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PASTURE BURNING IN AMAZONIA: DYNAMICS OF RESIDUAL BIOMASS AND THE STORAGE AND RELEASE OF ABOVEGROUND CARBON

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Abstract

Aboveground biomass in cattle pasture converted from tropical dense forest was studied both before and after reburning in Brazilian Amazonia. In a seven-year-old pasture studied in Apiaú, Roraima, the aboveground dry-weight of biomass (live + dead) exposed to burning consisted of 96.3 t ha^{-1} of original forest remains, 6.2 t ha^{-1} of secondary successional vegetation (woody invaders in the pasture), and 8.0 t ha^{-1} of pasture grass (carbon contents 48.2%, 45.4% and 42.2%, respectively). In terms of carbon, burning efficiencies for these three categories were 13.2%, 66.7% and 94.6%, respectively. Net charcoal formation was 0.35 t C ha^{-1}, or 0.63% of the carbon exposed to the reburn, while the total accumulated since conversion (including the initial burn) is estimated at 2.3 t ha^{-1} (1.82% of the pre-deforestation aboveground biomass carbon stock).

The dynamics of the original forest remains were represented in simulations that included parameters such as charcoal formation, burning efficiency and carbon concentration in different biomass components. Releases from initial burning of the cleared forest (44.0 t C ha^{-1}) plus releases over the course of the succeeding decade through combustion (12.5 t C ha^{-1}) and decay (51.5 t C ha^{-1}) total 92% of the original forest biomass carbon (126 t C ha^{-1}). Of biomass carbon remaining after the initial burn (84.3 t C ha^{-1}), 76.0% is released: 61.1% through decay and 14.9% through combustion in reburns, while 1.2% is net conversion to charcoal in the reburns. These results indicate an amount of charcoal accumulation that is smaller than some carbon calculations have assumed, therefore suggesting a greater impact on global warming from conversion of forest to pasture.

Introduction

Cattle pasture is the most widespread landscape in deforested parts of Brazilian Amazonia [Fearnside, 1986, p. 26]. Because of the vast extent and rapid expansion of pastures, understanding the carbon dynamics of this land use is important to help resolve controversies surrounding the role of Amazonia in emissions of greenhouse gases. The replacement of high-biomass forests with low-biomass pasture, which are repeatedly burned as long as the system is maintained, results in carbon stored in different compartments of the pasture being released as CO_2 and CH_4. These gases contribute to climatic change [IPCC, 1994].

For lack of data, models for estimating emissions have generally been based on the assumptions that carbon is completely released when the forest is initially converted. Reburning and decomposition of the residual biomass of the original forest are either left out of the calculations [cf. Houghton et al., 1987; Hao et al., 1990] or, the assumption is made that biomass is completely oxidized in the first reburn [cf. *Bogdonoff et al*., 1985, p. 347]. However, this is not the usual course of events for residual material that decomposes or is exposed to burning over the years before it disappears altogether.

Another parameter often not included in the models is the quantity of residual biomass converted to charcoal. This component of the landscape can function as a long-term reservoir of carbon. Therefore, the carbon contained in it must be subtracted from the total carbon released by the burn [*Crutzen and Andreae*, 1990]. The paucity of field measurements and the uncertainty of parameters related to the transformation of different categories of biomass makes the calculation of emissions unreliable. Uncertainties in these parameters have a multiplicative character, greatly increasing the uncertainty of estimated emissions [*Robinson*, 1989].

With this in mind, the present study investigates the total aboveground biomass and carbon at the time pastures are burned in Amazonia, especially the remains of original forest at the time of the fire event. Using simulations we analyze the dynamics of disappearance of the mass and carbon stock of these remains over time. For these purposes one takes into consideration the parameters for mass transformation during reburns, decomposition and formation of charcoal. The simulations are based on measurements obtained for aboveground biomass, burning efficiency (percentage of biomass burned), percentage of charcoal formation, and the carbon content of the fractions present at the time the pasture is burned.

The study site was at Vila de Apiaú (2°33'11"N, 61°18'27"W), a colonization area located 112 km southwest of the state capital at Boa Vista, Roraima, Brazil (Figure 1). The climate is classified as "Ami" in the Köppen system, with a mean annual precipitation of 1900-2000 mm [*Santos et al*., 1982; *Lameira and Coimbra*, 1988]. It has low relief (elevation at the study site approximately 120 m above mean sea level) with low hills bordering the settlement area. The major soil types are yellow-red podzolic (Oxisol) (at the study site), red-yellow latosol (Ultisol) and lithic soils [*Brazil, Projeto RADAMBRASIL*, 1975]. The dominant vegetation type in the area studied is an ecotone between ombrophilous forest/seasonal (non-dense) forest (ON) and the dense forest type (Ds) (ombrophilous dense sub-montane forest) [*Brazil, IBGE*, 1993; see *Fearnside and Ferraz*, 1995 for discussion of Amazonian vegetation types and codes]. The total aboveground biomass of the primary forest in this contact zone was estimated by *Barbosa* [1994, p. 37] at 266 t ha^{-1} (dry weight), or 126 t ha^{-1} of carbon. This estimate will be used in the simulations described in the present paper.

[Fig 1 here]

Criteria for Choice of the Study Site

In selecting the experimental areas, the following criteria were adopted: a) the species making up the pasture (*Brachiaria humidicola* or *quicuio da Amazônia*), b) age (6-10 years of use), c) area not abandoned, and d) known history. This was necessary in order to select pastures typical of the study area. One of the chosen pastures had been used for seven years and had been burned three times (once at the time of initial conversion and two reburns). The burn studied took place in March 1993. A second pasture had been used for nine years and had six previous burns; while study of this pasture was begun, it was not possible to complete it due to heavy rains that fell on the area out of season; therefore only a few preliminary results for the second pasture will be presented in this discussion.

Sampling Methods

Biomass in pastures is divided into three groups: 1) remains of the original forest, 2) secondary succession, and 3) pasture grass. All groups of aboveground biomass were subdivided into fractions and measured in two phases: pre-burn and post-burn. Two measurement methods were used: destructive and volumetric. The latter method was used only for remains of the original forest wood with diameter $\geq$10 cm, using the same experimental design in the field as for destructive sampling. Pieces were classified as "normal" (without visible decomposition) and "rotten" (with visible decomposition), in order to weight the mean burning efficiency in the fraction.

Two sampling points were chosen at random within the pasture. Each one of these determined the center of a circle from which six plots of 2 X 30 m radiated, each ray at intervals of 60^o, with the first ray in a north-south direction. Each point contained three plots for each phase (pre- and post-burn) in an alternating sequence (Figure 2). Each plot then was divided into three sub-plots (sampling units) of 2 X 10 m to obtain a better estimate of variation. The total number of sub-plots sampled was 36 in the seven-yr-old pasture (pre- and post-burn), and 24 in the second (nine-yr-old) pasture (pre-burn). The experimental design used in this study was originally conceived by Jennifer Robinson as a means of minimizing the bias in estimates in already felled areas.

[Fig. 2 here]

Destructive (Direct) Method

This method consisted of weighing each of the fractions by biomass group and by phase of the burn found in the sub-plots. The biomass of the pasture was calculated by laying out quadrats of approximately 1 m^2 inside the sub-plots and one supplementary quadrat at the end of each plot or ray (Fig. 2). In this area, all pasture was cut at a height of 2-3 cm above the ground and immediately weighed. Biomass of the remains of original forest and secondary vegetation underwent the same sampling process. Both were divided into "twigs" (pieces of wood with diameter <5 cm), "branches" (diameter 5 to 10 cm), "trunks" (diameter $\geq$10 cm), and "palms." The samples of twigs and branches were taken in a transect of 0.5 X 10 m along the length of each plot (Fig. 2). In addition, other fractions had to be separated (based on previous experience). These were defined in the following way: a) "weeds" (included in the biomass of secondary vegetation), b) "ashes" (collected in a transect of 0.1 X 10 m along each sub-plot), c) "litter" (remains of the three groups collected in the same "pasture" plot), d) "soil charcoal" (material from incomplete combustion present on the soil which was collected manually in the quadrat), and e) "biomass charcoal" (charcoal attached to the pieces of wood, collected by scraping with a metal blade).

In each fraction, a sample was taken for determination of humidity and dry weight per unit area. The material was then 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 with sodium hydroxide with standardized electrical conductivity. The carbon content of the material is calculated from the difference between the conductivity of the standard solution and the carbonated solution.

Volumetric (Indirect) Method

This method was used to calibrate and adjust the destructive method, producing better results for burning efficiency than the direct method alone, since the indirect method compares "before" and "after" measurements of the same pieces of wood, thus avoiding the effect of high variability in the amount of biomass initially present in different plots. The indirect method was only used for pieces with diameter $\geq$10 cm (trunks). In our previous studies, pieces $\geq$10 cm in diameter has been the fraction with the greatest representativeness, but also with the highest variability, being capable of producing erroneous conclusions with destructive sampling (measuring of nearby but not identical locations), for example, resulting in greater biomass present in the post-burn quadrat than in the pre-burn quadrat. The volumetric method consisted of determining: a) the diameter of pieces in the different locations (two ends and center of each ray, with two measurements for each location), b) the length between the ends of the pieces that fall within the sub-plot, and c) the thickness of the layer of charcoal at the points on the piece where the diameter is measured (four points around the circumference of the piece). The volume of a cylinder with the measured diameter was calculated (with and without the layer of charcoal), and the length of each individual piece. This procedure was carried out with the tagging and mapping of the pieces in order to facilitate return measurements after the burn.

Treatment of the Data

We calculated the dry weight of the total biomass (t ha^{-1}) and the volume (m^3 ha^{-1}) of the remaining trunks ($\geq$10 cm). The mean and standard deviation for each fraction in each sub-plot was determined. The result for burning efficiency of trunks and biomass charcoal was redone using the method employed by Barbosa [1994], with a weighted average for "normal" and "rotten" pieces sampled using the indirect method. The pre-burn value of these fractions was considered as a simple average of the pre- and post-burn results obtained by the direct method. The post-burn value was determined by the inverse method using the burning efficiency obtained by the indirect method. This was an attempt to assess the natural variability of the system and obtain better quality data. Using the average carbon content of each fraction, we calculated the carbon stock before and after burning. With the results obtained for aboveground biomass, burning efficiency, percent of charcoal formation and carbon content, we limited the simulations to treatment of biomass and carbon in the remains of the original forest biomass, assuming that, due to their rapid regrowth, pasture and secondary biomass would not influence the net carbon loss of the system. The calculations presume that the combined annual rate of losses (combustion, decomposition and charcoal formation) follows a logarithmic pattern.

Results

Biomass, burning efficiency and charcoal formation

The total aboveground biomass determined by the direct method and adjusted by the indirect method in the pre-burn seven-yr-old pasture was 118.5 t ha^{-1} (Table 1). The total biomass consumed during the burn was 24.1 t ha^{-1}, representing a burning efficiency of 20.3%. The original forest remains fraction represented 81.2% (96.3 t ha^{-1}) of aboveground biomass for pre-burn and 90.4% (85.3 t ha^{-1}) for post-burn. The other fractions were as follows (pre- and post-burn): pasture grass: 6.8% and 0.5%; secondary succession: 5.2% and 2.2%; and other fractions (ashes, charcoal and litter): 6.8% and 6.9%. The fraction making up the largest single proportion of both pre- and post-burn biomass was the trunks, with 75.9% (pre-burn) and 86.6% (post-burn).

[Table 1 here]

The fraction with the lowest burning efficiency was the remains of the original forest (11.3%), with 9.1% for the trunk fraction and 43.6% for the others combined. Next came secondary succession (66.5%) and, most efficient, pasture grass (94%). Together, soil charcoal and biomass charcoal increased 16.7% between pre- and post-burn. The percentage for charcoal formation was 0.43%, considering total pre-burn biomass and total charcoal found post-burn (0.51 t ha^{-1}). Considering the original forest remains separately indicates 0.52% of the pre-burn carbon in this fraction converted to charcoal; the corresponding percentage for trunks was 0.77% (in both cases discounting the biomass charcoal of the secondary succession). Of the total aboveground biomass present before the burn, 0.21% (0.25 t ha^{-1}) was transformed into ashes.

The aboveground pasture biomass for nine-yr-old pasture (pre-burn) was estimated at: pasture = 8.1 t ha^{-1} (n = 3, SD = 1.7); secondary succession = 0 (n = 24); trunks = 21.3 t ha^{-1} (n = 24, SD = 53.6); litter = 2.7 t ha^{-1} (n = 3, SD = 2.2); palms = 1.6 t ha^{-1} (n = 3, SD = 0.09); biomass charcoal = 0.9 t ha^{-1} (n = 24, SD = 7.8), soil carbon = 0.05 (n = 3; SD = 0.09) and total = 34.6 t ha^{-1}.

Carbon stocks and releases

The pre-burn carbon stock was 56.2 t C ha^{-1} (Table 2). Of this total, presumably 11.6 t C ha^{-1} (20.6%) was released to the atmosphere during burning (Figure 3). Of the remaining preexisting carbon stock, 71.3% remains as carbon stock in the biomass, 4.1% as charcoal (soil and biomass), 2.0% as litter, and 2.0% as ashes, pasture grass and secondary succession. The original forest remains contained 87.0% of their pre-burn carbon stocks, while pasture grass at 5.4% and secondary succession at 33.3% had lower averages. The lowest burning efficiency was for the trunks of the original forest remains (11.4%), while together the rest of this group averaged 39.7%. The charcoal of the original forest remains increased by 18.1% after the burn. Charcoal formation represented 0.63% of the original total carbon stock exposed to burning, or 0.74% if only the original forest remains are considered, and 1.06% if only the "trunk" fraction is considered (without secondary succession charcoal included).

[Table 2 and Fig. 3 here]

Excluding the ashes (contaminated by soil particles), the weighted average for carbon content for this group was as follows (pre- and post-burn): pasture grass = 42.4% and 38.4%; secondary succession = 45.4% and 45.1%; original forest remains = 48.2% and 47.2%; litter = 38.1% and 41.5%; charcoal = 64.4% and 65.5%; and total = 47.9% and 47.9%.

Estimates of biomass transformation and carbon dynamics of original forest remains

Biomass

Based on the parameter values in Table 3, we estimate an annual rate (k_b) of mass loss of 0.214 for the original forest biomass. This value was derived using a logarithmic function similar to that derived by Buschbacher [1984] for shifting cultivation fallows in Venezuela. The disaggregated rates were 0.176 for trunks and 0.513 for the other components.

[Table 3 here]

The parameter values in Table 3 can be used to simulate a typical 10-yr use scenario with one initial burn and three reburns (Figure 4). The simulation indicates mass transformation in the following proportions: combustion = 45.0%; natural decomposition = 40.7%; and charcoal formation = 2.5%. Of the total mass in original forest remains, 88.2% is transformed over the 10-yr period while 11.8% of remains as biomass.

[Fig. 4 here]

Carbon

Using the same model we estimated the total carbon stocks in the original forest remains would be released to the atmosphere or stored as charcoal at a rate similar to that of the biomass (Table 4). The simulation indicated that 90.9% of all pre-burn carbon would be released by combustion or decomposition by the end of the 10-yr use period. Of the rest, 3.3% would remain in the form of charcoal and 5.8% would continue on as biomass. The annual rate of C release (k_c) was 0.285 for the total carbon stock, with a rate of 0.248 for trunks and 0.621 for other components.

[Table 4 here]

Discussion

Biomass

The biomass results presented here indicate high variability. In the case of pasture, variability is associated with the frequency and quality of burns, which mainly affect the least durable fractions. For example, in our preliminary data for the nine-yr-old pasture pre-burn, the value for the biomass of the original forest remains was 4.2 times lower than that for seven-yr-old pasture, with no pieces under 10-cm diameter remaining in nine-yr-old pasture. The two-year use interval was not the only variable: the greater number of reburns and the quality of the last two burns in the nine-yr-old pasture also influenced the results (RIB, personal observation).

Trunks represent the largest group of remaining biomass, partly as a reflection of the high resistance of this material to decay and burning. Less resistant fractions (pasture and secondary succession), besides being subjected to periodic burning, have a rapid natural rate of regrowth. The result is that, as long as a pasture remains productive, its carbon balance will be near equilibrium.

The model presented for the decay of original forest remains in pasture systems is not intended to be used for predicting values at specific times (point predictions). The utility of the model is to show the general trend for the decay of the main component of the pasture landscape in Amazonia in the first years after establishment. It indicates the importance of the carbon source from combustion combined with natural decomposition during the first years after conversion of forest to pasture. In the simulation, the combined losses of original forest remains totaled 86% (representing 91% of the carbon) in a scenario of four burns up to the tenth year. Assuming the value of 266 t ha^{-1} for the initial aboveground biomass of the forest from Table 3, the loss of the original biomass in the seven-yr-old pasture (pre-burn) was 64%, while that of nine-yr-old pasture (pre-burn) was 90%. The model results indicate 81% and 87% loss by the seventh and ninth years, respectively. With the regrowth of biomass in the seven-yr-old pasture of only 19.2 t ha^{-1} (grass plus secondary succession plus litter), the net biomass loss was about 57%, or 72 t C ha^{-1}.

The conversion from a high to a low biomass system results in carbon being released to the atmosphere, where this net addition will remain for a long time before being reabsorbed by regrowing vegetation on the site. Studies in old shifting cultivation plots in the Upper Rio Negro area of Venezuela and Colombia indicate an approximate recovery time of 190 years for the original forest biomass [Saldariagga et al., 1988]. Considering the use time as pasture plus the recovery time from abandonment, one would expect that the carbon in the biomass destroyed to have a long residence period in the atmosphere. This is because the regrowth in pastures is slower than regrowth in abandoned shifting cultivation fields, making it improbable that carbon released by burning would be rapidly recuperated [Fearnside and Guimarães, 1996].

Burning efficiency

The burning efficiency we found in the pasture burn was lower than efficiencies that have been reported by for initial burns of felled tropical forests. Wong [1978] suggests 75% for the tropics. This number is 6.6 times greater than that found in this study for seven-yr-old pasture (11.3%). Wong derived his value using an experimental burn of partially dry wood residues in the temperate and boreal zones [Fahnestock, 1979]. On the other hand, Goudriaan and Ketner [1984, p. 179] assumed burning efficiencies of 90% for branches and 30% for trunks for an initial burn in a simulation of the carbon cycle, while our values (for a reburn) were 19.8% and 9.1%, respectively. The great resistance of some components of the original forest remains is one factor affecting burning efficiency in pasture systems. This is reflected in the annual rates of decay (k) in our model. For example, the rate for trunks (0.176) was 2.9 times smaller than that for other (less-durable) components (0.513).

Charcoal formation

Our simulation results indicate only a small amount of carbon (2.5 t C ha^{-1} or 2.0% of the pre-deforestation aboveground carbon stock) is transformed into charcoal by the initial burn plus three re-burns over 10 yrs of use as pasture.

A small percentage of charcoal formation has been reported for an initial burn of primary forest near Manaus, with only 2.7% of pre-burn carbon transformed to charcoal [Fearnside et al., 1993]. Seiler and Crutzen [1980] estimated a much higher charcoal formation rate of 14-20% (20-30% of post-burn C), subsequently revised by Crutzen and Andreae [1990, p. 1672] to 5%.

Our field measurements confirm the small stocks of carbon in biomass charcoal. Before the burn in seven-yr-old pasture, biomass charcoal (without secondary succession) was only 1.9 t C ha^{-1}, or 1.5% of the pre-deforestation carbon stock, while after the burn 2.3 t C ha^{-1} was present, corresponding to 1.8% of the pre-deforestation carbon stock. The nine-yr-old pasture pre-burn charcoal percentage was also low at 0.7 t C ha^{-1}, or 0.6% of the pre-deforestation carbon stock.

Stocks and releases of carbon

Point estimates for carbon release per unit area in pasture systems can result in misleading calculations of the energy balance. Pasture landscapes are affected by a series of components which vary in accord with the type and quantity of biomass, such that the total carbon presumably released from pasture burning of seven-yr-old-pasture (11.6 t C ha^{-1}) must be compared only to the original forest remains (6.1 t C ha^{-1}) since this carbon is considered as a net release to the atmosphere. Pasture and secondary succession, in the scenario used in this study, must be discounted owing to their rapid regrowth which almost completely incorporates all carbon released by their combustion. However, in a more detailed analysis of energy balance and the carbon cycle, trace gases and methane (CH_4) released must be measured because even in small volumes these gases affect atmospheric chemistry [IPCC, 1994].

The simulation of carbon release produces results similar to those of biomass because the stocks and releases of carbon are a direct function of the biomass dynamics in the landscape. In the model, about 85% of the carbon stock is released, mainly in the initial burn and the second reburn (sixth yr). This result appears to be consistent with the direct measurements, which imply a release of 63% of pre-burn pasture carbon for seven-yr-old pasture, and 87% for nine-yr-old pasture, considering the original forest stock to be 126 t C ha^{-1} from Table 3, and considering the differences between the two pastures.

The simulation also shows that combustion and decomposition are responsible for the majority of carbon released in the system (91%). This result is similar to that calculated by Fearnside [1991, p. 98] under the same use scenario. In the same way as for biomass, the relative importance of combustion and decomposition was different, respectively, for trunks (28.1% and 60.4%) and other components (69.3% and 30.0%). These results are a reflection of the slow decay of trunks and the susceptibility to fire of the other components of the original forest remains. However, the distinction between the two paths taken by carbon are important because each pathway involves different processes emitting greenhouse gases. For example, trunks consumed in pasture reburns are burned in large part by smoldering instead of flaming combustion, thereby emitting substantially more methane than in the initial burn [Fearnside, 1992, p. 33].

In the field, we observed that the original forest remains were the ones with the greatest carbon stocks in seven-yr-old pasture post-burn, with more than 70% of the pre-burn total, or 87% of the original carbon stock. Besides this, the trunk fraction of this group released the most carbon (4.9 t C ha^{-1}). In this way, independent of the quantity released by pasture or secondary succession biomass, the results indicate that, under the scenario proposed, it is the original forest remains which are most responsible for net carbon releases to the atmosphere. However, these emissions happen over the period of pasture use, varying as a function of the management practices and intensity of use, and can result in almost complete release in the first years after pasture formation. Therefore, this behavior differs from that used by some models which discard reburns and decomposition and assume complete carbon release in the initial burn [cf. Houghton, 1991]. This assumption causes the calculations of carbon emissions stemming from conversion of natural ecosystems to have greater weight at the time of transformation, instead of being distributed over a longer period of time.

Conclusions

1.) The original forest remains are responsible for most of the carbon stocks and net carbon emissions in the first decade after conversion of forest to pasture.

2.) Carbon releases from pasture derived from primary tropical forest cannot be considered as instantaneous, but about 90% of the carbon in the original forest biomass is released by the end of the first decade.

3.) Of biomass carbon remaining after the initial burn, 76.0% is released over the course of the succeeding decade: 61.1% through decay and 14.9% through combustion in reburns.

4.) The amount of charcoal formed is small, totaling 4.2 t C ha^{-1} from the initial burn plus three reburns over the course of a decade. This represents 3.4% of the aboveground biomass carbon of the original forest.

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TABLE 1. Dry Weight (t ha^{-1}) and Burning Efficiency (%) of Aboveground Biomass in 7-yr-old Pasture in Roraima, Brazil

Group/Fraction	N[a]	Pre-burn	SD	Pos-burn	SD	Burnin Eff(%)
Pasture Biomass	24	8.05	5.25	0.48	0.50	94.0
Second Growth Biomass[b]						
Herbs[c]	18	1.91	1.54	1.00	1.02	47.5
Twigs	18	2.82	2.26	0.91	1.29	67.6
Branches	18	0.75	1.70	0.09	0.32	87.9
Trunks	18	0.63	1.61	0.02	0.11	97.0
Palms (leaves)	18	0.09	0.15	0.05	0.09	45.1
Second Growth Sub-total		6.20		2.07		66.5
Biomass of original forest remains[b]						
Twigs	18	1.29	1.49	0.82	0.90	36.1
Branches	18	3.43	4.96	2.76	3.44	19.8
Trunks	18	0.00	(d)	0	(e)	9.1
Palms (stems)	18	1.62	4.43	0.001	0.004	99.9
Original Forest Remains Sub-total		96.26		85.34		11.3
Litter	24	4.96	5.77	2.70	1.65	45.6
Ash	18	-		0.25	0.19	-
Charcoal						
Soil	24	0.32	0.51	0.51	1.14	-58.0
Biomass						
Second growth	18	0.00	0.01	0.02	0.02	-263.2

		6	5	1	7	
Original forest						
Trunks	18	2.38	(f)	2.88	(g)	-21.1
Other components[h]	18	0.36	0.59	0.16	0.21	54.1
Charcoal Sub-total		3.06		3.57		-16.7
Total		118.5		94.4		20.3

---

[a] Number of sub-plot samples per collection period.

[b] Dry weight of wood pieces not including biomass charcoal.

[c] Woody second growth and herbaceous weeds.

[d] Result of simple average of direct measurement of preburn sub-plots ("normal" = 77.78 t ha^{-1}; SD = 125.3 and "rotten" = 15.21 t ha^{-1}; SD = 20.9) with those of postburn ("normal" = 78.41 t ha^{-1}; SD = 122.7 and "rotten" = 8.44 t ha^{-1}; SD = 11.3).

[e] Result of weighted average of burning efficiency between "normal" (7.8%) and "rotten" (17.4%) determined by the volumetric method.

[f] Result of simple average of direct measurement of preburn sub-plots ("normal" = 2.8 t ha^{-1}; SD = 5.56 and "rotten" = 0.43; SD = 0.53) with those of postburn ("normal" = 1.2 t ha^{-1}; SD = 1.57 and "rotten" = 0.32 t ha^{-1}; SD = 0.46).

[g] Result obtained from weighted average of burning efficiency between "normal" (-21.6%) and "rotten" (-18.7%) determined by the volumetric method.

[h] Others = charcoal from branches, twigs and palms.

TABLE 2. Carbon Stock and Release (t ha^{-1}) in Different Biomass Fractions

Group/Fraction[a]	Preburn Carbon Stock	 % C	 n; SD
Pasture Biomass	3.42	42.4	(22; 3.1)
Second Growth Biomass			
Herbs	0.90	47.2	(18; 2.1)
Twigs	1.26	44.6	(21; 2.1)
Branches	0.33	43.6	(4; 5.5)
Trunks	0.28	45.2	(6; 4.9)
Palms (leaves)	0.04	45.7	(14; 1.3)
Second Growth sub-total	2.8	45.4	-
Biomass of Original Forest Remains			
Twigs	0.60	46.8	(16; 3.7)
Branches	1.64	47.7	(13; 4.0)
Trunks	43.26	48.1	(33; 2.7)
Palms (stems)	0.64	39.7	(8; 7.0)
Original Forest Remains sub-total	46.1	48.2	-
Litter	1.89	38.1	(24; 4.8)
Ash	-	-	-

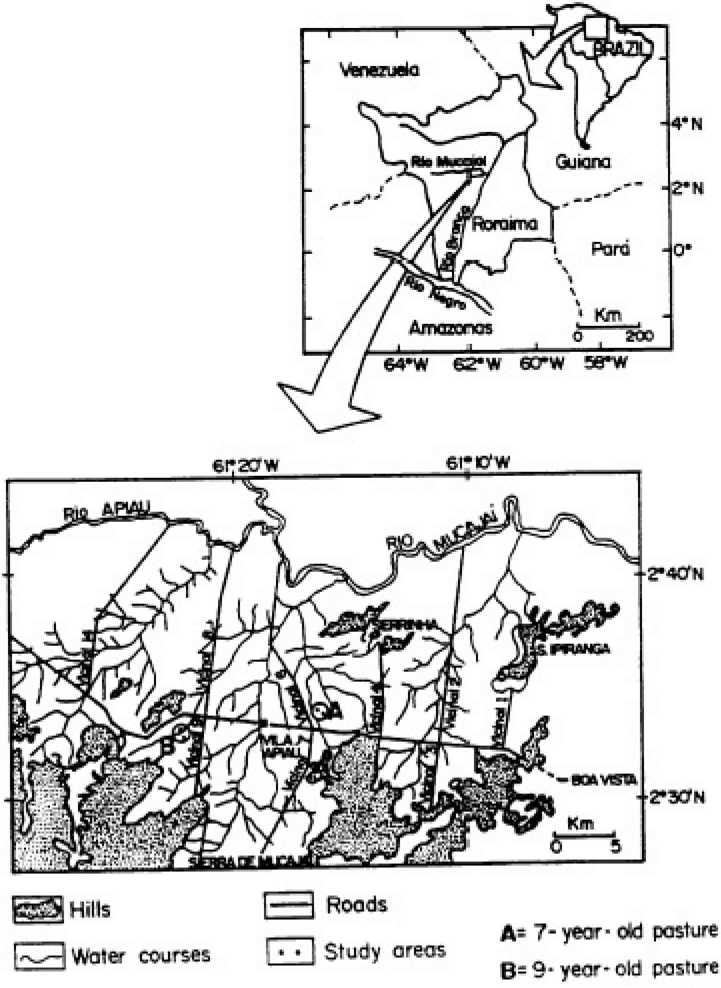
Charcoal			
Soil	0.20	63.4	(23; 6.1)
Biomass			
Second Growth	0.00	55.8	(7; 5.4)
Original Forest Remains			
Trunks	1.52	63.7	(26; 6.4)
Other components[e]	0.22	60.4	(26; 6.7)
Charcoal sub-total	1.94	64.4	-

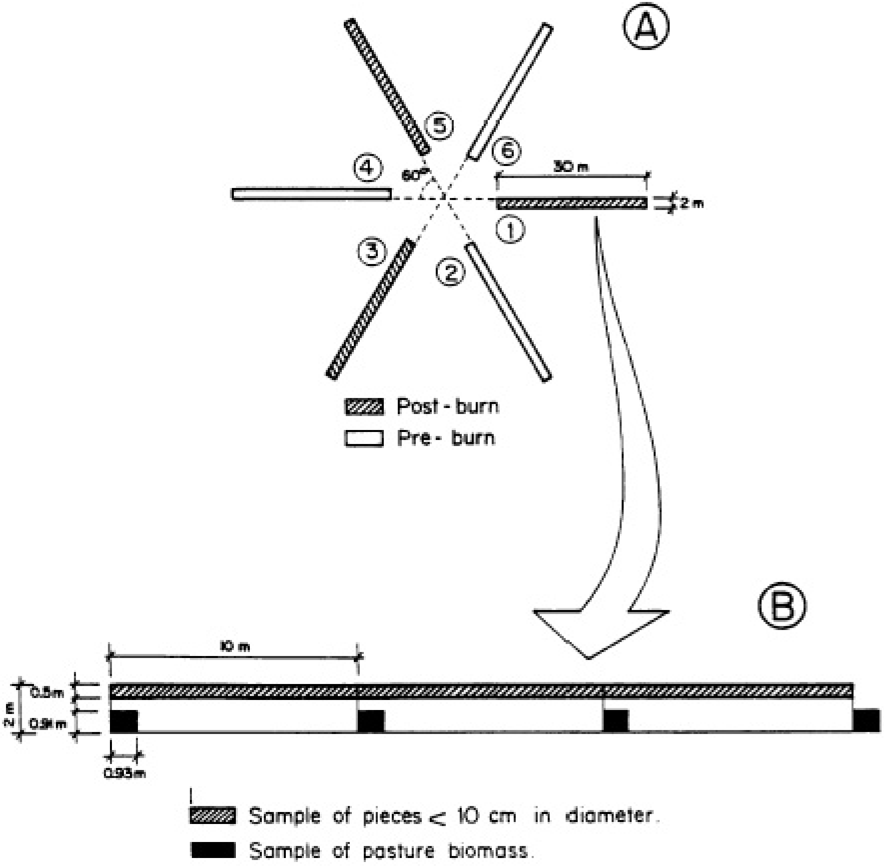
Total	56.2	47.9	-
Presumed release	-	(f)	-
---			
[a] Biomass used in the calculations is the same as Table 1.			
[b] Percent C postburn in palms remaining assumed to be equal to preburn.			
[c] Value registered as ash represents particulate matter (carbon in the form of particles deposited on the soil).			
[d] Negative numbers represent carbon stored in the system.			
[e] Other components = carbon in the charcoal of palms + twigs + branches.			
[f] Percent of total C and of C in the biomass groups represent the weighted average of the fractions.			

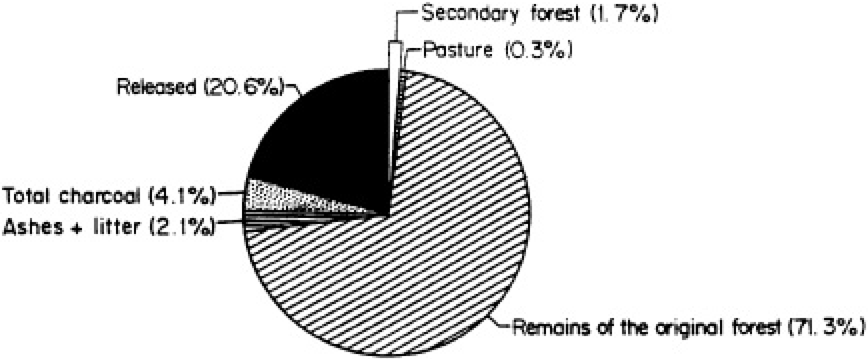
TABLE 3

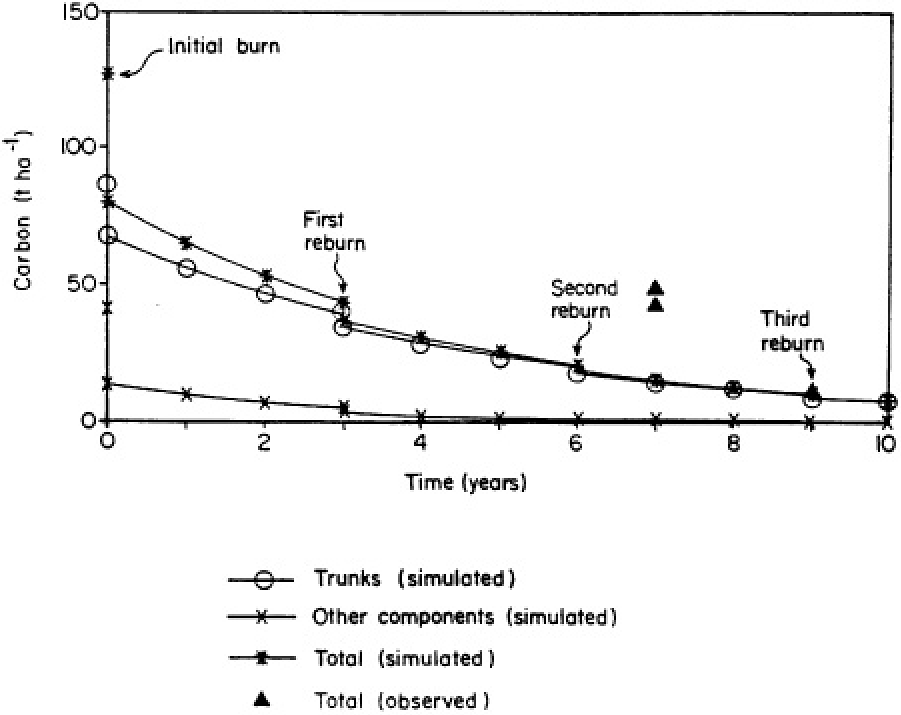
Carbon Postburn			Release of	Efficiency
--------------------			C	of Carbon
				Transformation
Stock	% C	n; SD	(t ha^{-1})	(%)
0.19	38.4	(21; 4.3)	3.23	94.6
0.45	44.7	(18; 2.9)	0.45	50.3
0.41	45.5	(14; 2.4)	0.84	67.0
0.04	47.2	(2; -)	0.28	86.9
0.01	41.3	(1; -)	0.28	97.2
0.02	43.8	(14; 2.0)	0.02	47.3
0.9	45.1	-	1.87	66.7
0.39	47.2	(18; 3.6)	0.22	35.7
1.35	49.1	(16; 3.3)	0.28	17.4
38.31	47.4	(28; 1.7)	4.94	11.4
0.0004	39.7	(8; 7.0)	0.64	99.9
	(b)			
40.1	47.2	-	6.09	13.2
1.12	41.5	(24; 7.1)	0.77	40.7
0.04	16.1	(18; 7.8)	-0.04	_
	(c)		(d)	
0.34	66.9	(22; 7.1)	-0.14	-67.1

0.01	58.0	(13; 5.0)	-0.01	-263.8
1.84	63.8	(29; 6.9)	-0.32	-21.1
0.10	61.6	(28; 5.4)	0.11	53.2
2.29	65.5	-	-0.35	-18.1
44.6	47.9	-	-	20.6
-	(b)	-	11.6	-


BRAZIL
Venezuela
Guiana
Roraima
Pará
Amazonas
Rio Mucajaí
Rio Branco
Rio Negro
4° N
2° N
0°
64°W
62°W
60°W
58°W
Km
0
200
61° 20' W
61° 10' W
2° 40' N
2° 30' N
RIO APIAU
RIO MUCAJAI
SERRINHA
S. IPIRANGA
VILA APIAU
BOA VISTA
SIERRA DE MUCAJAI
A
B
Km
0
5
Hills
Roads
Water courses
Study areas
A= 7- year- old pasture
B= 9- year- old pasture


A
⑤
⑥
④
60°
30 m
2 m
①
③
②
▨ Post - burn
▭ Pre - burn
B
10 m
0.5 m
2 m
0.91 m
0.93 m
▨ Sample of pieces < 10 cm in diameter.
■ Sample of pasture biomass.


Secondary forest (1.7%)
Pasture (0.3%)
Released (20.6%)
Total charcoal (4.1%)
Ashes + litter (2.1%)
Remains of the original forest (71.3%)


150
100
50
0
Carbon (t ha^{-1})
0
2
4
6
8
10
Time (years)
Initial burn
First reburn
Second reburn
Third reburn
Trunks (simulated)
Other components (simulated)
Total (simulated)
Total (observed)