum of the two biomass categories (original forest remains plus secondary forest) was 28.8 Mg C ha^{-1} or 41.6% of the total carbon present before the burn (Fig. 4). The remainder of the carbon remained as residual biomass (39.2 Mg C ha^{-1} or 56.4%) or was left as charcoal or ashes (1.4 Mg C ha^{-1} or 2.0%).

[Figure 4 here]

4. Discussion

The above-ground carbon stock in the secondary forest biomass and charcoal declined from 18.5 Mg C ha^{-1} to 6.0 Mg C ha^{-1} as a result of the burn studied, implying a release of 67.8% of the pre-burn carbon stock in this category (burning efficiency) (see Table 2). Burning efficiency was 32.0% for remains of original forest. The corresponding transformation efficiencies (% of pre-burn biomass converted to charcoal and other components post-burn) were 69.1% for secondary forest biomass and 30.7% for original forest remains.

For comparison, in Costa Rica, Ewel et al. (1981) found a burning efficiency of 30% in an 8-9 year-old secondary forest. Guimarães (1993) found a burning efficiency of 25.9% and a transformation efficiency of 27.0% in secondary forest stands averaging four years of age in abandoned pastures near Altamira, Pará. Barbosa and Fearnside (1996b) found a burning efficiency of 13.2% (and transformation efficiency of 14.1%) in original forest remains in an abandoned pasture seven years after felling in the same settlement area. Hughes et al. (2000) found burning efficiencies averaging 57.0% (range 38.3 to 84.4%) in six secondary forests in Pará and Rondônia.

Our percentage of charcoal formation is low compared with Seiler and Crutzen's (1980) estimate. Seiler and Crutzen's (1980,

p. 237) charcoal carbon value (20-30% of above-ground post-burn carbon) corresponds to 15-23% of the above-ground pre-burn carbon using the 25% burning efficiency they assumed (p. 219). We found charcoal formation of 0.7% for carbon in original forest remains and 1.1% for carbon in secondary forest biomass, with a mean for all material of 0.8%. Our 0.8% mean for the pre-burn above-ground carbon converted to charcoal is only 3.5-5.5% as high as Seiler and Crutzen's (1980) value. However, burn quality varies greatly among fires (Fearnside, 1989), and we have data from only one fire. More measurements are needed to assure that the estimated charcoal formation percentage approaches the population mean.

The charcoal production estimate excludes particulate graphitic carbon released as soot in the smoke. This can be estimated (following Fearnside, 1996b) by assuming that secondary forest biomass burns through flaming combustion and original forest remains through smoldering combustion. Graphitic particulate carbon represents 7% of the total particulate release in Amazonian burning (calculated by Kaufman et al., 1990 from Andreae et al., 1988). Total particulates can be calculated from the ratio of methane gas release to total particulates derived by Kaufman et al. (1990) from Ward and Hardy (1984) and Ward (1986): 0.3 for flaming combustion and 0.6 for smoldering combustion. In a low trace gas scenario (Fearnside, 1996b), methane gas release is 0.005 t CH_4 per ton of fuel burned (Kaufman et al., 1990 from Ward, 1986) and in a high trace gas scenario it is 0.006 t CH_4 per ton of fuel burned (Kaufman et al., 1990 from Greenberg et al., 1984). Fuel carbon content for conversion of these values to emissions per ton of fuel carbon burned is 48.15% (Fearnside, 1996b). The emissions of graphitic carbon in kg graphitic C per ton of fuel C burned in the low and high trace gas scenarios are 2.42 and 2.91 for flaming combustion and 1.70 and 2.67 for smoldering combustion; the lower emission of particulate carbon from smoldering combustion is mainly the result of the higher ratio of CH_4 to total particulates found in the laboratory combustion studies mentioned above (Ward, 1986; Ward and Hardy, 1984). The 12.27 Mg C ha^{-1} (excluding ashes and charcoal) of secondary forest biomass carbon released (flaming combustion) in the burn we studied therefore released 29.6-35.7 kg C ha^{-1} as graphitic particulate carbon, while the 15.2 Mg C ha^{-1} from original forest remains (smoldering combustion) released 25.8-40.6 kg C ha^{-1}, making the total release 0.0554-0.0763 Mg C ha^{-1} in this form, or 4.1-5.6% as much as the 1.36 Mg C ha^{-1} left as charcoal and ashes.

Globally, an estimated 555×10^6 Mg of secondary forest biomass is exposed to burning annually in short-fallow and long-fallow shifting cultivation that is allowed to recover, plus 12×10^6 Mg of biomass in short-fallow secondary forest that is permanently cleared, based on 1981-1990 rates derived from FAO (1993) (Fearnside, 2000). FAO (1996, p. 89) defines short fallow as a “mosaic of young secondary forest, various stages of natural

regrowth and cultivated areas with cultivated areas covering between 30 and 50% of total area," and long fallow as a "mosaic of mature forest, secondary forest, various stages of natural regrowth and cultivated areas with cultivated areas covering between 5 and 30% of total area." The three existing studies have mean charcoal formation rates (% of pre-burn above-ground carbon converted to charcoal) of 0.8% from the present study, 1.1% in a secondary-forest burn in Altamira, Pará (Guimarães, 1993), and 0.8% for secondary forest remains in a pasture burn in Roraima (Barbosa and Fearnside, 1996b). Variation in charcoal formation percentages among burns is to be expected as a result of differing fuel characteristics and fire temperatures. Based on this mean charcoal formation percentage, global burning of secondary forest biomass annually converts 5.0×10^6 Mg of C to charcoal. Long-fallow shifting cultivation cleared permanently is lumped with original forest clearing in FAO (1993) data; these two processes together expose 1497×10^6 Mg of biomass to burning annually, transforming 33.0×10^6 Mg of C to charcoal (Fearnside, 2000). Black carbon, if defined as that resisting oxidation at 340°C, makes up 52-63% of the charcoal mass (Kuhlbusch and Crutzen, 1995). The annual production of $5.0 + 33.0 = 38.0 \times 10^6$ Mg of charcoal C from primary and secondary forest biomass burning in the tropics therefore leads to an annual deposition of $19.8\text{-}23.9 \times 10^6$ Mg C in the form of black carbon. Black carbon deposited in soil and in ocean sediments is a key factor affecting atmospheric CO_2 and O_2 levels over geological time scales (Kuhlbusch, 1998).

5. Conclusions

Secondary forest biomass burns much more thoroughly than primary forest biomass, either in the burns accompanying the initial deforestation or the burning of original forest remains when the areas are reburned either as pasture or as secondary forest. This study found burning efficiencies (% of above-ground pre-burn carbon stock that is released to the atmosphere) of 67.8% for secondary forest biomass, 32.0% for original forest remains, and 41.6% overall in the burn studied. The corresponding percentages considering only the fate of biomass (i.e., excluding pre-burn charcoal + ashes) were 69.5%, 30.4% and 43.1%. Charcoal was formed from 1.1% of the pre-burn above-ground biomass carbon stock for secondary forest biomass, 0.7% for original forest remains and 0.8% overall. These charcoal-formation percentages are lower than those sometimes assumed in global carbon models; nevertheless, charcoal can represent an important sink of atmospheric carbon over long time scales. The results of the present study have applications in estimates of carbon release from tropical land-use change, thereby helping to reduce the uncertainty in estimates of greenhouse-gas emissions.

Acknowledgments

The Pew Scholars Program in Conservation and the Environment, the National Council of Scientific and Technological Development (CNPq AIs 350230/97-98 and 523980/96-5), the "Capacidade de Suporte Humano na Amazônia" project of the Fundação Banco do Brasil (FBB) (No. 10/1615-2) and the National Institute for Research in the Amazon (INPA PPIs 5-3150 and 1-3160 provided financial support. We thank Sr. David for allowing us to conduct this study in his lot. Embrapa Roraima in Boa Vista kindly permitted us to use their ovens and laboratory facilities. We thank S.V. Wilson and four anonymous reviewers for comments on the manuscript.

References

Achard, F., Eva, H.D., Stibig, H.J., Mayaux, P., Gallego, J. Richards, T., Malingreau J-P., 2002. Determination of deforestation rates of the world's humid tropical forests. Science 297, 999-1002.

Andreae, M.O., Browell, E.V., Garstang, M., Gregory, G.L., Harriss, R.C., Hill, G.F., Jacob, D.J., Pereira, M.C., Sachse, G.W., Setzer, A.W., Silva Dias, P.L., Talbot, R.W., Torres, A.L., Wofsy, S.C., 1988. Biomass-burning emissions and associated haze layers over Amazonia. Journal of Geophysical Research (Atmospheres) 93(D2), 1509-1527.

Araújo, T.M., Carvalho Jr., J.A., Higuchi, N., Brasil Jr., A.C.P., Mesquita, A.L.A., 1999. A tropical rainforest clearing experiment by biomass burning in the state of Pará, Brazil. Atmospheric Environment 33, 1991-1998.

Barbosa, R.I., 1997. Distribuição das chuvas em Roraima. In: Barbosa, R.I., Ferreira, E., Castellon, E.B. (Eds.) Homem, Ambiente e Ecologia no Estado de Roraima. Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brazil. pp. 273-285

Barbosa, R.I., Fearnside, P.M., 1996a. Carbon and nutrient flows in an Amazonian forest: Fine litter production and composition at Apiaú, Roraima, Brazil. Tropical Ecology 37(1), 115-125.

Barbosa, R.I., Fearnside, P.M., 1996b. Pasture burning in Amazonia: Dynamics of residual biomass and the storage and release of aboveground carbon. Journal of Geophysical Research (Atmospheres) 101(D20), 25,847-25,857.

Barbosa, R.I., Fearnside, P.M., 1999. Incêndios na Amazônia brasileira: Estimativa da emissão de gases do efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento "El Niño" (1997/98). Acta Amazonica 29(4): 513-534.

Brown, S., Lugo, A.E., 1990. Tropical secondary forests. Journal

of Tropical Ecology 6: 1-32.

Carvalho Jr., J.A., Higuchi, N., Araújo, T.M., Santos, J.C., 1998. Combustion completeness in a rainforest clearing experiment in Manaus, Brazil. Journal of Geophysical Research (Atmospheres) 103(D11): 13,195-13,199.

Carvalho Jr., J.A., Santos, J.M., Santos, J.C., Leitão, M.M., Higuchi, N., 1995. A tropical rainforest clearing experiment by biomass burning in the Manaus region. Atmospheric Environment 29(17), 2301-2309.

Ewell, J., Berish, C., Brown, B., Price, N., Raich, J., 1981. Slash and burn impacts on a Costa Rican wet forest site. Ecology 62(3), 816-829.

FAO (Food and Agriculture Organization of the United Nations), 1993. Forest Resources Assessment 1990: Tropical Countries. FAO Forestry Paper 112, FAO, Rome, Italy. 61 pp.

FAO (Food and Agriculture Organization of the United Nations), 1996. Forest Resources Assessment 1990: Survey of Tropical Forest Cover and Study of Change Processes. FAO Forestry Paper 130, FAO, Rome, Italy. 152 pp.

Fearnside, P.M., 1989. Burn quality prediction for simulation of the agricultural system of Brazil's Transamazon Highway colonists. Turrialba 39(2), 229-235.

Fearnside, P.M., 1996a. Amazonian deforestation and global warming: Carbon stocks in vegetation replacing Brazil's Amazon forest. Forest Ecology and Management 80(1-3), 21-34.

Fearnside, P.M., 1996b. Amazonia and global warming: Annual balance of greenhouse gas emissions from land-use change in Brazil's Amazon region. In: Levine, J. (Ed.) Biomass Burning and Global Change. Volume 2: Biomass Burning in South America, Southeast Asia and Temperate and Boreal Ecosystems and the Oil Fires of Kuwait. MIT Press, Cambridge, Massachusetts. pp. 606-617.

Fearnside, P.M., 1997. Greenhouse gases from deforestation in Brazilian Amazonia: Net committed emissions. Climatic Change 35(3), 321-360.

Fearnside, P.M., 2000a. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change 46(1/2), 115-158.

Fearnside, P.M., 2000b. Greenhouse gas emissions from land-use

change in Brazil's Amazon region. In: Lal, R., Kimble, J.M., Stewart, B.A. (Eds.) Global Climate Change and Tropical Ecosystems. Advances in Soil Science. CRC Press, Boca Raton, Florida. pp. 231-249.

Fearnside, P.M., Graça, P.M.L.A., Leal Filho, N., Rodrigues, F.J.A., Robinson, J.M., 1999. Tropical forest burning in Brazilian Amazonia: Measurements of biomass loading, burning efficiency and charcoal formation at Altamira, Pará. Forest Ecology and Management 123(1), 65-79.

Fearnside, P.M., Graça, P.M.L.A., Rodrigues, F.J.A., 2001. Burning of Amazonian rainforests: Burning efficiency and charcoal formation in forest cleared for cattle pasture near Manaus, Brazil. Forest Ecology and Management 146(1-3), 115-128.

Fearnside, P.M., Guimarães, W.M., 1996. Carbon uptake by secondary forests in Brazilian Amazonia. Forest Ecology and Management 80(1-3), 35-46.

Fearnside, P.M., Leal Filho, N., Fernandes, F.M., 1993. Rainforest burning and the global carbon budget: Biomass, combustion efficiency and charcoal formation in the Brazilian Amazon. Journal of Geophysical Research (Atmospheres) 98(D9), 16,733-16,743.

Graça, P.M.L.A., Fearnside, P.M., Cerri, C.C., 1999. Burning of Amazonian forest in Ariquemes, Rondônia, Brazil: Biomass, charcoal formation and burning efficiency. Forest Ecology and Management 120(1-3), 179-191.

Greenberg, J.P., Zimmerman, P.R., Heidt, L., Pollock, W., 1984. Hydrocarbon and carbon monoxide emissions from biomass burning in Brazil. Journal of Geophysical Research (Atmospheres) 89(D1), 1350-1354.

Guild, L.S., Kauffman, J.B., Ellingston, L.J., Cummings, D.L., Castro, E.A., 1998. Dynamics associated with total aboveground biomass, C, nutrient pools, and biomass burning of primary forest and pature in Rondonia, Brazil during SCAR-B. Journal of Geophysical Research (Atmospheres) 103(D24), 32,091-32,100.

Guimarães, W.M., 1993. Liberação de Carbono e Mudanças nos Estoques dos Nutrientes Contidos na Biomassa Aérea e no Solo Resultante de Queimadas de Florestas Secundárias em Áreas de Pastagens Abandonadas, em Altamira, Pará. Masters thesis in ecology, Instituto Nacional de Pesquisas da Amazônia/Fundação Universidade do Amazonas (INPA/FUA), Manaus, Amazonas, Brazil. 69 pp.

Houghton, R.J.A., Skole, D.L., Nobre, C.A., Hackler, J.L., Lawrence, K.T., Chomentowski, W.H., 2000. Annual fluxes of carbon

from deforestation and regrowth in the Brazilian Amazon. Nature 403, 301-304.

Hughes, R.F., Kauffman, J.B., Cummings, D.L., 2000. Fire in the Brazilian Amazon. 3. Dynamics of biomass, C, and nutrient pools in regenerating forests. Oecologia 124(4), 574-588.

Kauffman, J.B., Cummings, D.L., Ward, D.E., Babbitt, R., 1995. Fire in the Brazilian Amazon: Biomass, nutrient pools, and losses in slashed primary forest. Oecologia 104, 397-408.

Kaufman, Y.J., Setzer, A.W., Justice, C., Tucker, C.J., Pereira, M.G., Fung, I., 1990. Remote sensing of biomass burning in the tropics. In: Goldammer, J.G. (Ed.) Fire in the Tropical Biota: Ecosystem Processes and Global Challenges. Springer-Verlag, Heidelberg, Germany. pp. 371-399.

Kuhlbusch, T.A.J., 1998. Black carbon and the carbon cycle. Science 280, 1903-1904.

Kuhlbusch, T.A.J., Crutzen, P.J., 1995. Toward a global estimate of black carbon in residues of vegetation fires representing a sink of atmospheric CO_2 and a source of O_2. Global Biogeochemical Cycles 9(4), 491-501.

Lameira, O.A., Coimbra, J.M., 1988. Levantamento e distribuição da precipitação em Roraima. Empresa Brasileira de Pesquisa Agropecuária-Unidade Experimental de Âmbito Territorial (EMBRAPA-UEPAT)/Boa Vista-Roraima. Pesquisa em Andamento No. 12, Boa Vista, Roraima, Brazil. 5 pp.

Schimel, D. and 75 others, 1996. Radiative Forcing of Climate Change. In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.) Climate Change 1995: The Science of Climate Change. Cambridge University Press, Cambridge, U.K., pp. 65-131.

Seiler, W., Crutzen, P.J., 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. Climatic Change 2, 207-247.

Van Wagner, C.E., 1968. The line intersect method for forest fuel sampling. Forest Science 14(1), 20-26.

Ward, D.E., 1986. Field scale measurements of emission from open fires. Technical paper presented at the Defense Nuclear Agency Global Effects Review, Defense Nuclear Agency, Washington, DC.

Ward, D.E., Hardy, C.C., 1984. Advances in the characterization and control of emissions from prescribed fires. Paper presented at the 77th annual meeting of the Air Pollution Control Association, San Francisco, California.

Warren, W.G., Olsen, P.F., 1964. A line intersect technique for assessing logging waste. Forest Science 10, 267-276.

FIGURE LEGENDS

Figure 1. Location of study site.

Figure 2. Layout of sampling plots.

Figure 3. Distribution of carbon in the pre- and post-burn phases.

Figure 4. Fate of pre-burn carbon for secondary forest aboveground biomass, original forest remains, and all biomass.

Table 1: Dry weight of above-ground material before and after burn

Secondary Forest

Fraction	Diameter class (cm)	Quality	Pre-burn mean (Mg ha^{-1})	Pre-burn sd	Pre-burn cv	Post-burn mean (Mg ha^{-1})	Post-burn sd	Post-burn cv	Dry weight loss (%)
Vines	< 5		1.28	0.97	0.76	0.08	0.16	2.10	94.1
Wood	< 5	Sound	17.85	8.38	0.47	3.52	2.95	0.84	80.3
		Rotten	0.26	0.54	2.07				100.0
	5-10	Sound	6.93	5.50	0.79	4.93	3.37	0.68	28.8
		Rotten	0.56	0.90	1.60				100.0
	> 10[a]	Sound	5.47	8.80	1.61	2.58	3.21	1.24	52.7
		Rotten	0.05	0.14	3.00				100.0
Other			0.89	0.78	0.88	0.35	0.40	1.14	60.1
Litter[b]			9.76	4.14	0.42	0.84	1.02	1.20	91.3
Charcoal									
Wood						0.35	0.14	0.39	--
Other (palms+vines)						0.00	0.00	1.15	--
Ashes[c]						0.64	0.72	1.12	--
Sub-total Secondary forest			43.04	6.48	--	13.30	2.77	--	69.1

Original Forest Remains

Vines	< 5		0.03	0.08	3.00				100.0
	5-10		0.22	0.67	3.00				100.0
Wood	< 5	Sound	0.005	1.43	318.02				100.0
		Rotten	1.75	1.44	0.82	0.003	0.012	4.04	99.8
	5-10	Sound				0.52	1.11	2.14	--
		Rotten	4.44	0.08	0.02	0.66	1.13	1.73	85.2
	> 10 [a]	Sound	47.30	52.93	1.12	32.36	45.34	1.40	31.6
		Rotten	49.20	45.18	0.92	36.90	40.84	1.11	25.0
Palms	> 10 [a]		2.09	4.42	2.12	0.44	1.36	3.07	78.8
Charcoal									
Wood			0.21	0.21	1.00	0.95	0.89	0.93	-346.0
Other (palms+vines)			0.03	0.10	3.00	0.01	0.03	3.00	69.2
On ground[d]			0.55	0.35	0.64	0.37	0.26	0.71	32.5
Ashes[c]						1.13	1.27	1.12	--
Sub-total: Original forest remains			105.83	23.68		73.35	20.04		30.7
Total			148.86	18.71		86.65	17.39		41.8

(a) Values for dry weight of pieces >10 cm in diameter are the total of direct (destructive) and indirect (LIS) measurements.

(b) Litter assumed all to be from secondary forest.

(c) Ashes apportioned between secondary forest and original forest remains based on presumed carbon releases from these sources.

(d) Charcoal in soil assumed to be from burning of original forest biomass.

Table 2: Carbon stocks of above-ground material before and after burn

Secondary Forest

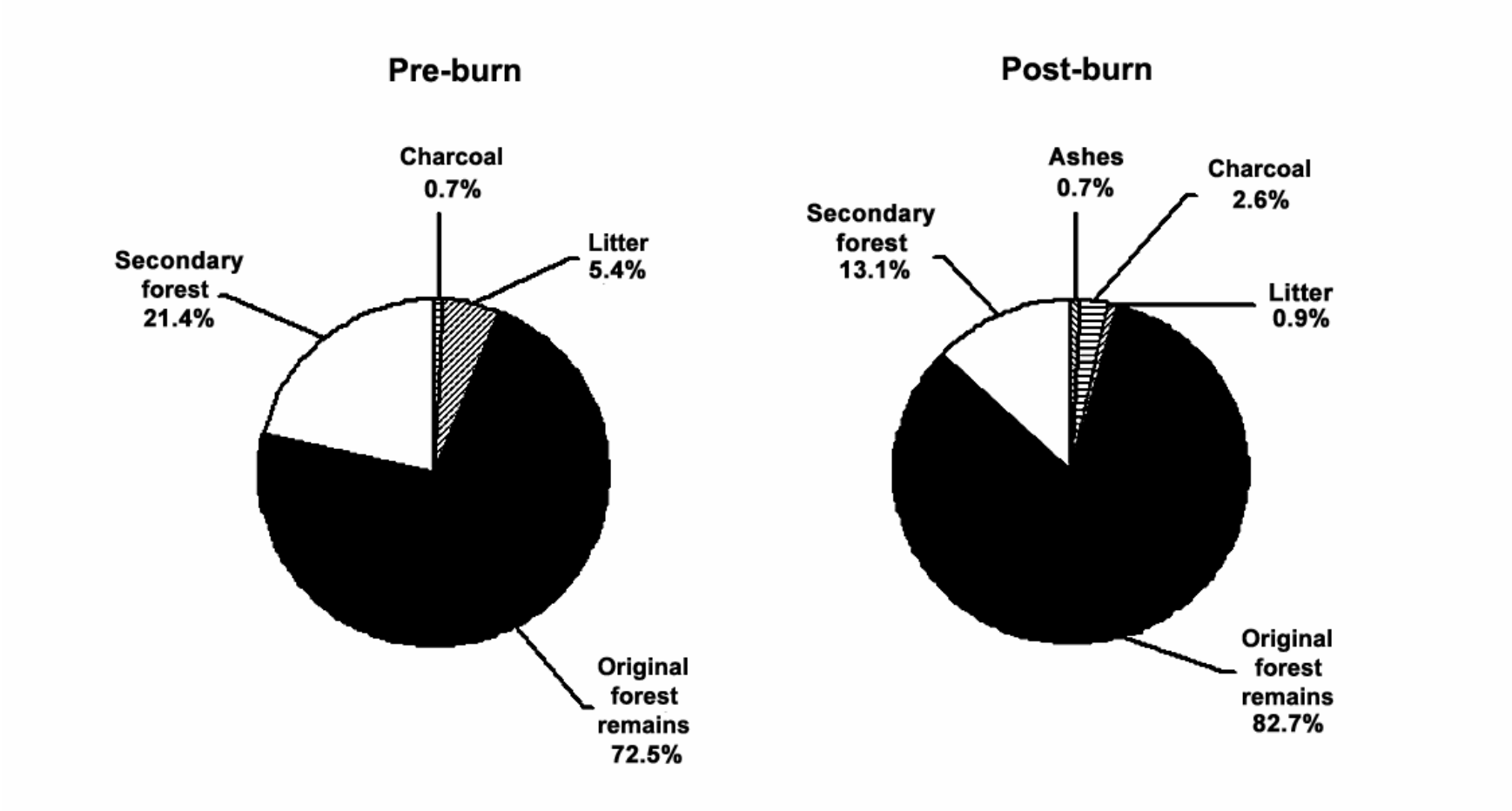
Fraction	Diameter class (cm)	Quality	Pre-burn C content (% C)	sd %C	Pre-burn C stock (Mg ha^{-1})	Post-burn C content (% C)	sd %C	Carbon loss C stock (Mg ha^{-1})	Carbon loss (%)	Carbon partitioning (%)[a]
Vines	<5		42.31[g]	4.20	0.54	41.87[g]	4.70	0.03	94.2	0.2
Wood	<5	Sound	44.58[h]	2.10	7.96	45.51[h]	2.40	1.60	79.9	8.6
		Rotten	44.58[h]	2.10	0.12					
	5-10	Sound	43.57[h]	5.50	3.02	47.22[h]	--	2.33	22.8	12.6
		Rotten	43.57[h]	5.50	0.25					
	>10	Sound	46.09[h]	5.50	2.52	46.09[h]	--	1.19	52.7	6.4
		Rotten	43.78[h]	5.60	0.02					
Other[b]			46.42[h]	1.30	0.41	44.24[h]	2.00	0.16	62.0	0.8
Litter[c]			38.13[h]	4.80	3.72	41.53[h]	7.10	0.35	90.6	1.9
Charcoal										
Wood						58.00[h]	5.00	0.21	--	1.1
Other (palms+vines)						58.00[h]	5.00	0.0004	--	0.002
Ashes[d]						16.13[h]	7.80	0.11	--	0.2
Sub-total: secondary forest[d]					18.55			5.97	67.8	32.2
Presumed release								12.58		67.8
Original Forest Remains										
Vines	<5		42.31[g]	4.20	0.01				100.0	0.0
	5-10		42.31[g]	4.20	0.09				100.0	0.0
Wood	<5	Sound	46.81[h]	3.70	0.002					

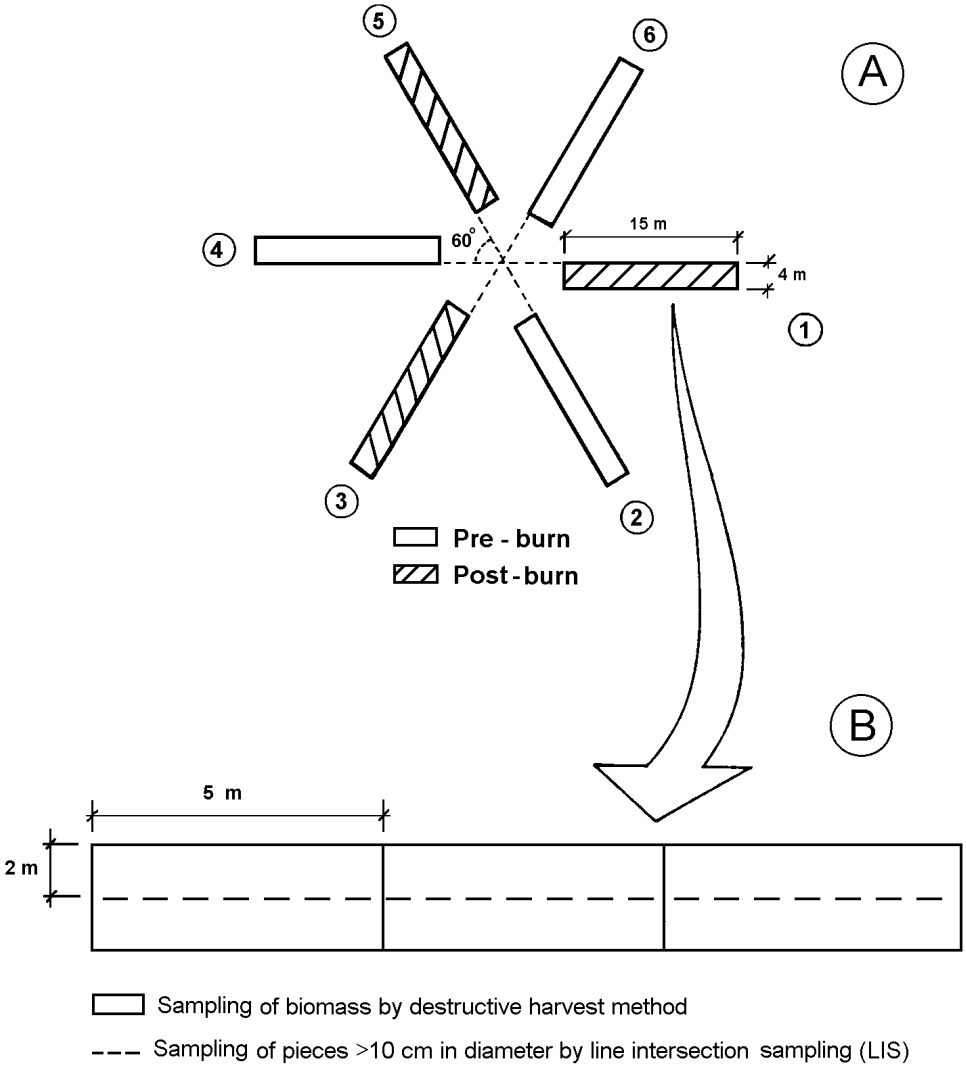
		Rotten	46.81 [h]	3.70	0.82	47.20 [h]	3.60	0.000	100.0	0.0
	5-10	Sound				49.10 [h]	3.30	0.32	84.7	0.6
		Rotten	47.65 [h]	4.00	2.11					
	>10	Sound	48.38 [h]	2.10	22.88	47.40 [h]	1.70	15.34	33.0	30.2
		Rotten	47.93 [h]	3.00	23.58	47.93 [h]	1.70	17.69	25.0	34.8
Palms	>10		39.65 [h]	7.00	0.83	39.65 [h]	7.00	0.18	78.8	0.3
Charcoal										
Wood			63.70 [h]	6.40	0.14	63.90 [h]	6.90	0.61	--	1.2
Other (palms)			60.39 [h]	6.70	0.02	61.63 [h]	5.40	0.01	--	0.0
On ground[e]			63.36 [h]	6.10	0.35	66.89 [h]	7.10	0.25	--	0.5
Ashes[d]						16.13 [h]	7.80	0.18	--	0.4
Sub-total: Original forest remains[e]					50.84			34.57	32.0	68.0
Presumed release								16.27		32.0
Total					69.39			40.54	41.6	58.4
Presumed release								28.85		41.6

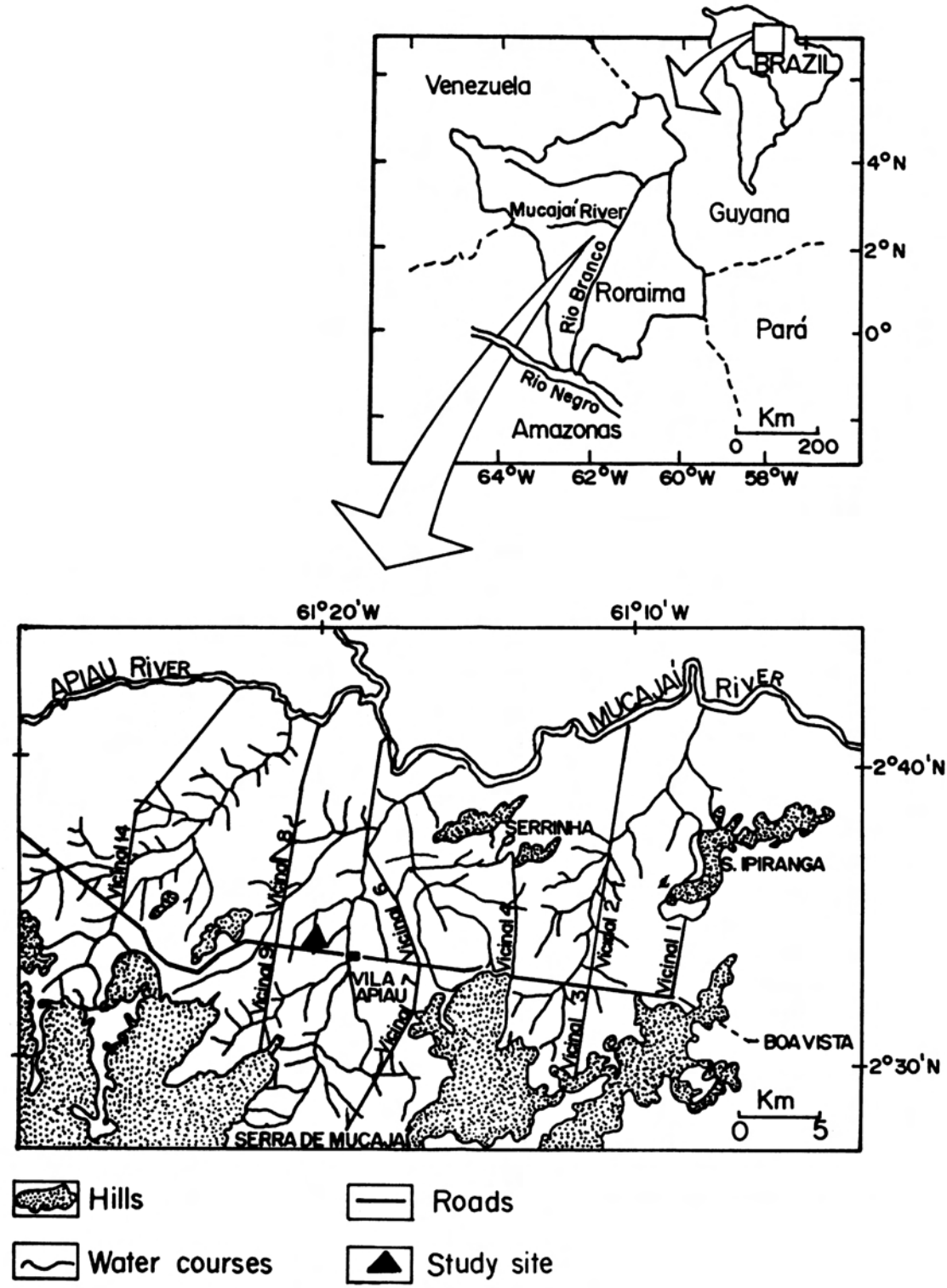
(a) Percentage of the total pre-burn stock in each category (secondary forest or original forest remains) left in each fraction.
(b) Palm fruits, pasture grass, bamboo and bromeliads.
(c) Litter assumed all to be from secondary forest.

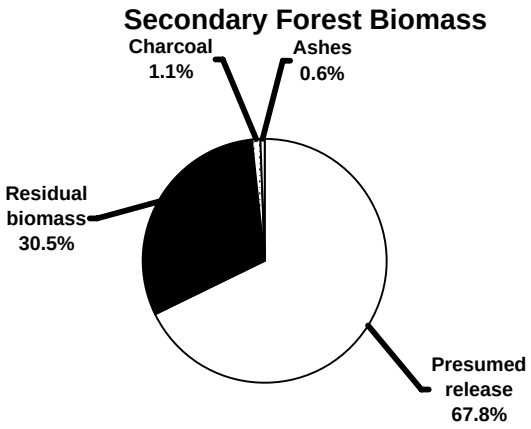
(d) Ashes apportioned between secondary forest and original forest remains based on presumed carbon releases from these sources.
(e) Including charcoal and/or ashes.
(f) Charcoal in soil assumed to be from burning of original forest biomass.
(g) from Guimarães (1993).
(h) from Barbosa and Fearnside (1996).

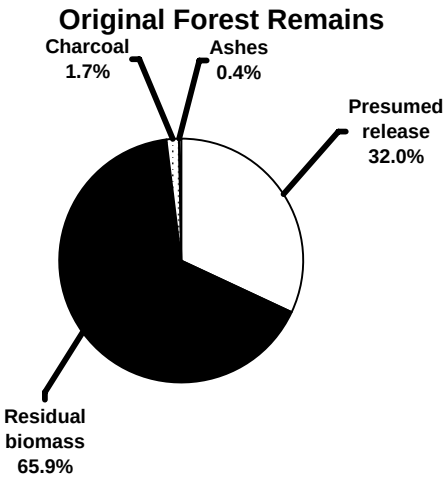
Fig. 3

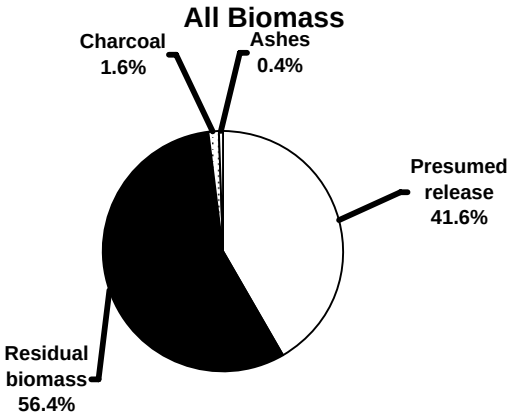

Pre-burn
Charcoal
0.7%
Litter
5.4%
Secondary
forest
21.4%
Original
forest
remains
72.5%
Post-burn
Ashes
0.7%
Charcoal
2.6%
Secondary
forest
13.1%
Litter
0.9%
Original
forest
remains
82.7%


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


Venezuela
BRAZIL
Guyana
Mucajaí River
Rio Branco
Roraima
Pará
Rio Negro
Amazonas
Km
0 200
4°N
2°N
0°
64°W
62°W
60°W
58°W
61°20'W
61°10'W
APIAU RIVER
MUCAJAÍ RIVER
2°40'N
SERRINHA
S. IPIRANGA
Vicinal 14
Vicinal 8
Vicinal 6
Vicinal 4
Vicinal 2
Vicinal 1
Vicinal 5
VILA APIAU
Vicinal 3
BOA VISTA
2°30'N
SERRA DE MUCAJAÍ
Km
0 5
Hills
Roads
Water courses
Study site


Secondary Forest Biomass
Charcoal
1.1%
Ashes
0.6%
Residual
biomass
30.5%
Presumed
release
67.8%


Original Forest Remains
Charcoal
1.7%
Ashes
0.4%
Presumed
release
32.0%
Residual
biomass
65.9%


All Biomass
Charcoal
1.6%
Ashes
0.4%
Presumed
release
41.6%
Residual
biomass
56.4%