JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D11, PAGES 13,195–13,199, JUNE 20, 1998

Combustion completeness in a rainforest clearing experiment in Manaus, Brazil

João A. Carvalho Jr.
Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, Brazil

Niro Higuchi
Instituto Nacional de Pesquisas da Amazônia, Manaus, Brazil

Thaís M. Araújo and José C. Santos
Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, Brazil

Abstract. Results are described for a forest clearing experiment conducted in the forest reserve of the Tropical Silviculture Experimental Station of the National Institute for Research in the Amazon (INPA), located 60 km from Manaus, the capital of the Brazilian state of Amazonas. An area of 1 ha of virgin forest was cut in July 1995 and left to dry until October of the same year. It was burnt using a procedure similar to that followed by native people in the region to prepare the land for cultivation. The fresh biomass content in the test location, 684.8 t ha^{-1}, was determined using a formula with parameters from forest inventory. The dry biomass content was 401.5 t ha^{-1}. Combustion completeness, 20.5 %, was estimated by selecting ten 2x2 m^2 subareas, 20 trunks with diameter at breast height (DBH) between 10 and 30 cm, and 71 trunks with DBH higher than 30 cm. Their consumption rates by fire were measured. The 2x2 m^2 areas were used to determine the combustion completeness of smaller plant components (characteristic diameters lower than 10 cm) and the trunks to determine the efficiency of the medium and large components (characteristic diameters between 10 and 30 cm and larger than 30 cm, respectively). Combustion completeness for small, medium and large components were 88.2%, 4.39%, and 0.43%, respectively. On the basis of the biomass content (684.4 t ha^{-1}), the average biomass moisture and carbon contents (41.6% and 47.8%, respectively, the latter on dry basis), and the obtained combustion completeness (20.5%), the average carbon, CO_2 and CO mass rates released to the atmosphere were estimated to be 37.7, 121, and 8.6 t ha^{-1}, respectively.

1. Introduction

Around one quarter of the world's tropical forest is found in Brazil, the largest country in South America [*Myers*, 1991]. The Legal Amazon or Amazon Basin of Brazil covers an area of 4,906,784 km^2, of which approximately 4,090,000 km^2 is forested, 850,000 km^2 is cerrado or tropical savanna, and 90,000 km^2 is water [*Skole and Tucker*, 1993]. Land use practices are associated with forms of development, and the rate of deforestation continues to increase in the Brazilian Amazon region. *Fearnside* [1983] concluded that the land use trends reflect the needs of the rising human population, with consequent rapid deforestation or heavy disturbance of vast areas. The political objective of integrating the region into the Brazilian territory is connected to the region's environmental problems. Biomass burning is an integral part of the land clearing and maintenance process.

Uncertainties in the estimate of emissions due to land use are higher than uncertainties related to fossil fuel consumption mainly because of (1) difficulties in measuring regional-scale deforestation and the extent of burning, (2) variability and difficulties related to biomass fuel load estimates, and (3) the fate of deforested land [*Martinelli et al.*, 1996]. According to *Hao et al.* [1994], one of the largest uncertainties in assessing the impact of biomass burning on atmospheric chemistry and global climate is the amount of biomass burned in various ecosystems.

Such difficulties and uncertainties are intensified in Brazil, since the country has the largest stocks of carbon in vegetation (almost five times higher than Zaire's, which contains the second largest contiguous forest [*Food and Agriculture Organization*, 1992]). CO_2 emissions linked to deforestation and biomass burning are a major concern for Brazil and at the global scale.

Each year, forest clearing in the Amazon region starts with the arrival of the dry season in July. The burning is carried out approximately 2-3 months after cutting, just before the start of the rainy season, when the material has lost sufficient moisture to sustain a fire. This procedure is followed regularly by the people of the region. The area burned has increased annually [*Cunha*, 1989; *Martinelli et al.*, 1996].

Attention has therefore been given to studies involving deforestation and burning biomass in the Brazilian Amazon. Several researchers have been working to obtain more accurate and representative data [*Ward et al.*, 1992; *Fearnside*, 1993; *Araújo*,

Paper number 98JD00172.
0148-0227/98/98JD-00172$09.00

Table 1. Data From Forest Inventory

DBH Interval, cm	Number of Specimens
$5 \le DBH < 10$	584
$10 \le DBH < 20$	408
$20 \le DBH < 30$	150
$30 \le DBH < 40$	76
$40 \le DBH < 50$	29
$50 \le DBH < 60$	8
$DBH \ge 60$	6
Total	1261

DBH, diameter at breast height.

1995; *Kauffman et al.*, 1995; *Carvalho et al.*, 1995]. Data of this kind for Africa, as well as procedures adopted to determine main burn parameters, can be found in the Southern Africa Fire-Atmosphere Research Iniciative (SAFARI) special issue (*Journal of Geophysical Research 101*(D19), 23,521-23,863) [*Scholes et al.*, 1996a,b; *Shea et al.*, 1996; *Ward et al.*, 1996].

The rate of CO_2 emission to the atmosphere due to the biomass burning process is related in part to combustion completeness. The term "combustion completeness" is used here instead of combustion efficiency. Combustion efficiency identifies, for a hydrocarbon fuel, how much carbon reacts to form carbon dioxide and how much hydrogen reacts to form water. The term combustion completeness, which identifies how much biomass is converted to gas, aerosols, and particulates by the combustion process is therefore more appropriate.

The main task of this work was to estimate the combustion completeness from biomass burning and the amount of carbon released to the atmosphere due the process. The data were obtained by burning a typical patch of forest.

2. Experimental Procedure

The experiment was performed in a tropical forest reserve located approximately 60 km from Manaus, the capital of the Brazilian northern state of Amazonas. The site is at the Silviculture Experiment Station of the Brazilian National Institute for Research in the Amazon (INPA) and it is located along the Manaus - Boa Vista Highway (BR-174) at kilometer 40. The approximate geographic coordinates of the area are 60°10'W longitude and 2°37'S latitude [*Projeto RADAMBRASIL*, 1978]. Annual average rainfall is over 2000 mm. The annual average temperature is 26.7°C, with maximum and minimum temperatures of 31.2°C and 23.5°C, respectively. The vegetation is a representative sample of a humid tropical dense forest of "terra firma" (never flooded).

A square area of 1 ha was selected to conduct the experiment. It was divided into 10 sub sample units, each measuring 10 x 100 m^2, to simplify the activities and the localization of trunks and small areas.

As a first step, a forest inventory was carried out in the test area. Each specimen had its main characteristics measured (diameter at breast height (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 July. The burning of the biomass was performed in October, when the vegetation was sufficiently dry. Measurements taken before and after the fire are described in the following section.

Combustion completeness for small size material was estimated by weighing the biomass, before and after the burning, in ten 2 x 2 m^2 sub areas chosen before the fire in the test area. Small size material is composed of leaves, small bushes and branches, litter, and liana. The sub areas were bounded with wires for identification after the fire. Weighing was performed with scales which were transported inside the 1-ha area.

Trunks and larger branches (DBH > 10 cm), considered as medium and large size material, were consumed only at the surface by the fire. The combustion completeness for this category was estimated based on observations of 20 trunks with 10 cm < DBH < 30 cm, randomly selected in the area and identified before the fire, and 71 trunks with DBH > 30 cm.

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

3. Results and Discussion

A total of 1261 specimens were inventoried, of which 584 were in the range $5 \le DBH < 10$ cm, and 677 had DBH ≥ 10 cm. Table 1 presents the summary of the number of specimens by DBH intervals.

According to *Santos* [1996], for this typical forest, the allometric equation which gives the best estimates of the biomass for specimens with DBH $\ge$ 5 cm is

$$FW = \Sigma \exp [\alpha + \beta \ln (DBH)] , \qquad (1)$$

where FW is the fresh weight (corresponding to 10^3 kg), α and β are regression coefficients whose values are 3.323 and 2.546, respectively, and DBH is inserted in meters (m). Applying the equation to the data of this biomass category, the total fresh weight of the test site was found to be 606 t ha^{-1}.

In this work, fresh weights for litter, liana, and small trees (DBH < 5 cm) were assumed to be the same as those obtained in the experiment conducted by *Carvalho et al.* [1995]. In their study, the test site was also located in the Silviculture Experiment Station of INPA, with the same vegetation characteristics. The masses for those categories were determined by direct weighing and extrapolation. The values utilized for litter, liana, and small trees in this study were 68.3 t ha^{-1}, 9.4 t ha^{-1}, and 1.1 t ha^{-1}, respectively, totaling 78.8 t ha^{-1}.

Table 2. Fresh and Dry Aboveground Biomass in 1 ha

Category	m_{fresh}*, %	m_{fresh}, t ha^{-1}	H_2O*, %	m_{dry}, t ha^{-1}
Trees				
Trunks, DBH > 30 cm	47.0	321.9	38.3	198.6
Trunks, DBH < 30 cm	9.46	64.8	39.3	39.3
Branches, ϕ > 10 cm	18.5	126.7	40.0	76.0
Branches, ϕ < 10 cm	10.5	71.9	41.7	41.9
M2, H > 1 m, DBH < 5 cm	2.28	15.6	40.5	9.3
Leaves	1.40	9.6	51.9	4.6
Litter*	9.38	68.3	62.3	25.7
Liana*	1.29	9.4	40.0	5.6
M1, H < 1 m*	0.151	1.1	55.0	0.5
Total	100.0	684.8	—	401.5

Here m_{fresh} is fresh mass, m_{dry} is dry mass, M1 stands for individuals with height below 1 m, and M2 stands for individuals with height above 1 m but with DBH below 5 cm.

* *Carvalho et al.* [1995]

Table 3. Individual Combustion Completeness for Small Size Material, for Individuals With $\phi > 10$ cm and $\phi < 10$ cm, and for Fine Material

	$\phi > 10$ cm			$\phi < 10$ cm			Fine Material		
Area	m_{before}, g	m_{after}, g	η_{ind}, %	m_{before}, g	m_{after}, g	η_{ind}, %	m_{before}, g	m_{after}, g	η_{ind}, %
1	16,200	15,300	5.6	16,000	8,700	45.6	32,800	16,600	49.4
2	125,500	6,200	95.1	1,450	0	100.0	126,000	9,200	92.7
3	38,500	13,050	66.1	17,200	3,700	78.5	31,000	1,700	94.5
4	101,200	2,600	97.4	—	—	—	81,700	7,900	90.3
5	116,000	69,250	40.3	—	—	—	93,000	5,920	93.6
6	213,000	36,500	82.9	49,600	0	100.0	86,100	8,900	89.7
7	38,500	26,900	30.1	20,000	9,400	53.0	22,500	2,300	89.8
8	—	—	—	45,000	250	99.4	56,000	8,100	85.5
9	53,200	9,200	82.7	18,400	0	100.0	77,200	11,400	85.2
10	121,900	25,800	78.8	—	—	—	78,700	6,600	91.6
Total	824,000	204,800	75.1	167,650	22,050	86.8	685,000	78,620	88.5

Fine material is small branches, litter and leaves. Individual completeness is η_{ind}, diameter is ϕ, and mass before and after the fire are m_{before} and m_{after}, respectively.

Results of biomass weight per category are presented in Table 2. The percentage of fresh biomass for each category in this specific region was that established by *Carvalho et al.* [1995]. Adding 78.8 t ha^{-1} to the 606 t ha^{-1} determined with the biomass equation (1), the total fresh vegetation weight (m_{fresh}) of the test area was 684.8 t ha^{-1}. This result corresponds to 94% of the biomass content estimated by *Carvalho et al.* [1995]. Values of biomass relative to other regions in the Amazon forest vary between 290 and 900 t ha^{-1} [*Klinge and Rodrigues*, 1973; *Higuchi and Carvalho*, 1994; *Brown et al.*, 1992, 1995].

Table 4. Individual Combustion Completeness for Trunks With $10 \le$ DBH < 30 cm

Trunk	DBH, cm	L, m	V_{total}, m^3	L_{burn}, cm	t_{burn}, cm	V_{burn}, m^3	η_{ind}, %
1	20	15.0	0.47	1.10	0.50	0.0034	0.03
2	25	9.5	0.47	—	—	—	—
3	13.5	11.0	0.16	0.40	0.10	0.0002	0.00
4	21	12.0	0.42	6.00	5.25	0.1559	1.61
4	21	12.0	0.42	6.00	0.50	0.0193	0.20
5	28	12.0	0.74	6.50	0.50	0.0281	0.29
6	17	7.7	0.17	3.80	0.50	0.0098	0.10
6	17	7.7	0.17	1.95	0.25	0.0026	0.03
6	11.5	5.5	0.06	5.50	0.50	0.0095	0.10
7	15.5	4.8	0.09	3.70	0.30	0.0053	0.05
7	12.6	3.6	0.04	3.60	0.50	0.0068	0.07
8	18	10.5	0.27	1.50	0.50	0.0041	0.04
9	17	13.0	0.30	3.00	0.20	0.0032	0.03
10	27	18.0	1.03	0.20	13.50	0.0115	0.12
10	27	18.0	1.03	14.00	0.20	0.0236	0.24
11	25	12.6	0.62	5.00	0.20	0.0078	0.08
11	25	12.6	0.62	1.00	6.25	0.0368	0.38
12	16	16.0	0.32	10.00	0.30	0.0148	0.15
13	14	9.1	0.14	4.10	0.30	0.0053	0.05
14	30	13.5	0.95	13.50	0.20	0.0253	0.26
15	30	12.7	0.90	5.70	0.20	0.0107	0.11
16	28.5	14.7	0.94	14.70	0.20	0.0261	0.27
17	24	14.7	0.67	0.00	0.00	0.0000	0.00
18	12	18.1	0.20	13.00	0.30	0.0143	0.15
19	24	15.0	0.68	0.00	0.00	0.0000	0.00
20	12	6.8	0.08	2.10	0.20	0.0016	0.02
Total			9.71			0.4259	4.39

DBH is the diameter at breast height; L and V_{total} are the total length and total volume of the trunk, respectively; L_{burn}, t_{burn}, and V_{burn} are total burned length, burned thickness, and total burned volume, respectively, of the trunk, and η_{ind} is the individual completeness.

Also shown in Table 2, the total dry biomass aboveground (m_{dry}) was estimated to be 401.5 t ha^{-1}, a value calculated with the average moisture content of biomass for each plant component.

Data of specimen combustion completeness (η_{ind}) for small size material obtained by the weighing procedure of the ten 2 x 2 m^2 sub areas are summarized in Table 3. In the table, m_{before} and m_{after} stand for mass weighed before and after the fire. The respective values for specimens with diameters (ϕ) higher than 10 cm, lower than 10 cm, and fine material (small branches, litter, leaves) were found to be 75.1%, 86.8% and 88.5%. The average completeness for small size material was 81.8%. For pieces with $\phi < 10$ cm, the average completeness was 88.2%.

Initially, the completeness of 75.1% for material with $\phi > 10$ cm within the 10 square sub areas seems high (Table 3), but it is relative to the small length of the material. The branches in the 2 x 2 m^2 areas were cut into pieces of a maximum length of the order of 1 m. Biomass consumption rates in the longitudinal direction, toward the section where the trunk or branch is cut, are orders of magnitude larger than consumption in the radial direction and short pieces tend to burn much more completely.

Data on combustion completeness for the 20 trunks with DBH between 10 and 30 cm are presented in Table 4. Before the fire, the DBH and total length (L) of the trunks were measured and the total volume (V_t) determined. The total burned volume (V_{burn}) was obtained from the total length of burned trunk (L_{burn}) and the burned thickness (t_{burn}). The results show that the majority were burned only superficially. The total individual combustion completeness (η_{ind}) for trunks with $10 \le$ DBH < 30 cm was estimated at 4.39%.

After the burning process, the procedure to estimate combustion completeness was conducted for 71 trunks with DBH ≥ 30 cm. The data for this category are shown in Table 5. The overall combustion completeness for this category was 0.43%.

It was observed that trunks, which constitute the major vegetation size category, burn only slightly during the fire, and the combustion completeness depended on the size of the material, as expected. The majority of trunks burned only at the tip, where the cut was made. After the fire, three trunks continued to burn slowly, smoldering for almost 1 day. Their contribution to combustion completeness was insignificant.

From the data, the value of the total combustion completeness (η_g) was determined to be 20.5 %. Table 6 presents the individual and overall results, where η_{ind} is the individual contribution for each category, m_{dry} is the dry mass, [C] is the biomass carbon content, m_C is the carbon mass, $m_{dry(burn)}$ is the mass of dry biomass burned, and

Table 5. Individual Combustion Completeness for Trunks With DBH ≥ 30 cm

DBH, cm	Number of Individuals	V_{total}, m^3	V_{burn}, m^3	η_{ind}, %
30 to 39	35	48.37	0.26	0.53
40 to 59	22	47.03	0.32	0.69
50 to 59	09	30.76	0.06	0.18
60 to 69	03	12.89	0.02	0.15
70 to 79	02	12.39	0.00	0.00
Total	71	151.47	0.65	0.43

DBH is the diameter at breast height, V_{total} is total volume of the trunk, V_{burn} is total burned volume of the trunk, and η_{ind} is the individual completeness.

$m_{C(burn)}$ is the mass of carbon burned. Data on carbon content, shown in the table for each vegetation size category, were assumed to be the same used by *Carvalho et al.* [1995].

For comparison, the experiment conducted by *Araújo* [1995] adopted a similar procedure to calculate biomass consumption of small size material; the overall combustion completeness obtained was 21.9 %. The aboveground biomass measured by Araújo was 214.2 t ha^{-1} (i.e., 53% of that at the present test site). *Carvalho et al.* [1995] assumed that 100% of the small size material was consumed during the fire, and obtained a value of 25.1% for combustion completeness. *Fearnside* [1992] reported that the aboveground biomass carbon released to the atmosphere by the combustion process during the first burn is 28.4%. He also stated that with three reburnings, a total of 35.0% of the carbon is released by combustion. *Fearnside et al.* [1993] reported a combustion efficiency of 27.4% in a forest cleared for pasture near Manaus, for which the aboveground biomass on a dry basis averaged 265 t ha^{-1}. *Seiler and Crutzen* [1980] stated that, considering that trunks contain about 90% of the aboveground biomass, the burning efficiency is of the order of 25%.

With the determined combustion completeness, the carbon release rate to the atmosphere by the burning was 37.7 t ha^{-1}. The amounts of CO_2 and CO released to the atmosphere by the burning process could be estimated assuming that in practice these gases account for 95 to 99% of the carbon released from the fuel [*Ward and Hardy*, 1991], and that about 90% of the CO_2/CO mixture is CO_2 on a volumetric basis [*Crutzen and Andreae*, 1990].

Hao et al. [1996] reported that the CO_2 percentage varies from 85 to 95%, depending if the burning is at the initial or final phase. In terms of mass of CO_2, this represents an error of ±5.6% in relation to the value calculated using 90% of CO_2 in volumetric basis. Taking 97% as the average of Ward and Hardy's values and 90% CO_2 in the CO_2/CO mixture, the release rates of CO_2 and CO by the experiment were estimated to be 121 t ha^{-1} and 8.6 t ha^{-1}, respectively.

4. Conclusion

A forest clearing combustion experiment was conducted in the Silviculture Experiment Station of INPA, located approximately 60 km from Manaus. Aboveground biomass content in the test area was determined from forest inventory data. A careful procedure to determine consumption rates by fire of biomass in different size categories was applied, and combustion completeness, carbon, CO_2 and CO release rates were then estimated.

The main results can be summarized as follows:

1. The total fresh and dry weight of the aboveground biomass in the one hectare test site were 684.8 and 401.5 t ha^{-1}, respectively.

2. The combustion completeness of the experiment was determined to be 20.5%.

3. The average carbon, CO_2 and CO mass rates released to the atmosphere by the burning experiment were 37.7, 121, and 8.6 t ha^{-1}, respectively.

Combustion completeness is expected to depend on the relative weight of the material distributed over the several vegetation size categories, and on the aboveground biomass. This paper showed a strong decrease of combustion completeness as the material size increases. Aboveground biomass itself is also expected to vary, even more significantly than combustion completeness.

The results of this paper should be regarded as an estimate. They refer to the single burn and to the aboveground biomass related to the particular experiment conducted in Manaus. Results of this kind may vary from place to place over the Amazon region.

Table 6. Data of the Total Combustion Completeness in a 1-ha Area

Category	m_{dry}, t ha^{-1}	η_{ind}, %	[C]*, %	m_C, t ha^{-1}	$m_{dry(burn)}$, t ha^{-1}	$m_{C(burn)}$, t ha^{-1}	η_R, %
Trees							
Trunks, DBH > 30 cm	198.6	0.4	48.4	96.1	0.9	0.4	0.21
Trunks, DBH < 30 cm	39.3	4.4	48.4	19.1	1.7	0.8	0.43
Branches, ϕ > 10 cm	76.0	4.4	48.4	36.8	3.3	1.6	0.83
Branches, ϕ < 10 cm	41.9	86.9	48.4	20.3	36.4	17.6	9.07
M2, H > 1 m, DBH < 5 cm	9.3	86.9	48.4	4.5	8.1	3.9	2.01
Leaves	4.6	87.5	50.4	2.3	4.0	2.0	1.00
Litter*	25.7	87.5	39.3	10.1	22.5	8.8	5.60
Liana*	5.6	86.9	48.4	2.7	4.9	2.4	1.21
M1, H < 1 m*	0.5	87.5	46.5	0.2	0.4	0.2	0.11
Total	401.5	—	—	192.1	82.2	37.7	20.47

Here m_{dry} is dry mass, [C] is biomass carbon content, m_C is carbon mass, $m_{dry(burn)}$ is mass of dry biomass burned, $m_{C(burn)}$ is mass of carbon burned, and η_{ind} and η_R are individual and overall completeness, respectively.

**Carvalho et al.* [1995]

Acknowledgment. The authors are grateful to FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) for supporting this research through project 93/4753-8.

References

Araújo, T.M., Investigação das taxas de dióxido de carbono gerado em queimadas na região amazônica, Doctoral thesis, Faculdade de Eng. de Guaratinguetá, Univ. Estadual Paulista, Guaratinguetá, Brazil, 1995.

Brown, I.F., D.C. Nepstad, I.O. Pires, L.M. Luz, and A.S. Alechandre, Carbon storage and land-use in extractive reserves, Acre, Brazil, *Environ. Conserv.*, *19*, 307-315, 1992.

Brown, I.F., L.A. Martinelli, W.W. Thomas, M.Z. Moreira, C.A.C. Ferreira, and R.L. Victoria, Uncertainty in the biomass of Amazonian forests: An example from Rondônia, Brazil, *For. Ecol. Manage.*, *75*, 175-189, 1995.

Carvalho, J.A.Jr., J.M. Santos, J.C. Santos, M.M. Leitão, and N. Higuchi, A tropical rainforest clearing experiment by biomass burning in the Manaus region, *Atmos. Environ.*, *29*, 2301-2309, 1995.

Crutzen, P.J. and M.O. Andreae, Biomass burning in the tropics: Impact on atmospheric chemistry and biochemical cycles, *Science*, *250*, 1669-1678, 1990.

Cunha, R.P, Deforestation estimates through remote sensing: The state of the art in the Legal Amazonia, in *Proceedings of the Meeting Amazônia: Facts, Problems and Solutions*, pp. 240-273, USP/INPE, São Paulo, Brazil, 1989.

Fearnside, P.M., Land-use trends in the Brazilian Amazon region as factors in accelerating deforestation, *Environ. Conserv.*, *10*, 141-148, 1983.

Fearnside, P.M. Greenhouse gas emissions from deforestation in the Brazilian Amazon. in *Tropical Forestry and Global Climate Change: Landuse Policy, Emission and Sequestration*, edited by W. Makundi and J. Sathaye, Lawrence Berkeley Laboratory, Berkeley, California, USA, 1992.

Fearnside, P.M., N. Leal Jr., and F.M. Fernandes, Rainforest burning and the global carbon budget: Biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon, *J. Geophys. Res.*, *98*(9), 16,733-16,743, 1993.

Food and Agriculture Organization (FAO), *Forest Resources Assessment 1990: Tropical Countries*, FAO For. Pap., Rome, 1992.

Hao, W.M., M.H. Liu and D.E. Ward, Impact of deforestation on biomass burning in the tropics, paper presented at Air & Waste Management Association International Specialty Conference, Phoenix, Ariz., April 5-8, 1994.

Hao, W.M., D.E Ward, G. Olbu and S.P. Baker, Emissions of CO_2 and CO and hydrocarbons from fires in diverse African savanna ecosystems, *J. Geophys. Res.*, *101*(D19), 23,577-23,584, 1996.

Higuchi, N., and J.A. Carvalho Jr., Fitomassa e conteúdo de carbono de espécies arbóreas da Amazônia, in *Seminário Emissão x Seqüestro de CO_2: Uma Nova Oportunidade de Negócios para o Brasil*, pp. 125-153, Companhia Vale do Rio Doce, Rio de Janeiro, Brazil, 1994.

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

Klinge, H., and W.A. Rodrigues, Biomass estimation in a central Amazonian rain forest, *Acta Cient. Venez.*, *24*, 225-237, 1973.

Martinelli, L.A., A.V. Krushe, and R.L. Victoria, Changes in carbon stock associated to land-use/cover chugs and emissions of CO_2, in *Proceedings of Latin-American Workshop on Greenhouse Gas Emission of Energy Sector and Their Impacts*, pp. 90-101, COPPE/UFRJ, Rio de Janeiro, Brazil, 1996.

Myers, N., Tropical forests: Present status and future outlook, *Clim. Change*, *9*, 3-32, 1991.

Projeto RADAMBRASIL, *Folha SA.20-Z-B Novo Airão, Levantamento de Recursos Naturais, 18*, Rio de Janeiro, 1978.

Santos, J., Análise de modelos de regressão para estimar a fitomassa da floresta tropical úmida de terra-firme da Amazônia Brasileira, Doctoral thesis, Curso de Ciência Florestal, Univ. de Viçosa, MG, Brazil, 1996.

Scholes, R.J., J. Kendall, and C.O. Justice, The quantity of biomass burned in southern Africa, *J. Geophys. Res.*, *101*(D19), 23,667-23,676, 1996a.

Scholes, R.J., D.E. Ward, and C.O. Justice, Emissions of trace gases and aerosol particles due to vegetation burning in southern hemisphere Africa, *J. Geophys. Res.*, *101*(D19), 23,677-23,682, 1996b.

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

Shea, R.W., B.W. Shea, J.B Kauffman, D.E. Ward, C.I. Haskins, and M.C. Scholes, Fuel biomass and combustion factors associated with fires in savanna ecosystems of South Africa and Zambia, *J. Geophys. Res.*, *101*(D19), 23,551-23,568, 1996.

Skole, D. and C. Tucker, Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *Science*, *260*, 1905-1910, 1993.

Ward, D.E. and C.C. Hardy, Smoke emissions from wildland fires, *Environ. Int.*, *17*, 18, 1991.

Ward, D.E., R.A. Susott, J.B. Kauffman, R.E. Babbitt, D.L. Cummings, B. Dias, B.N. Holben, Y.J. Kaufman, R.A. Rasmussen, and A.W. Setzer, Smoke and fire characteristics for cerrado and deforestation burns in Brazil: Base-B experiment, *J. Geophys. Res.*, *97*(D13), 14,601-14,619, 1992.

Ward, D.E., W.M. Hao, R.A. Susott, R.E Babbitt, R.W. Shea, J.B Kauffman, and C.O. Justice, Effect of fuel composition on combustion efficiency and emission factors for African savanna ecosystems, *J. Geophys. Res.*, *101*(D19), 23,569-23,576, 1996.

T. M. Araújo, J. A. Carvalho Jr. (corresponding author), and J. C. Santos, Instituto Nacional de Pesquisas Espaciais, Rod. Presidente Dutra km 40, 12630 000, Cachoeira Paulista, São Paulo, Brazil. (e-mail: joao@yabae.cptec.inpe.br)

N. Higuchi, Instituto Nacional de Pesquisas da Amazônia, Alameda Cosme Ferreira 1756, 69083-000, Manaus, Amazonas, Brazil.

(Received July 30, 1997; revised January 9, 1998;
accepted January 13, 1998.)