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Biomass fire consumption and carbon release rates of rainforest-clearing experiments conducted in northern Mato Grosso, Brazil

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Abstract. Biomass consumption and carbon release rates during the process of forest clearing by fire in five test plots are presented and discussed. The experiments were conducted at the Caiabi Farm, near the town of Alta Floresta, state of Mato Grosso, Brazil, in five square plots of 1 ha each, designated A, B, C, D, and E, with different locations and timing of fire. Plot A was located in the interface with a pasture, with three edges bordering on the forest, and was cut and burned in 1997. Plots B,C, D, and E were located inside the forest. Plot B was cut and burned in 1997. Plot C was inside a deforested 9-ha area, which was cut and burned in 1998. Plot D was inside a deforested 4-ha area, which was cut in 1998 and burned in 1999. Plot E was inside a deforested 4-ha area, which was cut and burned in 1999. Biomass consumption was 22.7%, 19.5%, 47.5%, 61.5%, and 41.8%, for A, B, C, D, and E, respectively. The effects of an extended curing period and of increasing the deforested area surrounding the plots could be clearly observed. The consumption, for areas cut and burned during the same year, tended toward a value of nearly 50% when presented as a function of the total area burned. The aboveground biomass of the test site and the amount of carbon before the fire were 496 Mg ha^{-1} and 138 Mg ha^{-1}, respectively. Considering that the biomass that remains unburned keeps about the same average carbon content of fresh biomass, which is supported by the fact that the unburned material consists mainly of large logs, and considering the value of 50% for consumption, the amount of carbon released to the atmosphere as gases was 69 Mg ha^{-1}. The amounts of CO_2 and CO released to the atmosphere by the burning process were then estimated as 228 Mg ha^{-1} and 15.9 Mg ha^{-1}, respectively. Observations on fire propagation and general features of the slash burnings in the test areas complete the paper.

1. Introduction

Approximately one quarter of all tropical rainforests are located in Brazil [*Myers*, 1991]. The Brazilian Amazon Basin occupies a total area of 3,940,000 km^2, including 3,648,000 km^2 of forested land and 292,000 km^2 of nonforested land [*Braga*, 1979]. *Fearnside et al.* [1993] and *Higuchi et al.* [1994] have estimated the average stock of carbon per hectare in the aboveground biomass as 151 ± 39 Mg throughout the Amazon Basin in dense forestland.

Uncertainties in the estimates of emission rates from forest burning for land conversion are very high, mainly because of (1) uncertainties about the rate of deforestation and land area cleared by fires, (2) difficulties in determining total biomass, and (3) the purpose, and therefore the future vegetation type, of the land being deforested [*Martinelli et al.*, 1996]. Uncertainty in the amount of biomass burning in each ecosystem causes large uncertainties in the assessment of its impact on the atmospheric chemistry and on global climate change [*Hao and Liu,* 1994; *Hao et al.*, 1994; *Ferguson et al.*, 2000].

The vegetation in Brazil contains 5 times more carbon than that of Zaire, the world's second largest carbon-storing country [*Food and Agriculture Organization*, 1992]; therefore, these difficulties and uncertainties are more significant in Brazil than anywhere else in the world. Carbon dioxide emission resulting from deforestation and biomass combustion is of great concern not only in Brazil but worldwide because of its influence on global warming.

Clearing and biomass burning are part of the land conversion process that follows the colonization of the Amazon region. Every year, the land preparation process for farming in the Amazon begins in the dry season, during June and July, when the felling starts. Fires are initiated 2 or 3 months later, prior to the rainy season, after the biomass has dried out enough to sustain combustion. An increasing number of clearing fires have been observed in recent years [*Cunha*, 1989; *Martinelli et al.*, 1996].

Researchers have been working to obtain more accurate and representative data on deforestation and burning of biomass in the Brazilian Amazon [*Ward et al.*, 1992; *Fearnside et al.*, 1993; *Kauffman et al.*, 1995; *Carvalho et al.*, 1995, 1998; *Araújo et al.*, 1999; *Fearnside*, 2000]. Data of this kind for Africa, as well as the procedures adopted to determine the main burning parameters, can be found in the special issue "Southern Africa Fire-Atmosphere

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Figure 1. The Brazilian Amazon region and the location of Alta Floresta and the Arc of Deforestation.

Research Initiative (SAFARI)" (*Journal of Geophysical Research, 101*(D19), 23,521-23,863, 1996) [e.g., *Scholes et al.*, 1996a, 1996b; *Shea et al.*, 1996; *Ward et al.*, 1996].

Results of the work undertaken to estimate the biomass consumption and the carbon release rates to the atmosphere through the process of forest clearing in five test plots are presented and discussed. The forest in the 1-ha test plots and in their surrounding areas, each with different characteristics of location and timing of the fire, was cut and burned between 1997 and 1999. Experiments were carried out at the Caiabi Farm, 30 km Southwest of the town of Alta Floresta, state of Mato Grosso, Brazil.

Alta Floresta, shown in the map of Figure 1, is located in the Amazonian arc of deforestation and has experienced a very active expansion of its agricultural frontier. The region is characterized by a long and relatively well defined drought season from June to August, which facilitates the execution of field burn tests.

2. Experimental Procedure

The sequence for land clearing using fire in the Amazon follows seasonal variations. At the beginning of the dry season, farmers cut small trees whose diameter at breast height (DBH) is ≤5 cm (breast height is ~1.3 m); these are left to cure. These small trees act as fuel to sustain the fire to burn the larger trees. The next step, generally 1 month later, is to complete felling of all trees and vegetation in the area. After 2 months of exposure to sunlight drying the vegetation is sufficiently dry to sustain fire. This is the peak period of emission of gases in the region. Another step, not always necessary, is the so-called "coivara," which is the gathering and burning of the remaining unburned or partially burned logs and branches to clean the soil for planting. It is usually performed 1 month after the main fire. The biomass burned in this second step is of the order of 3% of the initial biomass in the main fire [*Araújo et al.*, 1999].

The tests were performed in five square plots of 1 ha each, designated A, B, C, D, and E, as shown in Figure 2. The following are the main characteristics of each plot: A was located in the interface with a pasture, with three sides facing directly the forest; it was cut and burned in 1997. B was located approximately 400 m inside the forest, with four sides directly bordering the forest; it was cut and burned in 1997. C was located inside a deforested 9-hectare area, which was cut and burned in 1998. D was located inside a deforested 4-hectare area, which was cut in 1998 and burned in 1999. E, was located inside a deforested 4-hectare area, which was cut and burned in 1999.

Tests in plots A and B were designed to investigate the edge effect of the interface with pastures on the consumption. The pasture adjacent to A was formed in 1994, and its original forest vegetation was felled in 1977. From 1977 to 1994 the area was a coffee plantation. The test in C was planned to investigate the effects of the border width with the adjacent forest. The tests in D and E were planned to provide differences between two curing periods in areas with reasonable border widths.

In C, D, and E, not only were the test plots burned but also the area around them. The border width here is defined as the distance from the sides of the square test plot to the uncut forest. For C the border width was of the order of 100 m (the total area felled was not a square), and for D and E it was 50 m.

Each of the test plots was divided into 10 subsample rectangle units, each measuring 10 x 100 m, to simplify the activities and the location of trunks and small sampling areas. As a first step, a forest inventory was carried out in the test areas. Tree measurements included DBH, trunk height, and canopy height. The next step was the clearing of the forest. This activity was done at the beginning of the dry season in May. Fires were lit in August.

Consumption of small size material was estimated by weighing the biomass before and after the burning in 10 square 2 x 2 m subplots identified before the fire in each test area. Small-size material was composed of leaves, small bushes and branches, litter, and lianas. The sub plots were bounded with wires for identification after the fire. Weighing was performed on site with a portable scale with a precision of 0.01 kg.

Logs and larger branches (diameter (D) > 10 cm) were considered as medium- and large-size materials. In the tests of A and B the consumption for these categories was estimated by direct

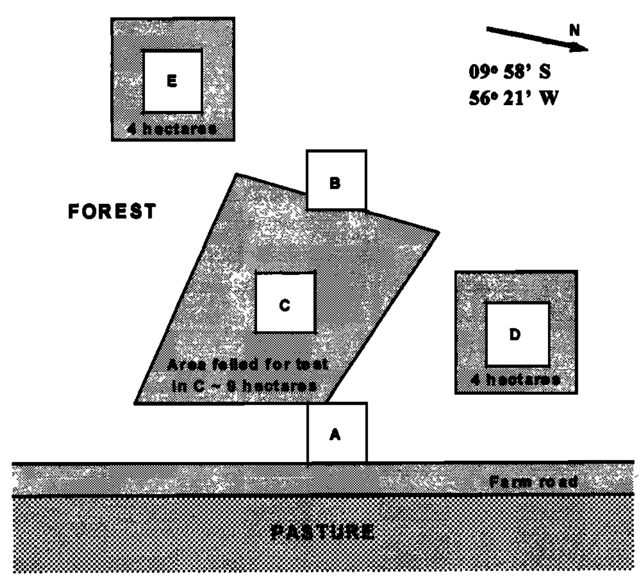

Figure 2. Location of the 100 x 100 m test plots on Caiabi farm. A and B were felled and burned in 1997, C was felled and burned in 1998, D was felled in 1998 and burned in 1999, and E was felled and burned in 1999.

Table 1. Results of Weighing Procedure With 37 Individuals[a]

	DBH, cm	D_{AVE}, cm	H, m	W_{LOG}, kg	$W_{B>10}$, kg	$W_{B<10}$, Kg	W_L, kg	W_{TOT}, kg
1	17.0	15.7	5.2	70.5	16.4	6.5	11.8	105.2
2	22.0	18.8	13.0	276.0	26.0	61.5	53.2	416.7
3	21.0	18.0	7.0	175.0	67.0	73.7	22.7	338.4
4	20.8	16.4	13.2	244.5	24.0	23.0	10.6	302.1
5	22.0	20.1	9.0	273.5	183.0	138.0	82.0	676.5
6	36.5	30.2	14.7	719.0	298.0	229.2	54.9	1301.1
7	22.1	17.5	8.3	243.0	56.0	47.8	64.2	411.0
8	29.0	27.0	6.1	356.5	373.5	51.3	44.9	826.2
9	17.0	13.5	7.4	203.0	15.0	39.3	46.6	303.9
10	16.8	13.4	12.7	182.0	0.0	26.3	20.4	228.7
11	33.0	28.0	14.8	860.5	236.0	122.4	117.9	1336.8
12	24.5	21.3	14.0	307.5	62.3	76.5	45.2	491.5
13	37.0	30.5	12.7	589.0	422.0	120.4	110.2	1241.6
14	28.0	23.5	16.5	606.0	52.0	150.3	51.1	859.4
15	19.0	15.7	10.4	197.0	62.0	9.1	29.5	297.6
16	32.0	26.8	16.3	1088.5	352.0	42.0	38.7	1521.2
17	16.8	13.9	11.4	148.5	32.0	12.0	55.1	247.6
18	20.0	18.7	8.0	180.0	73.5	24.0	29.5	307.0
19	93.0	83.5	18.1	8812.0	7662.0	190.0	305.0	16969.0
20	17.0	14.8	7.3	95.0	53.0	22.5	15.8	186.3
21	22.5	19.8	8.6	286.0	7.0	56.0	111.4	460.4
22	29.0	23.8	15.6	695.0	135.0	39.0	27.6	896.6
23	27.0	23.0	12.7	548.0	71.0	60.0	52.2	731.2
24	45.0	37.5	18.0	2413.0	835.0	307.0	241.0	3796.0
25	30.0	27.0	10.7	435.0	144.0	38.0	29.2	646.2
26	35.0	30.5	11.8	521.5	283.0	144.0	45.1	993.6
27	21.0	16.6	16.4	395.5	0.0	47.0	7.6	450.1
28	23.0	19.3	9.8	133.5	85.0	40.0	42.7	301.2
29	19.0	16.5	11.3	235.0	72.0	36.0	39.0	382.0
30	23.5	19.3	12.7	371.5	74.0	86.0	86.3	617.8
31	19.0	14.5	11.6	221.5	18.0	14.0	10.7	264.2
32	45.0	39.0	11.7	1107.0	1122.0	178.0	164.6	2571.6
33	44.0	37.0	14.3	883.0	368.0	219.0	78.5	1548.5
34	55.0	48.5	15.4	2069.0	1026.5	195.0	285.2	3575.7
35	52.0	49.5	17.0	3754.0	1593.0	289.2	110.5	5746.7
36	61.0	50.5	20.0	5034.0	1397.0	237.0	176.5	6844.5
37	71.0	53.8	25.3	6042.0	978.0	199.5	117.5	7337.0

[a] Abbreviations are as follows: DBH, diameter at breast height; D_{AVE}, log diameter at half height; H, log height; W, weight; LOG, log; B>10, branches with diameter higher than 10 cm; B<10, branches with diameter lower than 10 cm; L, leaves; TOT, total.

observations of a number of randomly selected logs, using the same procedure described by *Carvalho et al.* [1998] and *Araújo et al.* [1999]. In the tests of C, D, and E the consumption of these categories was estimated using the log-wiring procedure of *Sandberg and Ottmar* [1983]. Both procedures led to similar results.

Table 2. Summary Results of the Weighing Procedure of 37 Individual Trees

DBH class, cm	Trees	Logs, kg	Branches, D>10 cm, kg	Branches, D<10 cm, kg	Leaves, kg
10 – 20	9	1532.5	341.9	189.7	258.4
20 – 30	15	5346.5	1359.8	988.1	730.9
30 – 40	5	3778.5	1591.0	658.0	366.8
40 – 50	3	4403.0	2325.0	704.0	484.1
50 – 60	2	5823.0	2619.5	484.2	395.7
60 – 70	1	5034.0	1397.0	237.0	176.5
70 – 80	1	6042.0	978.0	199.5	117.5
> 80	1	8812.0	7662.0	190.0	305.0

Table 3. Number of Individual Trees in Each DBH Class in Plot C

DBH Class, cm	Individual Trees
10 – 20	231
20 – 30	156
30 – 40	62
40 – 50	14
50 – 60	8
60 – 70	5
70 – 80	7
> 80	5

The present method is an alternative to the line intersect method [*Brown*, 1974; *Van Wagner*, 1982]. It is especially appropriate for the rain forest vegetation, which contains a large number of species and has significant differences in biomass densities and burning characteristics.

The data for consumption and mass of carbon in each dry biomass size category present in the 1-ha plots allowed the estimation of the quantity of CO_2 released to the atmosphere by the combustion process.

The unburned fuel that will eventually end up as atmospheric CO_2 via biological processes and the amount of carbon sequestered in soil are not considered here. *Fearnside* [1992] reports that the carbon released to the atmosphere by biological decay over the years can be as high as 69% of the original aboveground biomass.

3. Biomass Distribution and Total Biomass per Hectare

In order to estimate the biomass distribution among tree biomass categories, 37 individual trees were felled in a site adjacent to the burns, and the logs, branches, and leaves were weighted. Results of this activity are presented in Table 1. Data were then grouped by DBH class, as shown in Table 2.

The mass of litter per hectare was estimated with weight measurements in three randomly chosen areas: 30.4 kg in area 1 (16 m^2), 73 kg in area 2 (25 m^2), 53.4 kg in area 3 (25 m^2). The mass of litter (M_{litter}) per unit area was then calculated:

$$M_{litter} = \frac{30.4 + 73 + 53.4}{16 + 25 + 25} \frac{kg}{m^2} = 23758 \frac{kg}{m^2}.$$

Table 3 gives the number of individual trees in each DBH class in plot C. Using the data of C, the results of Table 2 were extrapolated to yield estimates of biomass distribution per biomass category and the total weight of fresh biomass in the test field (Table 4). The biomass in the test field added up to

Table 4. Biomass Distribution as Function of Biomass Category

Biomass Category	Total Weight in 1 ha, kg	Biomass Distribution, %
Logs, 10 cm < DBH < 30 cm	94938	19.1
Logs, DBH > 30 cm	202972	40.9
Branches, D > 10 cm	116433	23.5
Branches, D < 10 cm	32190	6.5
Leaves	25927	5.2
Litter	23758	4.8
Total	496218	

Table 5. Biomass Consumption of Plots A to E

		Plot A		Plot B		Plot C		Plot D		Plot E	
Biomass category	Dist, %	η_{ind}, %	Ctb, %	η_{ind}, %	Ctb, %	η_{ind}, %	Ctb, %	η_{ind}, %	Ctb, %	η_{ind}, %	Ctb, %
Logs, 10 cm < DBH < 30 cm	19.1	13.3	2.6	10.4	2.0	51.0	9.8	72.5	13.9	42.2	8.1
Logs, DBH > 30 cm	40.9	5.3	2.2	3.1	1.3	24.7	10.1	36.2	14.8	20.5	8.4
Branches, D > 10 cm	23.5	13.3	3.1	10.4	2.4	51.0	12.0	72.5	17.0	42.2	9.9
Branches, D < 10 cm	6.5	84.0	5.4	82.6	5.4	94.8	6.1	95.5	6.2	93.6	6.1
Leaves	5.2	93.7	4.9	84.0	4.4	94.8	5.0	95.5	5.0	93.6	4.9
Litter	4.8	93.7	4.5	84.0	4.0	94.8	4.6	95.5	4.6	93.6	4.5
Total	100.0		22.7		19.5		47.5		61.5		41.8

[a] Abbreviations are as follows: Dist, mass distribution among biomass categories; η_{ind}, individual biomass consumption of biomass category; Ctb, contribution of biomass category to biomass consumption.

496 Mg ha^{-1}. Values of fresh biomass in the Amazon forest vary between 290 and 900 Mg ha^{-1} [*Klinge and Rodrigues*, 1973; *Higuchi and Carvalho*, 1994; *Brown et al.*, 1992, 1995].

4. Biomass Consumption and Carbon Release Rates to the Atmosphere

Data on the consumption for each of the biomass categories in areas A to E, determined with the procedure described in section 3, are presented in Table 5. Specific data of consumption in areas C, D, and E for the 2 x 2 m subplots and in areas D and E for the logs are presented in Tables 6 – 10.

The consumption obtained for plot A (22.7%) was 16% higher than that obtained for plot B (19.5%). This is the effect of the single free border with a pasture in plot A. As the total burned area increases, the consumption also increases. This change is drastic in the interval of total deforested area of 1 to 4 ha: The consumption for plot E (41.8%) is 84% higher in comparison with that of plot A; for plot C (47.5%) it is 14% higher in comparison with that of plot E.

A long period of curing under the Sun produced a significantly higher consumption. The result of 61.5% for plot D is the highest of all.

Combustion results for consumption of plots A and B qualitatively reproduce previous results obtained by *Araújo et al.* [1999] in Tomé Açu, state of Pará, and *Carvalho et al.* [1998] in Manaus, state of Amazonas, which also had similar test site configurations of 100 x 100 m with no felled borders with the surrounding forest. This can be seen in Table 11. Figure 3 presents the consumption, given in Table 11, as a function of the total deforested and burned area. This curve indicates the tendency to a maximum value of the order of 50% for burns occurring in the same year that the biomass is cut, which is the usual burning procedure in the Amazon region. A similar asymptotic trend in fire intensity that may be related to the amount of biomass combusted was observed by *McNaughton et al.* [1998]. They suggested that for higher intensities, combustion may be limited by oxygen starvation and thermal quenching due to air entrainment.

Using the average carbon content of dry biomass (48%) and the average moisture content of fresh biomass (42%, in terms of mass of moisture per total biomass) determined by *Carvalho et al.* [1995], and considering the determined biomass of the test site, 496 Mg ha^{-1}, the amount of carbon on the ground before the burning is calculated as 138 Mg ha^{-1}. Assuming that the biomass which remains unburned on the ground keeps the same average of 48% carbon, which is supported by the fact that the unburned material consists mainly of large logs, and considering the value of 50% for the consumption, then the amount of carbon released to the atmosphere as gases during the burn is calculated as 69 Mg ha^{-1}.

The amounts of CO_2 and CO released to the atmosphere by the burning process are estimated by assuming that, in practice, these gases account for 95 - 99% of the carbon released from the fuel [*Ward and Hardy*, 1991] and that ~ 90% of the CO_2/CO mixture is CO_2 on a volumetric basis [*Crutzen and Andreae*, 1990]. The latter

Table 6. Biomass Consumption of Fine Material in the 2 x 2 m Subareas

Plot C[a]			Plot D[b]			Plot E[c]		
Number	Before, g	After, g	Number	Before, g	After, g	Number	Before, g	After, g
540	23,200	0	391	51,540	450	375	21,380	1600
538	27,500	3500	392	35,200	850	376	22,690	1400
650	28,400	0	393	26,100	600	378	33,980	2300
542	24,600	4500	394	41,220	550	379	129,100	5500
2	25,800	1600	395	105,400	2850	380	81,300	2100
535	24,800	0	396	45,340	10,700	381	54,340	4500
534	91,300	0	397	52,680	1100	382	69,800	12,200
533	69,630	11,600	398	128,060	5250	383	138,240	6400
651	33,400	0	399	41,040	1400	386	71,260	5300
542	59,200	0	400	44,040	2200	387	53,040	2200
Total	407,830	21,200		570,620	25,950		675,130	43,500

[a] Efficiency is 94.8%.
[b] Efficiency is 95.5%.
[c] Efficiency is 93.6%.

Table 7. Biomass Consumption of Logs With 10 cm < DBH < 30 cm in Plot D[a]

Identification	Species	Orientation, deg	DBH, cm	Diameter,[b] cm Before	Diameter,[b] cm After	Height, m	Volume,[c] m³ Before	Volume,[c] m³ After	Volume,[c] m³ Burned
745	Jambo	28	26.5	20	17.1	14.9	0.2340	0.1711	0.0630
				19.3	16.5		0.2180	0.1593	0.0587
746	Not Identified	360	24.2	18.6	0	21.8	0.2962	0.0000	0.2962
				18.3	0		0.2867	0.0000	0.2867
749	Seringueira	336	27.7	22.2	0	9.0	0.1742	0.0000	0.1742
				20.3	0		0.1456	0.0000	0.1456
765	Embaúba	51	27.2	27	0	13.8	0.3951	0.0000	0.3951
				23.5	0		0.2993	0.0000	0.2993
768	Jambo	302	17.7	15.9	6.6	8.3	0.0824	0.0142	0.0682
				18	0		0.1056	0.0000	0.1056
771	Morcegueira	220	24.2	14.2	0	9.2	0.0728	0.0000	0.0728
				18.4	0		0.1223	0.0000	0.1223
772	Jambo	225	23.2	21.1	15.8	12.7	0.2220	0.1245	0.0975
				20.8	18.2		0.2158	0.1652	0.0506
773	Guatambu	296	25.9	36.7	0	10.1	0.5342	0.0000	0.5342
				41.1	0		0.6700	0.0000	0.6700
783	Inharé	151	22.7	20.5	20.5	7.3	0.1205	0.1205	0.0000
				21.2	20.6		0.1288	0.1217	0.0072
784	Morcegueira	324	30.0	23.5	23.5	10.7	0.2320	0.2320	0.0000
				28	23.4		0.3294	0.2301	0.0993
785	Canela	280	28.6	16.5	0	6.9	0.0738	0.0000	0.0738
				19.6	0		0.1041	0.0000	0.1041
789	Canela	317	23.0	21.5	19.8	10.4	0.1888	0.1601	0.0287
				19.5	16.7		0.1553	0.1139	0.0414
791	Embaúba	267	29.1	21	0	7.2	0.1247	0.0000	0.1247
				26.2	10.9		0.1941	0.0336	0.1605
792	Guatambu	161	22.8	19.6	0	8.9	0.1343	0.0000	0.1343
				20.8	0		0.1512	0.0000	0.1512
794	Laranjinha	48	24.7	19.2	0	8.3	0.1202	0.0000	0.1202
				20	0		0.1304	0.0000	0.1304
796	Laranjinha	246	28.9	24.9	0	9.8	0.2386	0.0000	0.2386
				27.2	0		0.2847	0.0000	0.2847
799	Maracatiara	282	27.2	23	22.2	8.3	0.1724	0.1606	0.0118
				24.4	22.1		0.1941	0.1592	0.0349
Total							7.1515		5.1856

[a] Efficiency of logs with 10 cm < DBH < 30 cm in plot D is 72.5% (= 5.1856/7.1515).
[b] Diameter at wire location, two wires by log, at ¼ and ¾ length.
[c] Volume corresponds to half height.

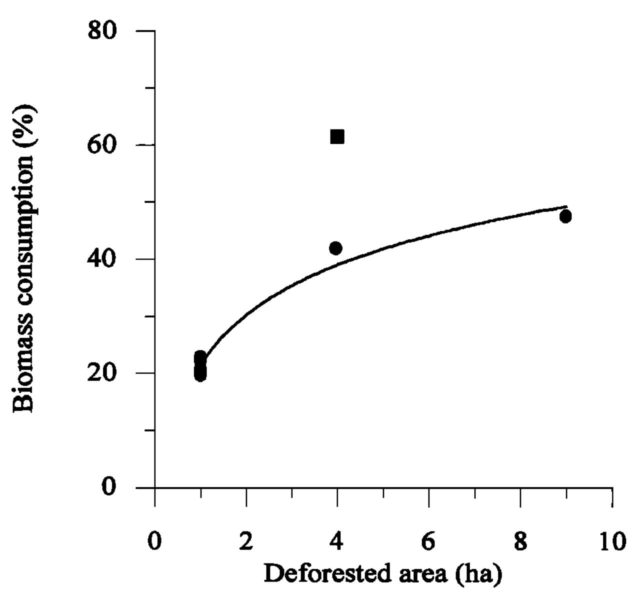

Figure 3. Biomass consumption in the central 1-ha plot as a funtion of the total deforested and burned area. The circles represent plots that were burned 3 months after they were cut; the square represents the plot that was burned 15 months after it was cut.

means that in the combustion reaction each Mg of C produces 3.30 Mg of CO_2 and 0.23 Mg of CO.

Taking 97% as the average of *Ward and Hardy*'s [1991] values and 90% CO_2 in the CO_2/CO mixture, the release rates of CO_2 and CO in the experiment were estimated to be 228 Mg ha^{-1} and 15.9 Mg ha^{-1}, respectively.

Alternative data on CO_2 and CO emission ratios could be used to estimate the release rates of these gases to the atmosphere in the Alta Floresta experiments. Those are reported by *Cofer et al.* [1990, 1998] for boreal forest fires and *Blake et al.* [1996] and *Cofer et al.* [1996] for savanna fires. Nearly 90% of the carbon gases are released in the form of CO_2 in boreal forest fires. For savanna fires this value increases to 93%. CO emissions vary depending on the conditions of the fire. *Cofer et al.* [1996] compare wetlands, savanna, and boreal forest fire CO emissions during flaming and smouldering conditions. They report the following CO/CO_2 ratios during flaming and smouldering: (1) 4.7 ± 1.1% and 5.3 ± 1.2%, respectively, for wetlands; (2) 4.8 ± 0.8% and 4.6 ± 2.0%, respectively, for savanna; (3) 6.7 ± 1.2% and 12.3 ± 1.9%, respectively, for boreal forests. The values for boreal forest fires, which are more similar to the "Terra Firme" Amazon forest than the other vegetation coverings mentioned, do not differ substantially from those indicated by *Ward and Hardy* [1991] and *Crutzen and Andreae* [1990].

Table 8. Biomass Consumption of Logs With DBH > 30 cm in Plot D[a]

				Diameter,[b] cm			Volume,[c] m^3		
Identification	Species	Orientation, deg	DBH, cm	Before	After	Height, m	Before	After	Burned
741	Ingazeiro	318	47.0	41.1	21.1	12.1	0.8027	0.2115	0.5911
				36.7	22.3	12.1	0.6400	0.2363	0.4037
742	Embaúba	97	37.2	30.7	0	10.8	0.3997	0.0000	0.3997
				33.1	0	10.8	0.4647	0.0000	0.4647
744	Leiteira	332	75.0	54.3	0	18.1	2.0957	0.0000	2.0957
				56.5	0	18.1	2.2690	0.0000	2.2690
748	Mandiocão	317	37.0	34.4	24.9	18.4	0.8551	0.4480	0.4071
				33.2	30.5	18.4	0.7964	0.6722	0.1243
763	Morcegueira	276	35.4	31.2	27	14.8	0.5658	0.4237	0.1421
				26.6	25.1	14.8	0.4112	0.3662	0.0451
764	Morcegueira	6	31.2	25.6	20.3	13.7	0.3526	0.2217	0.1309
				28.2	20.8	13.7	0.4278	0.2328	0.1951
766	Ingá branco	320	38.8	38.1	38.1	17.4	0.9919	0.9919	0.0000
				40.3	40.3	17.4	1.1097	1.1097	0.0000
767	Garapeira	292	84.0	29	21	15.8	0.5218	0.2736	0.2482
				26.5	23.4	15.8	0.4357	0.3397	0.0960
769	Ingazeiro	289	58.0	51.3	51.3	12.3	1.2712	1.2712	0.0000
				53.6	49.2	12.3	1.3877	1.1692	0.2185
770	Ingazeiro	278	53.0	51.3	51.3	13.9	1.4365	1.4365	0.0000
				52.8	49.3	13.9	1.5217	1.3267	0.1951
774	Amesca	308	30.9	20.5	14.5	5.0	0.0825	0.0413	0.0412
				24.3	20.6	5.0	0.1159	0.0833	0.0326
778	Ingazeiro	133	51.0	44.1	41.3	13.4	1.0234	0.8976	0.1258
				51.1	49.2	13.4	1.3741	1.2738	0.1003
781	Murungu	315	30.4	29.8	19.7	19.7	0.6870	0.3002	0.3868
				29.7	22.4	19.7	0.6824	0.3882	0.2942
782	Guatambu	331	32.4	25.4	0	13.2	0.3344	0.0000	0.3344
				29.5	18.8	13.2	0.4511	0.1832	0.2679
786	Ingazeiro	199	51.0	32.8	27.3	16.5	0.6971	0.4829	0.2142
				35.1	30.4	16.5	0.7983	0.5988	0.1995
787	Ingazeiro	228	43.5	25.6	20.9	19.3	0.4967	0.3311	0.1656
				27.3	22.3	19.3	0.5649	0.3769	0.1880
788	Catuaba	330	35.0	29.6	13.7	8.5	0.2925	0.0626	0.2298
				29	8.7	8.5	0.2807	0.0253	0.2555
790	Embaúba	19	43.1	31.6	0	9.7	0.3804	0.0000	0.3804
				35.6	0	9.7	0.4828	0.0000	0.4828
793	Rosinha	268	51.0	40.9	37	13.2	0.8671	0.7096	0.1575
				43.5	40.2	13.2	0.9809	0.8377	0.1432
795	Rosinha	360	70.0	64.6	57	12.1	1.9829	1.5438	0.4391
				52.2	51.5	12.1	1.2948	1.2603	0.0345
797	Guatambu	227	30.2	37.8	34.7	16.4	0.9202	0.7755	0.1447
				39.3	35.2	16.4	0.9947	0.7980	0.1967
798	Ingazeiro	300	51.0	32.7	31	18.4	0.7726	0.6944	0.0782
				35.5	31.2	18.4	0.9106	0.7034	0.2072
Total							36.2249		13.1262

[a] Efficiency of logs with DBH > 30 cm in plot D is 36.2% (= 13.1262/36.2249).
[b] Diameter at wire location, two wires by log, at ¼ and ¾ length.
[c] Volume corresponds to half height.

According to Instituto Nacional de Pesquisas Espaciais (INPE) (Monitoring of the Brazilian forest by satellite (1998 – 1999) data available from World Wide Web server for INPE at http://www.inpe.br/Informacoes-Eventos/amazonia.htm) the annual deforestation rate for the state of Mato Grosso was 6466 km^2 yr^{-1} in the period from mid 1997 to mid 1998. This represents 37.2% of the area deforestation of the entire Brazilian Amazon forest (17,383 km^2 yr^{-1}) in the same period. Therefore, assuming as an approximation that the reported deforested areas are burned in the forestland-clearing processes, Mato Grosso emission rates of C, CO_2, and CO are estimated as 44.6 x 10^6 Mg yr^{-1}, 147 x 10^6 Mg yr^{-1}, and 10.3 x 10^6 Mg yr^{-1}, respectively. These values may overestimate the emissions, since INPE's deforestation data account for all types of vegetation in the state.

Considering again 97% as the average of *Ward and Hardy*'s [1991] values, 3% of carbon is released to the atmosphere as particles. This results in an upper limit of 1.34 x 10^6 Mg yr^{-1} of particles for the state. In Alta Floresta most of the burnings occur from mid July until the end of August. Therefore concentrating the 1.34 x 10^6 Mg over a 45-day period represents 29,800 Mg d^{-1} of particles released to the atmosphere during the burning season because of deforestation in Mato Grosso.

5. Some Characteristics of the Combustion Process

Some details of fire spreading in several instances during the burn of plots D and E are presented in Figure 4. Fire was always ignited along the borders of the test areas. It is clearly observed that the fire propagated faster on the dryer area, cut in 1998, as expected. In the dryer area the main frontal flame reached 40 m, a height above that of the trees in the region.

The burning process is highly transient on a local scale, and the fire front propagates rapidly onto the dry biomass. Small-size material, such as leaves and small branches, burn completely if they are reached by fire, since radiation and convection heat transfer is larger for geometries having a larger

Table 9. Biomass Consumption of Logs With 10 cm < DBH < 30 cm in Plot E[a]

Identification	Species	Orientation, deg	DBH, cm	Diameter,[b] cm Before	After	Height, m	Volume,[c] m^3 Before	After	Burned
325	Maracatiara	38	26.6	23.4	23.4	13.0	0.2795	0.2795	0.0000
				23	13	13.0	0.2701	0.0863	0.1838
326	Inharé	269	23.0	20.2	20.2	14.8	0.2372	0.2372	0.0000
				19.9	19.9	14.8	0.2302	0.2302	0.0000
327	Not Identified	35	18.5	16.2	16.2	8.6	0.0881	0.0881	0.0000
				10.8	10.8	8.6	0.0392	0.0392	0.0000
328	Amesca	205	15.7	16.1	16.1	5.0	0.0509	0.0509	0.0000
				11.9	11.9	5.0	0.0278	0.0278	0.0000
329	Inharé	205	27.1	25.9	25.9	8.6	0.2265	0.2265	0.0000
				24.1	24.1	8.6	0.1962	0.1962	0.0000
331	Amesca	120	18.5	16.2	0	10.4	0.1072	0.0000	0.1072
				15.9	0	10.4	0.1032	0.0000	0.1032
332	Jambo	19	18.5	17.7	0	12.7	0.1562	0.0000	0.1562
				12.7	NF[d]	12.7			
334	Perna moça	226	23.7	15.9	0	11.4	0.1132	0.0000	0.1132
				19	0	11.4	0.1616	0.0000	0.1616
335	Embaúba	242	19.7	15.3	0	12.5	0.1149	0.0000	0.1149
				13.6	0	12.5	0.0908	0.0000	0.0908
337	Jambo	270	19.7	18.4	15.3	10.0	0.1330	0.0919	0.0410
					NF[d]				
340	Inharé	110	28.8	22.7	0	11.8	0.2388	0.0000	0.2388
				23.4	12.5	11.8	0.2537	0.0724	0.1813
341	Canela	312	20.4	15.4	13.5	16.7	0.1555	0.1195	0.0360
				13.7	12	16.7	0.1231	0.0944	0.0287
343	Laranjinha	280	16.1	12.5	11.5	6.8	0.0417	0.0353	0.0064
				11.6	0	6.8	0.0359	0.0000	0.0359
346	Inharé	140	23.7	16.6	11.7	6.0	0.0649	0.0323	0.0327
				17.6	0	6.0	0.0730	0.0000	0.0730
347	Amesca	154	21.0	26.2	19.7	6.9	0.1860	0.1052	0.0808
				15.4	9.3	6.9	0.0643	0.0234	0.0408
348	Inharé	167	18.4	18.1	0	9.8	0.1261	0.0000	0.1261
				17.9	0	9.8	0.1233	0.0000	0.1233
350	Inharé	208	26.7	23.5	22.4	9.8	0.2125	0.1931	0.0194
				23.2	20.5	9.8	0.2071	0.1617	0.0454
351	Itaúba	161	28.0	24.4	24.3	17.4	0.4068	0.4035	0.0033
				25.1	25	17.4	0.4305	0.4271	0.0034
354	Inharé	112	23.5	21.2	0	7.8	0.1377	0.0000	0.1377
				20.3	0	7.8	0.1262	0.0000	0.1262
355	Canela	22	28.0	20.8	20.8	15.1	0.2565	0.2565	0.0000
				19.7	19.6	15.1	0.2301	0.2278	0.0023
357	Mandiocão	348	27.7	22.1	15.2	22.8	0.4373	0.2069	0.2304
				18.1	13	22.8	0.2933	0.1513	0.1420
358	Ipê	347	26.6	26.8	0	6.7	0.1890	0.0000	0.1890
				26	0	6.7	0.1779	0.0000	0.1779
359	Peroba branca	321	28.5	20.3	18.8	19.9	0.3220	0.2762	0.0458
				19.3	15.4	19.9	0.2911	0.1853	0.1058
362	Embaúba	354	25.9	18.1	15.4	14.8	0.1904	0.1378	0.0526
				15.6	10	14.8	0.1414	0.0581	0.0833
Total							8.1620		3.4404

[a] Efficiency of logs with 10 cm < DBH < 30 cm in plot E is 42.2% (= 3.4404/8.1620).
[b] Diameter at wire location, two wires by log, at ¼ and ¾ length.
[c] Volume corresponds to half height.
[d] Not found.

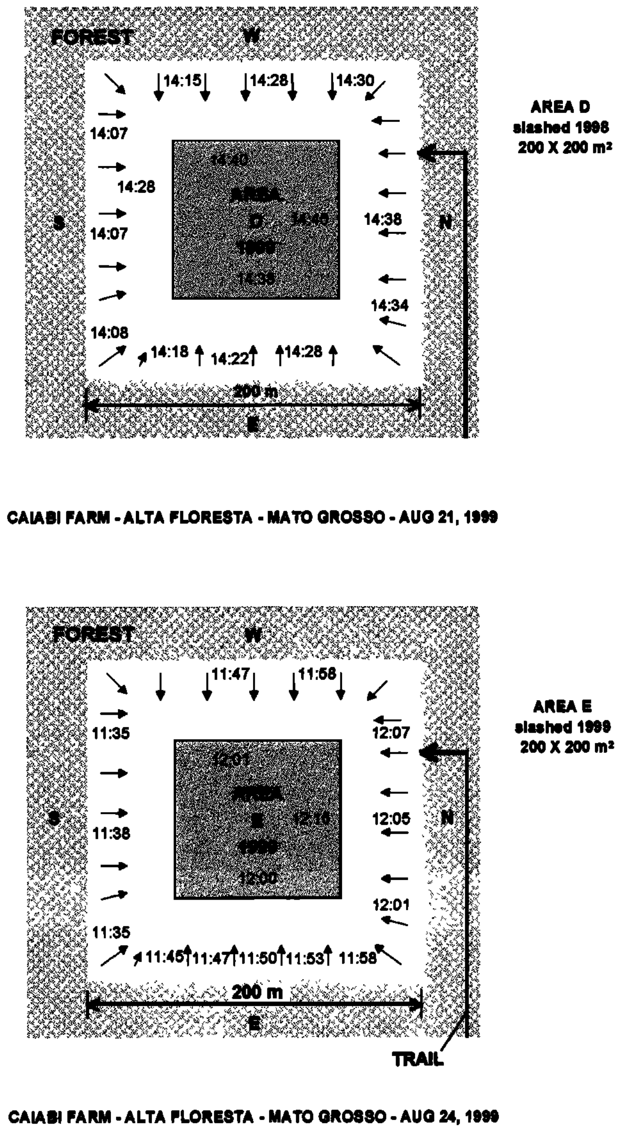

Figure 4. Depiction of fire propagation in plots D and E.

superficial area/volume ratio. We have observed that most of the logs and large branches, in general, burn only superficially in exposed surfaces and sometimes only around their whole circumference. However, some tree species and rotten material, even of large size, can burn completely.

The amount of released gases increases drastically with the pyrolysis temperature and the biomass volatile content. Especially in plots A, B, and C, there was no significant thermal degradation (volatilization/pyrolysis) of the large-size material. Despite the strong radiation from the flame front the exposition time is short, and below the superficial layer, there is no significant drying/pyrolysis or ignition and, consequently, no flame propagation. It should be pointed out that the ignition temperature can be attained many times, but after an ignition interval, there can be no stable point where heat losses are smaller than reaction heats. Flame stabilization, in the homogeneous phase (gas phase) or in the heterogeneous phase (solid-gas interface), depends strongly on the ignition and extinction aspects of the flame in the wood. This explains why many logs present only a superficial burning and have an intact core.

Smouldering is another important combustion mechanism during and after the flame front has crossed the burn site. Smouldering is characterized by combustion without flame and high emission rates of smoke due to the great quantity of unburned gases released by the thermal degradation of the biomass. These emissions are significantly related both to the safety of the fire fighters and the communities that live nearby the fires and to the local and global atmospheric chemistry. Emissions from smouldering combustion of biomass have been studied extensively in recent years [*Cofer et al.*, 1990, 1996, 1998; *Ferguson and Hardy*, 1994; *Mckenzie et al.*, 1995; *Yokelson et al.*, 1997; *Ferguson et al.*, 2000]. Emissions from smouldering combustion could be correlated to the low temperature and low heating rate of the biomass pyrolysis. However, the oxidative reaction zone through which the pyrolysis products flow, as they escape the hot substrate, may significantly alter the gas composition through processes such as tar cracking and partial oxidation of light hydrocarbons, for example. Emissions from different smouldering fires were presented by *Mckenzie et al.* [1995]. The major condensable compounds were acetic acid and methanol. The results for the noncondensable gases were mainly CO and CO_2, plus traces of ethene, methane, and ethane.

The advance of a smouldering front is a complex mechanism in which many different processes are observed. At some distance from the reacting solid surface (glowing surface) heat transfer provides energy for drying and thermal degradation of the biomass. Heat losses by convection and radiation to the surroundings are also important processes in the overall energy balance. The reactive surface needs an oxygen supply in order to be self sustaining. Therefore mass transfer plays an important role in this combustion mechanism. The heterogeneous reactions themselves are complex phenomena for which product formation is not very well quantified. To further complicate the process, gas phase reactions (homogeneous) may take place in the vicinity of the reacting surface, thus altering the composition of the gas that leaves the smoulder front, as well as consuming part of the oxygen that diffuses to the solid reaction zone. In practice, for some logs the process is not strictly heterogeneous since small flames are periodically observed near the glowing combustion of char. However, the release rate of volatiles from the virgin wood is not high enough to allow formation of a stabilized homogeneous flame near the solid surface; therefore, most of the volatiles are released directly into the atmosphere mixed with heterogeneous combustion products.

We observed that fibrous logs usually burn completely without exposing a visible glowing surface, since the solid reaction zone is covered by an ash layer in the form of fibers that are very stable. Thus oxygen must diffuse through this ash layer, lowering the speed of the propagation wave towards extinction; conversely, heat losses diminish, thus allowing the mechanism to be self sustaining. Visible glowing surfaces burning brightly occur only when blowing or continuous wind is present and for some specific types of logs, mostly those with an empty core and large diameters (~ 1 m). Besides the already mentioned presence of an ash layer it was frequently observed that the reacting front (glowing surface) propagates with an angle related to the floor as a means to reduce heat loss, thereby sustaining the propagation wave. The propagation of the reacting surface is faster near the ground than in the upper

Table 10. Biomass Consumption of Logs With DBH > 30 cm in Plot E[a]

Identification	Species	Orientation, deg	DBH, cm	Diameter,[b] cm Before	After	Height, m	Volume,[c] m^3 Before	After	Burned
324	Maracatiara	238	32.4	25.4	24	14.9	0.3775	0.3370	0.0405
				23.4	23.4	14.9	0.3204	0.3204	0.0000
330	Mandiocão	148	35.5	24.7	24	20.2	0.4840	0.4569	0.0270
				23.8	17.3	20.2	0.4493	0.2374	0.2119
333	Angelim	122	53.0	48	48	19.7	1.7824	1.7824	0.0000
				45.6	44.9	19.7	1.6086	1.5596	0.0490
336	Leiteira branca	274	34.3	29.3	28	24.0	0.5394	0.4926	0.0468
				20.3	20.3	24.0	0.2589	0.2589	0.0000
				19.3	17.7	24.0	0.2340	0.1968	0.0372
338	Guatambu	79	38.8	27.5	21	13.1	0.3890	0.2269	0.1622
				27.6	20	13.1	0.3919	0.2058	0.1861
339	Inhare	90	36.1	30.4	27	11.3	0.4101	0.3235	0.0866
				33.5	32.3	11.3	0.4980	0.4630	0.0350
342	Embaúba	46	31.5	21.8	19.3	9.8	0.1829	0.1434	0.0395
				18.4	13.4	9.8	0.1303	0.0691	0.0612
344	Ingazeiro	231	48.8	32.8	30.3	13.0	0.5492	0.4687	0.0805
				25.2	20.5	13.0	0.3242	0.2145	0.1097
345	Leiteira branca	282	44.7	30.4	25	26.7	0.9690	0.6553	0.3137
				30.7	22.4	26.7	0.9882	0.5261	0.4621
349	Maracatiara	226	34.9	29.3	25.5	14.1	0.4754	0.3600	0.1153
				26.4	22	14.1	0.3859	0.2680	0.1179
352	Guatambu	182	34.0	28.9	17.3	6.9	0.2263	0.0811	0.1452
				31.5	12.3	6.9	0.2689	0.0410	0.2279
353	Canela branca	70	32.1	26.8	24	14.1	0.3977	0.3189	0.0788
				24.8	14.7	14.1	0.3406	0.1197	0.2209
356	Cajueiro	4	43.8	37.8	36.3	20.5	1.1503	1.0608	0.0895
				31.2	29.3	20.5	0.7837	0.6911	0.0925
360	Maracatiara	38	37.2	38.2	33.4	12.5	0.7163	0.5476	0.1687
				36	WB[d]	12.5	WB[d]	WB[d]	WB[d]
361	Inharé	14	35.4	32.6	31	8.0	0.3339	0.3019	0.0320
				23.7	0	8.0	0.1765	0.0000	0.1765
363	Inharé	58	37.2	31.9	31.9	7.1	0.2845	0.2845	0.0000
				28.8	28.8	7.1	0.2319	0.2319	0.0000
Total							16.6591		3.4142

[a] Efficiency of logs with DBH > 30 cm in plot E is 20.5% (= 3.4142/16.6591).
[b] Diameter at wire location, two wires by log, at ¼ and ¾ length, except for number 336, which had three wires.
[c] Volume corresponds to half height.
[d] WB is wire broken.

Table 11. Comparison of Biomass Consumption Data of This Work in Alta Floresta With Experiments Conducted in Manaus and Tomé Açu

Experiment	η_{fine}, %	η_{5-10}, %	η_{10-30}, %	$\eta_{>30}$, %	η_{total}, %	Source
Tomé Açu, 1994, inside the forest[a]	83.4	61.0	6.3	2.3	21.9	*Araújo et al.* [1999]
Manaus, 1995, inside the forest[a]	88.5	86.8	4.39	0.43	20.5	*Carvalho et al.* [1998]
Alta Floresta, 1997, frontier with a pasture[a]	93.7	83.8	13.3	5.27	22.7	present work
Alta Floresta, 1997, inside the forest[a]	84.0	82.6	10.4	3.14	19.5	present work
Alta Floresta, 1998, borders of 100 m[a]	94.8	94.8	51.0	24.7	47.5	present work
Alta Floresta, 1999, borders of 50 m[b]	95.5	95.5	72.5	36.2	61.5	present work
Alta Floresta, 1999, borders of 50 m[a]	93.6	93.6	42.2	20.5	41.8	present work

[a]Area was felled and burned in the same year.
[b]Area was felled in 1998 and burned in 1999.

part of the log; therefore heat losses are lowered, both through convection and radiation.

It seems that the self-sustained propagation wave reaches a stable point because of the intrinsically related processes of oxygen supply, heterogeneous combustion and heat losses to the substrate as well as to the surroundings. Extinction at a log that reached this stable point was not frequently observed. Conversely, almost all the logs subjected to smouldering combustion burned completely without long periods of gas flame, except, as previously mentioned, in instances when oxygen supply was increased by wind effects and the log had an empty core throughout its length. The process can be explained as follows.

Higher oxygenation allows better penetration of the reaction zone into the porous structure. The temperature of the glowing surface is augmented with a subsequent increase in the production rate of CO. More carbon is then consumed, because of the stoichiometry, further increasing the reaction zone. The heat release then diminishes ~ 3 times, on account of the lower heat of reaction for the CO formation. As a consequence, the temperature of the reaction zone is lowered causing a shift to higher CO_2 production and smaller penetration of the reaction zone, but with nearly the same overall heat release. Therefore the shift to flaming is not sustained, and the predominant mechanism of combustion is smouldering.

Smouldering has been observed mostly in rotten wood, in decomposing material that was naturally downed, or in dead material surrounded by another specimen. There seems to be no available data in the literature about smouldering in rotten or dead wood material in the form of larger logs from tropical forests.

The effects of smouldering were observed in the recent Roraima fire [*Chambers et al.*, 1998], where low-intensity rain was enough to extinguish the main fire. Nevertheless, smouldering continued in many spots for several days.

It has also been observed that crossed logs are able to keep smouldering more frequently than isolated logs. This probably occurs because of the lower dissipation rate of heat in the crossing regions which act as flame holders, yielding better characteristics to sustain the combustion wave. The crossing surfaces burned more completely than the remaining log. Smouldering logs, however, do not contribute significantly to the overall biomass consumption.

6. Conclusion

The combustion characteristics of the biomass burning technique used in the process of forest clearing were investigated in five test plots of "Terra Firme" Amazon forest. The effects of the border widths, total clearing area sizes, and curing periods on the biomass consumption (or burned fraction) and on the amount of carbon release to the atmosphere were analyzed by measurements in 1-ha squares in the middle of the cleared areas.

Cleared areas with 1, 4, and 9 ha led to burned fractions of about 21%, 41.8% and 47.5%, respectively, for curing periods of 3 months, while a clearing area of 4 ha with a curing period of 15 months presented a burned fraction of 61.5%. Carbon release to the atmosphere was estimated as 69 Mg ha^{-1} for an estimated biomass consumption of 50%.

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