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Biomass consumption and CO_2, CO and main hydrocarbon gas emissions in an Amazonian forest clearing fire

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ABSTRACT

Biomass consumption and CO_2, CO and hydrocarbon gas emissions in an Amazonian forest clearing fire are presented and discussed. The experiment was conducted in the arc of deforestation, near the city of Alta Floresta, state of Mato Grosso, Brazil. The average carbon content of dry biomass was 48% and the estimated average moisture content of fresh biomass was 42%on wet weight basis. The fresh biomass and the amount of carbon on the ground before burning were estimated as 528 t ha^{-1} and 147 t ha^{-1}, respectively. The overall biomass consumption for the experiment was estimated as 23.9%. A series of experiment in the same region resulted in average efficiency of 40% for areas of same size and 50% for larger areas. The lower efficiency obtained in the burn reported here occurred possibly due to rain before the experiment. Excess mixing ratios were measured for CO_2, CO, CH_4, C_2–C_3 aliphatic hydrocarbons, and $PM_{2.5}$. Excess mixing ratios of CH_4 and C_2-C_3 hydrocarbons were linearly correlated with those of CO. The average emission factors of CO_2, CO, CH_4, NMHC, and $PM_{2.5}$ were 1,599, 111.3, 9.2, 5.6, and 4.8 g kg^{-1} of burned dry biomass, respectively. One hectare of burned forest released about 117,000 kg of CO_2, 8100 kg of CO, 675 kg of CH_4, 407 kg of NMHC and 354 kg of $PM_{2.5}$.

1. Introduction

The concentration of atmospheric trace gases is influenced by industrial and agriculture activities, as well as by different forms of using the soil. Agriculturists use fire in the Amazon Basin for establishing and maintaining farm and grazing land (Babbitt et aI., 1996). Biomass burning is one of the most important sources of atmospheric pollution on Earth ((rutzen and Andreae, 1990; (rutzen et aI., 1979), playing an important role in the balance of several chemical species in the atmosphere. Estimates indicate that 2-5 Pg (10^{15} g) of carbon are burned annually as biomass (Reinhardt and Ward, 1995; (rutzen and Andreae, 1990). The estimated global carbon emissions from biomass burning vary from about one fifth to one third of the carbon released from fossil fuel combustion. These figures are based on estimates of 2000 Tg ($year^{-1}$ (Seiler and (rutzen, 1980) and 2290 Tg ($year^{-1}$ as reported in another work (Ito and Penner, 2004) against data from fossil fuel combustion, cement production and gas flaring (8180 Tg ($year^{-1}$), as estimated by Barker et al. (2007) for 2004.

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Biomass is burned for heating, cooking and to prepare the soil in agriculture management. Controlled vegetation burning and accidental forest fires consume millions of hectares every year. In Brazil, 1.7 million hectares of primary forests are burned per year (Andreae and Merlet, 2001).

Biomass combustion releases a complex mixture of gases and particles. Several of these compounds are toxic and/or carcinogenic (Ward et al., 1993; Ward and Hao, 1992). The $C0_2$ released by biomass combustion is equivalent to about 12% of the $C0_2$ emitted by fossil fuel use (Barker et al, 2007). The composition of the smoke is dependent on the type of fuel and on fire characteristics. These characteristics include fuel composition, moisture content and load, fire intensity, wind conditions and combustion type (flaming or smoldering) (Griffith et al., 1991). These parameters determine the combustion efficiency, which is defined as the fraction of carbon emitted as $C0_2$ in relation to the total carbon emitted as $C0_2$ plus other carbon containing gases and particulate material. In open fires, the combustion efficiency is never 100%.

The main products generated during biomass combustion are $C0_2$ and water. The highest portion of $C0_2$ is emitted during the flaming phase, while methane, CO and other hydrocarbons are mainly emitted during the smoldering phase (Lobert et al., 1991 ; Ward and Hardy, 1991). These compounds significantly affect the atmospheric biogeochemical cycles. Therefore, the quantification of such emissions is essential to predict environmental impacts.

In spite of several scientific studies in this area in the past two decades, global and regional emissions of some of the compounds still need to be investigated. The main objectives of this research were: a) quantify biomass before and after fire in a 4-ha area located in the Amazonian deforestation arc, b) determine, at ground level, the emission factor of the main gases generated during the burn.

2. Methodology

2.1. Aboveground biomass

The field experiment was carried out in 2004 in the Caiabi farm (09° 58' S and 56° 21' W), near the town of Alta Floresta, state of Mato Grosso, Brazil. Alta Floresta, shown in the map of Fig. 1, is located in the Amazonian arc of deforestation, which is the geometric configuration of the advancing frontier of civilization towards the Brazilian rainforest, from South to North, as observed in satellite images. The region is characterized by a long and relatively well defined drought season from June to the first half of September, which facilitates the execution of field burn tests, though in the experiment reported in this work there was some precipitation just before the day of the burn, as shown in Table 1.

The vegetation in a 200 x 200 m^2 area was felled during June and burned three months later, on September 5, 2004. The central hectare of the area was divided into 100 squares of 10 x 10 m^2 each. Six of these square plots were randomly selected. Fig. 2 shows a scheme of the test site.

A forest inventory was performed in the central one-hectare area prior to the felling of the vegetation. The number of plant species with a diameter at breast height (DBH) of 10 cm or larger was 552 ha^{-1}. According to Santos (1996), the allometric equation that gives the best

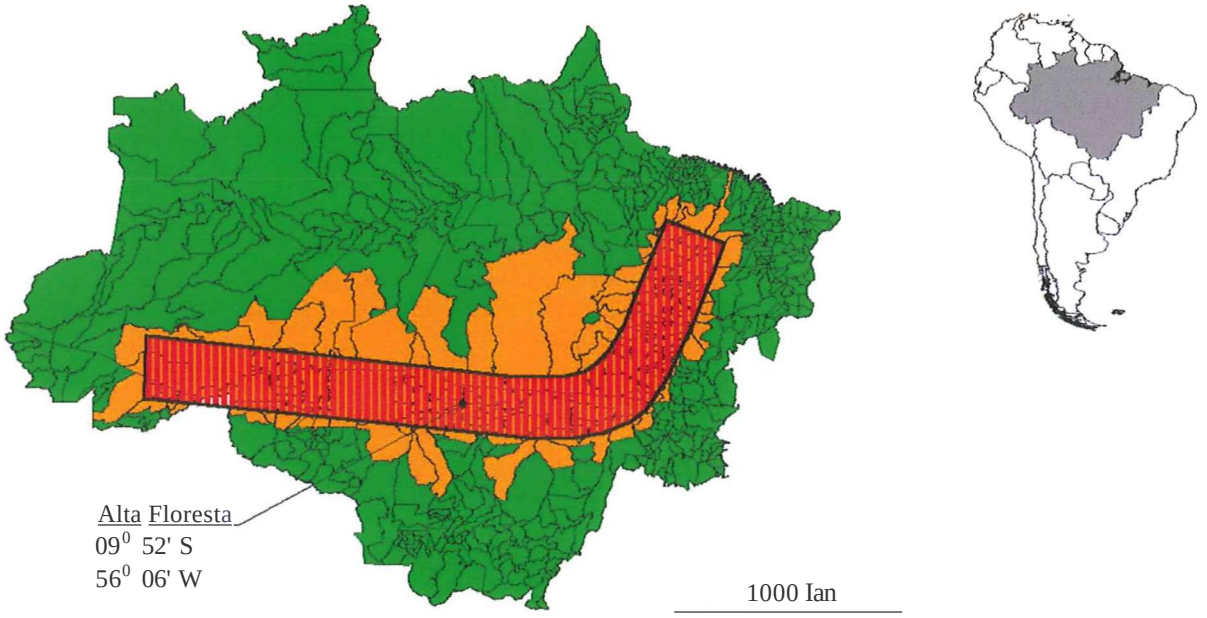

Fig. 1. The Amazonian deforestation arc and the location of Alta Floresta (Source: http//www2.ibama.gov.br/proarco/apresentacao.htm).

Table 1
Main meteorological data in the 15 days prior to the experiment.

Date	Rainfall (mm)	T_{mean} (°C)	T_{max} (°C)	Wind speed (m s)
August 22	1.02	18.2	36.0	1.7
August 23	1.52	19.0	35.0	2.1
August 24	0.51	19.9	34.0	2.7
August 25	0.25	20.3	31.6	2.1
August 26	0.51	18.6	31.7	2.3
August 27	0.25	18.4	32.9	2.1
August 28	20.32	17.9	24.2	2.2
August 29	34.29	18.7	21.4	2.8
August 30	4.32	19.0	33.3	1.8
August 31	3.81	19.7	33.9	1.9
September 1	1.02	19.6	34.9	1.8
September 2	5.33	18.8	23.8	1.7
September 3	0.25	18.8	31.5	2.2
September 4	0.00	19.8	34.1	2.0
September s[a]	0.00	19.2	33.9	2.8

[a] Day of burn.

estimation of the biomass for specimens with DBH > 10 cm for this typical forest is

$$FW = \sum \exp[3.323 + 2.546 \ln(DBH)], \quad (1)$$

where FW is the fresh weight (10^3 kg), and DBH is inserted in meters (m).

Individuals with DBH < 10 cm and litter were inventoried in the diagonally opposed 2 x 2 m^2 areas shown in Fig. 2.

2.2. Biomass consumption

Consumption of small-size material was estimated by weighing the biomass before and after the burning in 12 square 2 x 2 m^2 subplots identified before the fire in each test area (see diagonally opposed areas in Fig. 2). Small-size material was composed of leaves. small bushes and branches, litter, and lianas. The subplots 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. The consumption of these categories was estimated using the log-wiring procedure of Sandberg and Ottmar (1983).

Ignition was performed with drip-torches, from the central point of one of the sides, progressing towards the corners of the same side. The main fire took about 45 min to reach the border of the opposite side.

2.3. Sampling and analytical methods

Gas samples during the several phases of the burn were collected with a fire atmosphere sampling system (FASS) that was installed in the center of the experiment area. The FASS system collects ambient air or smokes from the top of a 15-m tower at a rate of 1.8 $Lmin^{-1}$, filters the gas through a two-Nupro stainless filtering system before entering the pump that directs it to a manifold, with four solenoid

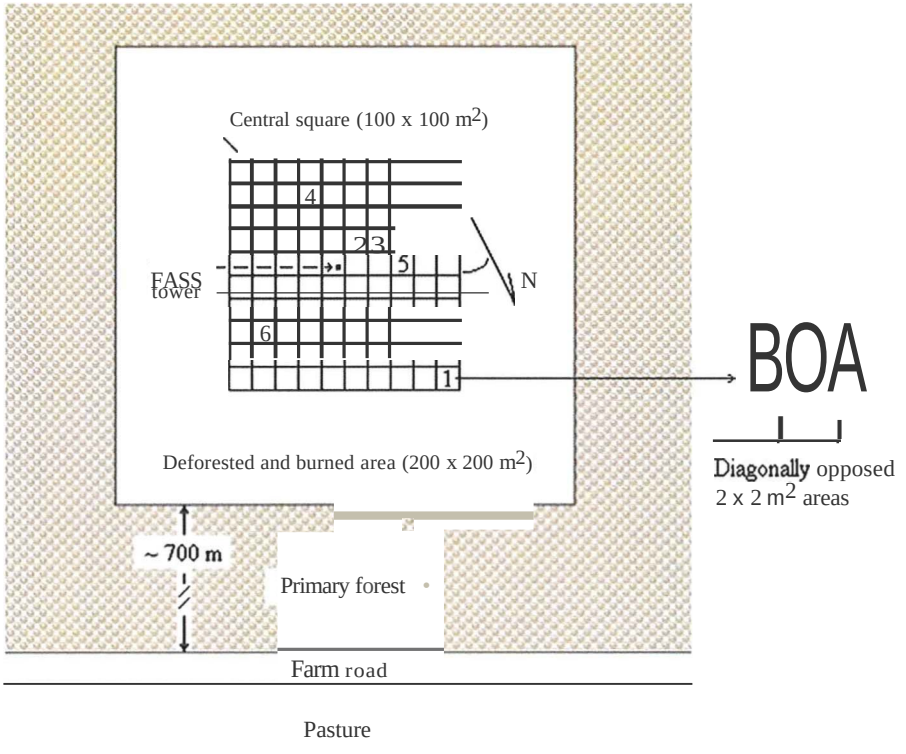

Fig. 2. Scheme of the test area with randomly selected plots.

Table 2
Biomass consumption.

Biomass category	Dist, %[a]	η_{ind}, %	Ctb, %
Logs, 10 cm < DBH < 30 cm	19.1	16.9	3.2
Logs, DBH > 30 cm	40.9	4.82	2.0
Branches, D > 10 cm	23.5	16.9	4.0
Branches, D < 10 cm	6.5	88.6	5.8
Leaves	5.2	88.6	4.6
Litter	4.8	88.6	4.3
Total			23.9

Abbreviations are as follows: Dist, mass distribution among biomass categories; Nind, individual biomass consumption of biomass category; Ctb, contribution of biomass category to biomass consumption, obtained from the product Dist x Nind. Values of Nind were calculated following the procedure outlined in Section 2.

[a] Taken from Carvalho et al. (2001).

valves, attached to each of the canisters (850 mL). The flow rate of the sample was controlled depending on the phase of the fire - 15 min for flaming, 15 min for intermediate phase and 30 min for smoldering (Hao et al., 1996). The FASS was preprogrammed to trigger at a $C0_2$ concentration of 850 ppm, and then collect three sets of data. These sets represented flaming, intermediate, and smoldering. Hewlett Packard 5890 Series II gas chromatographs were used for analyzing $C0_2$, CO, CH_4, and C_2–C_3 aliphatic compounds in canisters. The reader is referred to Hao et al. (1996) and Ward et al. (1992) for further details of the analytical methods.

Rainfall measurements were taken on a meteorological station installed in the site before the burning.

3. Results and discussion

3.1. Aboveground biomass and biomass consumption

The number of individuals in the central hectare was 552, from which 396 were in the DBH class 10-20 cm and 105 in the DBH class 20-30 cm. Therefore, there were 501 individuals, or 90.7% of the total. with DBH between 10 and 30 cm. Adding 34 individuals in the DBH class 30-40 cm (6.2% of the inventory), 97% of the individuals were in the range 10-40 cm DBH.

Applying Eq. (1) to the data of the forest inventory, the fresh weight corresponding to individuals with DBH $\geq$ 10 cm was calculated to be 410 t ha^{-1}. The fresh weight for individuals with DBH < 10 cm and litter was 118 t ha^{-1}. The total fresh biomass in the test field was estimated as 528 t ha^{-1}. For comparison, . 496 and 685 t ha^{-1} were determined in two other studies, one in the region of Alta Floresta (Carvalho et al., 2001), and the other in the region of Manaus (Carvalho et al., 1998).

The average carbon content of dry biomass and the average moisture content of fresh biomass were considered as 48 and 42%, respectively, the latter in terms of mass of moisture per total biomass reported in Carvalho et al. (1995). Taking the determined biomass of the test site, 528 t ha^{-1}, the amount of carbon in aboveground vegetation before burning was estimated as 147 t ha^{-1}. For comparison, the Amazon rainforest carbon content has been estimated as 151 ± 39 t ha^{-1} (Fearnside et al., 1993).

In the test described here there were heavy rains on two consecutive days one week before the fire. As shown in Table 1, clear weather (no precipitation) predominated from the day before the burning up to the moment fire was set. From August 22 to 27 the average rainfall was 0.68 mm. In the following two days (August 28-29) much higher precipitation levels were measured (27 mm average). There was, then, decay in rainfall for the next five days, resulting in an average of about 3 mm. Such events are not common for this time of the year in that region. The beginning of the rainy season takes place by mid September, and lasts about eight months.

Table 2 presents the biomass consumption for each of the categories. The overall biomass consumption for this experiment was 23.9%. Carvalho et al. (2001), in a series of burns conducted in the same farm, estimated a biomass consumption on the order of 40% for deforested areas equal to 4 ha, which are equivalent to the present test area. For areas larger than 4 ha, the biomass consumption was estimated as 50%. One possible reason for the differences observed in the test of this research could be the rain before the experiment. In the previous tests of Carvalho et al. (2001), there was no rain for at least 15 days before the fire.

Table 3
PM2.5, CO_2, CO and CH_4 total concentrations and CO_2, CO and CH_4 net concentrations (Test date: 09/0S/2004; FASS number: 29).

Canister number	Phase[b]	PMz.s (mg m^{-3})	Total concentrations			Net concentrations[c]		
			CO_2 (ppmv)	CO (ppmv)	CH_4 (ppmv)	CO_2 (ppmv)	CO (ppmv)	CH_4 (ppmv)
FC139	B		388	2.1	1.9			
FC247	F	5.97	841	28.4	4.4	452	26.3	2.5
FC267	I	14.32	2236	182.9	24.6	1847	180.9	22.8
FC295	S	4.48	988	88.0	15.9	599	86.0	14.0
RT[a]	B		364	1.2				
RT	F		985	34.2		621	33.0	
RT	I		2310	242.4		1946	241.2	
RT	S		922	103.9		558	102.7	

[a] RT _ Analysis conducted in real time at the FASS system, with specific analyzers.

[b] B: background; F: name, I: intermediate, S: smoldering.

[c] Net concentrations refer to the measurements during the burning (total) minus background concentrations.

Table 4
Net concentrations for C2 and C3 hydrocarbons.

Canister	Phase	Net concentrations (ppmv)						
		C_2H_4	C_2H_2	C_2H_6	C_3H_6	C_3H_8	C_3H_4	NMHC[a]
FC247	F	0.49	0.13	0.23	0.12	0.00	0.00	0.97
FC267	I	3.26	0.66	1.96	0.99	0.34	0.12	7.33
FC295	5	1.56	0.26	1.26	0.58	0.24	0.04	3.94

[a] Total hydrocarbons other than methane.

3.2. Gas and particle emissions

Table 3 presents the total and net (total minus background) concentrations relative to CO_2, CO and CH_4, obtained through chromatographic analysis of combustion products collected in canisters. PM2.5 (particulate material with diameter lower than 2.5 0101), obtained by filtering, is also included in the table. Real time concentrations of CO_2 and CO are also presented, as determined by specific analyzers installed in the FASS system. In this case, the value is an average corresponding to the specific period. The background concentrations for canister sampling and real time sampling are somewhat different, as seen in the table. The value of the R^2 between the CO_2 concentrations obtained with canister sampling and the specific analyzers (real time) was 0.9816, while for CO was 0.9967.

Table 4 presents the net concentrations of C_2 and C_3 determined by chromatographic analysis. These are the main hydrocarbons other than methane. Carbon monoxide, methane and other hydrocarbons are mainly released due to the incomplete combustion of biomass during the smoldering phase, while the majority of CO_2 is emitted during the flaming phase. The results presented in Tables 3 and 4 were analyzed to obtain correlations that would confirm such statements. A series of graphs were then prepared to show the degree of correlation between specific gases and particulate matter. The CO concentration was chosen as the independent variable. Figs. 3-5 show that there was a good correlation between the concentrations of CO and the other minority gases. Fig. 3 also

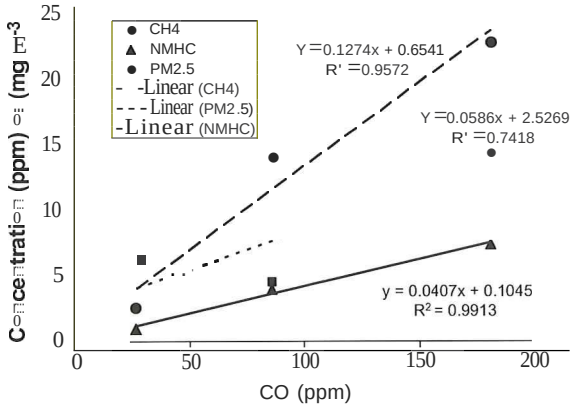

Fig. 3. Correlation between CH_4. NMHC, PM_{25} and CO concentrations obtained by chromatographic analysis of product gases collected in canisters.

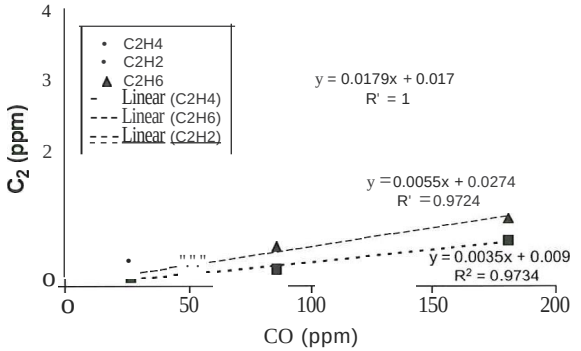

Fig. 4. Correlation between C2 species and CO concentrations obtained by chromatographic analysis of product gases collected in canisters.

presents the concentration of $PM_{2.5}$ versus the concentration of CO, as well as the correlation.

Table 5 presents the values for the emitted carbon associated with each of the analyzed gases, which were calculated from the corresponding volumetric concentrations. The gas mixture was assumed to be a perfect gas at 25 °C and 1 atm in the calculations. Eq. (2) is an instance of the calculation of the mass of carbon associated to CO_2:

$$M_{C\text{-}CO_2}\ (\text{mg m}^{-3}) = \frac{[CO_2] \times M_{CO_2} \times 10^3\,\text{mg} \times 12\,\text{g C}}{V_{CO_2} \times 10^{-3}\,\text{m}^3 \times 44\,\text{g CO}_2} = 221.4\,\text{mg m}^{-3}, \quad (2)$$

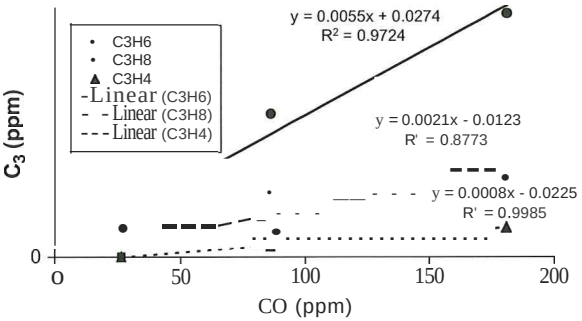

Fig. 5. Correlation between C3 species and co concentrations obtained by chromatographic analysis of product gases collected in canisters.

Table 5
Emitted carbon, associated to each of the analyzed gases.

Canisters	Phase	Total C(mg m^{-3})					
		$m_{C\text{-}CO2}$	$m_{C\text{-}CO}$	$m_{C\text{-}CH4}$	$m_{C\text{-}NMHC}$	$m_{C\text{-}PM2.5}$	$m_{C\text{-}total}$
FC247	F	221.44	12.90	1.24	1.01	3.58	240.17
FC267	I	904.77	88.59	11.15	7.89	8.59	1020.99
FC295	5	293.41	42.11	6.86	4.28	2.69	349.36
RT FA55	F	304.16	16.16				320.33
RT FA55	I	953.14	118.14				1071.28
RT FA55	5	273.31	50.30				323.61

Table 6
Emission factors (g kg I).

Canisters	Phase	Emission Factors (g kg I)[a]				
		EF CO_2	EF CO	EF CH_4	EF NMHC	EF PM2.5
FC247	F	1690	62.7	3.4	2.56	7.45
FC267	I	1625	101.2	7.3	4.72	4.21
FC295	S	1540	140.6	13.1	7.49	3.85
RT FASS	F	1741	58.9			
RT FASS	I	1631	128.7			
RT FASS	S	1548	181.3			

[a] *values* in gram of gas per kg of dryness biomass burn.

Table 7
Combustion efficiencies.

Canisters	Phase	CE[a] (ratio)	MCE[b] (ratio)
FC139	B		
FC247	F	0.922	0.945
FC267	I	0.886	0.911
FC295	S	0.840	0.874
RT FASS	F	0.949	0.950
RT FASS	I	0.889	0.890
RT FASS	S	0.844	0.845

[a] CE - Combustion efficiency.
[b] MCE - Modified combustion efficiency.

where $[CO_2]$ denotes concentration of CO_2 in ppmv (452/ 10^6), V_{CO_2} is 24.5 L for 1 mole of $C0_2$ at 25 °C and 1 atm, and M is the molecular mass of $C0_2$.

The carbon associated with the other gases was calculated in a similar manner. Thus, the values for the mass of emitted carbon were determined for the volumetric concentrations obtained both through gas chromatography and directly in real time (the latter for CO and $C0_2$ only). With the knowledge of the carbon content of each combustion product gas and of its concentration, the total carbon emitted by the fire was calculated. Particles $PM_{2.5}$ were assumed to be composed of 60% carbon, as indicated by Ward et al. (1992).

With the total carbon emitted, it was possible to calculate the mass of dry biomass that was burned. Nelson (1982) determined in laboratory that 2 g of the biomass are consumed for each gram of carbon emitted. This conversion rate has been used by others (Kaufman et al., 1992; Ward et al., 1982, 1989) in a method called CMB (carbon mass-balance) and it is used in the present article. Eq. (3) shows the example for calculation of the emitted mass of C02 associated to the mass of fuel burned, which was obtained from the total mass of carbon emitted, and considering the results of gas chromatography. The factor 2, given by the CMB method, was preferred, instead of 2.1, which represents the fuel carbon fraction of 48%, to provide values for direct comparison with others.

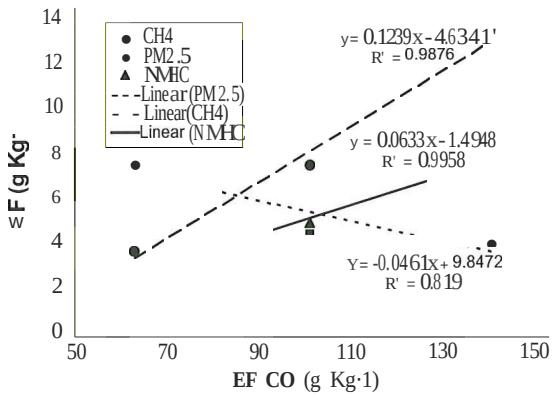

Fig. 6. Correlation between EF of CH_4, $PM_{2.5}$, NMHC and CO obtained by chromatographic analysis of product gases collected in canisters.

$$EF\ C0_2(g\,kg^{-1}) = \frac{C_1 \times 44 \times 1000}{12 \times 2 \times C} = 1690 g\ kg^{-1}, \quad (3)$$

where C_1 is the mass of carbon emitted as $C0_2$ (= 221.44 mg m^{-3}) and C is the total mass of carbon (= 240.17 mg m^{-3}) (Table 5).

Table 6 presents the emission factors calculated from the data of chromatography and those obtained in real time. Almost all of the carbon emitted was accounted for, except that in oxygenated compounds (alcohols, acids, aldehydes, etc.). This could have some small effect on emission factors.

Methane, $PM_{2.5}$, non-methane (C_2 and C_3) hydrocarbons and carbon monoxide emission factors are presented in Fig. 6. Good correlations for the data are observed. Hydrocarbons larger than C4 were not accounted. According to Ferek et al. (1998), who measured compounds higher than C_3, the estimated error of neglecting hydrocarbons larger than C_4 is less than 0.2%.

A possible explanation for the correlations for $PM_{2.5}$ and CO given in Figs. 3 and 6 is presented in the following, As the combustion efficiency increases, both concentrations of CO and $PM_{2.5}$ decrease, so the positive correlation between such concentrations is expected. On the other hand, the forest clearing fire is a fuel rich and very intense process, so higher amounts of particles are converted to gases ($C0_2$ and CO), which means that higher EF CO is expected for lower EF PM_{25}.

Table 7 presents calculated values for the combustion efficiency (CE) and the modified combustion efficiency (MCE). The combustion efficiency as defined in Ward and Hardy (1991) is the ratio of the carbon emitted as $C0_2$ to the

Table 8
Average emission factors (g kg^{-1} and t ha^{-1}).

	Average emission factors (g kg^{-1})[a]				
	EFCO_2	EFeO		EFNMHC	EFPM2.5
Canisters	1599	111.3	9.2	5.57	4.84
RT FASS	1617	137.6			
	Average emission factors (t ha^{-1})[b]				
	EFCO_2	EFCO		EFNMHC	EFPM2.5
Canisters	117.0	8.1	0.675	0.407	0.354
RT FASS	118.4	10.1			

[a] *values* in gram of gas per kg of dry biomass burned,
[b] values in t of gas per ha of burned forest.

Table 9
Comparison with data from other references.

CO_2 (gkg)	CO (gkg)	CH_4 (gkg)	NMHC(gkg)	$PM_{2.5}$ (g kg)	Type of measurement	Reference
1690	63	3.4	2.6	7.5	Ground, flaming	Present work. canisters
1625	101	7.3	4.7	4.2	Ground, intermediate	Present work. canisters
1540	141	13.1	7.5	3.9	Ground, smoldering	Present work, canisters
1741	59				Ground, flaming	Present work, real time
1631	129				Ground, intermediate	Present work, real time
1548	181				Ground, smoldering	Present work, real time
1674	70	5.3	4.3		Airborne, flaming	Ferek et al. (1998)
1524	140	8.3	10.4		Airborne, smoldering	Ferek et al. (1998)
1649	86	5.1	3.5	9.5	Airborne, average	Babbitt et al. (1996)
1671	85	5.0	2.7	3.5	Ground, flaming	Babbitt et al. (1996)
1562	140	9.8	4.4	4.2	Ground, intermediate	Babbitt et al. (1996)
1515	168	11.8	4.9	4.2	Ground, smoldering	Babbitt et al. (1996)
1666	98	4.9			Airborne, average	Kaufman et al. (1992)
1741	47	2.5		5	Airborne, average	Kaufman et al. (1992)
1586	121	7.2		16	Airborne, average	Kaufman et al. (1992)
1612	112	7.1		6.8	Ground, flaming	Ward et al. (1992)
1551	142	9.0		8.9	Ground, smoldering	Ward et al. (1992)
1531	152	10.8		6.8	Ground, smoldering	Ward et al. (1992)
1692	73	4.3		10.0	Ground, flaming	Ward et al. (1992)'
1652	91	4.8		9.2	Ground, smoldering	Ward et al. (1992)'
1637	94	4.9		10.4	Ground, flaming	Ward et al. (1992)'
1625	107	5.2		7.1	Ground, smoldering	Ward et al. (1992)'

[1] Secondary forest.

total carbon emitted (CO_2, CO, HC and $PM_{2.5}$). The modified combustion efficiency is defined as the ratio between the carbon emitted as CO_2 and the carbon emitted as CO_2 plus CO. Literature reports CE > 0.90 for flaming biomass combustion and 0.75 < CE < 0.85 for smoldering (Babbitt et al., 1996). The CE data from Table 7 are in good agreement with those.

Table 8 presents average values for the emission factor, pondered for different periods of the sampling procedure. for which the first 15 min correspond to the flaming phase, the following 15 min to the intermediate phase, and the last 30 min to the smoldering phase. The biomass average moisture content of 42% and the biomass consumption of 23.9% were used as a baseline to calculate values in t ha^{-1}. One hectare of burned forest released about 117,000 kg of CO_2, 8100 kg of CO, 675 kg of CH_4, 407 kg of NMHC and 354 kg of $PM_{2.5}$.

Table 9 presents a comparison of the emission data obtained from this investigation with others reported in the literature. EF CO_2 varies by over 200 g kg^{-1} in this set of data, which is significant. In general, EF is strongly dependent on MCE. Fig. 7 presents the variation of EF as function of MCE for CO_2, CO, and CH_4. Good correlations were found for the three compounds. This allows observations on how the burning conditions affect the emissions. MCE can be low for a number of reasons. including high moisture content and high degree of fuel packing. Opposite characteristics will lead to high MCE.

The magnitudes of methane emission obtained from forest clearing burns were compared to those for cattle enteric digestion. Brazil possesses approximately 191,300,000 animals, each producing an average of 56 kg $year^{-1}$ of methane (Nogueira, 2007). totalizing 10.71 Mt $year^{-1}$. The average deforestation rate in the Amazon region for the period 2001-2006 was 20,810 km^2 $year^{-1}$ (INPE, 2007). The annual emission rate for methane from biomass burning is, therefore. 1.40 Mt $year^{-1}$, calculated with the emission factor of 0.675 t ha^{-1} (from Table 8). This value is 13.1% of that for cattle enteric digestion.

If a biomass consumption of 50% is taken as an estimate for the situation with no rain prior the burn. as determined by Carvalho et al. (2001) for areas larger than 4 ha. the methane emission factor becomes 1.412 t ha^{-1}. It is more reasonable to use the consumption of 50% instead of that of 23.9%, because most of the burns in the region are conducted after a long period of draught. The result with a 50% consumption is 2.94 Mt $year^{-1}$ which is 27.5% of the value calculated for cattle enteric digestion.

Finally, the amount of methane was converted in an equivalent amount of carbon dioxide which was further compared to the amount of carbon dioxide produced during the burn. The contribution of methane as a greenhouse gas is 21 times that of carbon dioxide (Barker et al., 2007). From Table 8. the average emission factor for CO2 is 1608 g kg^{-1}, while for CH4 is 9.2 g kg^{-1}. Multiplying the latter by 21, the emission factor for CO_2 equivalent to the emitted CH_4 is 193.2 g kg^{-1}, which is 12.0% of the original 1608 g kg^{-1}.

The experiment of this study provided an emission rate of CO_2 of 117 t ha^{-1}, for a combustion consumption of 23.9%. Extrapolation to a consumption of 50% would result in 244 t ha^{-1} of CO2. which compares favorably with the value of 228 t ha^{-1} obtained by Carvalho et al. (2001) without the help of a FASS system. The contribution of CH4 to the CO_2 equivalent is about 12%. Therefore. the total amount of CO_2 released to the atmosphere by an Amazonian forest clearing process will be. for an average of 20,810 km^2 $year^{-1}$ of deforestation and 50% combustion consumption will be 531 Mt $year^{-1}$ (20,810 x 228 x 100 x 1.12 Mt $year^{-1}$).

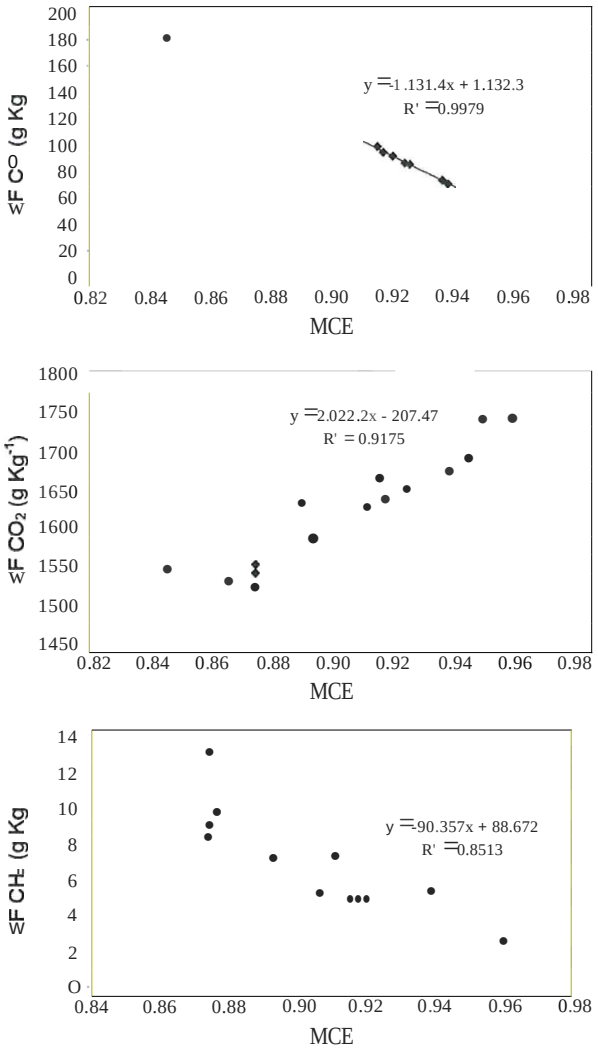

Fig. 7. Correlation *between* EF of C02. CO. CH. and MCE.

The CO_2 emission rate of 531 Mt year^{-1} for the Amazonian forest represents 1.06% of the global GHG emissions as reported by Barker et al. (2007).

4. Conclusion

The main results of the experiment can be summarized as follows:

(a) Fresh weight for individuals with DBH $\geq$ 10 cm was 410 t ha^{-1}. Fresh weight for individuals with DBH < 10 cm and litter was 118 t ha^{-1}. The aboveground biomass of the test site was 528 t ha^{-1}. The amount of carbon contained in the aboveground biomass before the burning was estimated as 147 t ha^{-1}, which is within the range determined for the Amazon rainforest, 151 ±39 t ha^{-1} (Fearnside et al., 1993).

(b) The overall biomass consumption for the test was 23.9%, a value lower than the 40% determined by Carvalho et al. (2001), in a series of burns conducted in the same farm for test areas of the same size (4 hal. The lower biomass consumption occurred because of rainfall 15 days prior to the test.

(c) Despite the lower biomass consumption, the emission factors for $C0_2$, CO, CH_4, C_2-C_3 hydrocarbons, and $PM_{2.5}$, in g kg^{-1} of burned biomass, were within the range of other emission factors reported in the literature.

(d) Using 50% as the estimate for the average biomass consumption for areas larger than 4 ha, the methane emission factor is estimated as 1.412 t ha^{-1}. With the average deforestation rate for the period 2001-2006, 20,810 km^2 year^{-1}, the methane emission from rainforest burning is 2.94 Mt year^{-1} which is 27.5% of the value calculated for cattle enteric digestion in Brazil.

(e) The emission factor for CO_2 equivalent to the emitted CH_4 from rainforest burning is 193.2 g kg^{-1}, which is 12.0% of the original 1608 g kg^{-1} for CO_2 only.

Results presented in this paper should not be regarded as definitive values. They were obtained in the particular experiment conducted in the region of Alta Floresta, in the deforestation arc. These figures may vary from place to place for different densities of vegetation and meteorological conditions prior to the burns.

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References

Andreae, M.O., Merlet, P., 2001. Emissions of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15, 955-966.

Babbitt, R.E., Ward, D.E., Susot, RA, Artaxo, P., Kauffman, j.B., 1996. A comparison of concurrent airborne and ground-based emissions generated from biomass burning in the amazon bazin. In: SCAR-B: Smoke/Sulfate, Clouds and Radiation-Brasil: Proceedings. Transtec, São José dos Campos, SP, pp. 23-26.

Barker, T., Bashmakov, I., Bernstein, L., Bogner, J.E., Bosch, P.R., Dave, R., Davidson, O.R., Fisher, B.S., Gupta, S., Halsnæs, K., Heij, G.J., Kahn Ribeiro, S., Kobayashi, S., Levine, *MD.*, Martino, D.L., Masera, 0., Metz, B., Meyer, L.A., Nabuurs, G.-J., Najam, A., Nakicenovic, N., Rogner, H.-H., Roy, J., Sathaye, J., Schock, R., Shukla, P., Sims, R.E.H., Smith, P., Tirpak, D.A., Urge-Vorsatz, D., Zhou, D., 2007. Technical Summary. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Carvalho, J.A., Costa, F.S., Veras, CAG., Sandberg, D.V., Alvarado, E.C., Gielow, R., Serra, A.M., Santos, J.E., 2001. Biomass fire consumption and carbon release rates of rainforest-clearing experiments conducted in Northern Mato Grosso, Brazil. Journal of Geophysical Research 106 (D16), 17877- 17887.

Carvalho, J.A., Higuchi, N., Araujo, T.M., Santos, J.E., 1998. Combustion completeness in a rainforest clearing experiment in Manaus, Brazil. journal of Geophysical Research 103 (D11), 13195-13200.

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

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

Crutzen, P.J., Heidt, L.E., Krasneck, J.P., Pollock, W.H., Seiler, W, 1979. Biomass burning as a source of atmospheric trace gases: CO, H_2, $N_2$0, NO, CH_3Cl and COS. Nature 282, 253-256.

Fearnside, P.M., Leal, N., Fernandes, EM., 1993. Rainforest burning and the global carbon budget: biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon. journal of Geophysical Research 98 (09), 16733-16743.

Ferek, R.j.. Reid, J.S., Hobbs, P.V., 1998. Emission factors of hydrocarbons, halocarbons, trace gases and particles from biomass burning in Brazil. journal of Geophysical Research 103 (024), 32107-32118.

Griffith, D.WT., Mankin, WG., Coffey, MT., Ward, D.E., Riebau, A., 1991. FTIR remote sensing of biomass burning emissions of C02, CO, CH4, CH_2O, NO, NO_2, NH_3, and N_2O. In: Levine, J.S. (Ed.), Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications. MIT Press, pp. 3-21.

Hao, W.M., Ward, D.E., Olbu, G., Baker, S.P.,1996. Emissions of CO_2, CO, and hydrocarbons from fires in diverse African savanna ecosystems. journal of Geophysical Research 101 (019),23577-23584,

INPE (Instituto Nacional de Pesquisas Espaciais), 2007, Taxa de desmatamento anual. Available at: http://www.obt.inpe.br/prodes/prodes_1988_2006,htm.

Ito, A., Penner, J.E.. 2004, Global estimates of biomass burning emissions based on satellite imagery for the year 2000. Journal of Geophysical Research 109 (014), 014505.

Kaufman, V.J., Setzer, A., Ward, D., Tanre, D., Holben, B.N., Menzel, P., Pereira, M.E., Rasmussen, R., 1992. Biomass burning airborne and space borne experiment in the Amazonas (BASE - A). Journal of Geophysical Research 97 (DB), 14581 - 14599.

Lobert, J.M., Scharffe, D.H., Hao, WM., Kuhlbusch, T.A., Seuwen, R., Warneck, P., Crutzen, P.J., 1991. Experimental evaluation of biomass burning emissions: nitrogen and carbon containing compounds. In: Levine, J.S. (Ed.), Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications. MIT Press, pp. 289-304.

Nelson, R.M., An Evaluation of Carbon Mass Technique for Estimating Emission Factors and Fuel Consumption in Forest Fires. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experimental Station, Asheville, Ne. Research Paper SE-231, 1982.

Nogueira, M.P., 2007. Gases de pecuaria - o outro lado da moeda. Available at: http://www.pecuaria.com.br/info.php?ver=1294.

Reinhardt, T.E., Ward, D.E.. 1995. Factors affecting methyl chloride emissions from forest biomass combustion. Environmental Science and Technology 29, 825-832.

Sandberg, D.V.. Ottmar, R.G.. Slash burning and fuel consumption in the Douglas-fir subregion. Presented at 7th Conference on Fire and Forest Meteorology, Fort Collins, Colorado. 1983.

Santos.].. 1996. Analysis of Regression Models to Estimate the Fitomass for the Brazilian Amazon "Terra Firme" Humid Tropical Forest (in Portuguese). Doctoral thesis, Federal University of Viçosa, Brazil.

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

Ward, D.E., Peterson,J.. Hao, W.M.. An inventory of particulate matter and air toxic emissions from prescribed fires in the USA for 1989. Proceedings of the 86th Annual Meeting and Exhibition of the Air and Waste Management Association, Denver, Colorado, 1993.

Ward, D.E., Susott, RA., Kauffman, J.B., Babbitt, R.E., Cumming, D.L., Dias, B., Holben, B.N., Kaufman, V.L., Rasmussen, R.A., Setzer, A.W.. 1992. Smoke and fire characteristics for cerrado and deforestation burns in Brazil: base-B experiment. journal of Geophysical Research 97 (DB), 14601-14619.

Ward, D.E., Hao, W.M., Air toxic emissions from burning of biomass globally - preliminary estimates. Proceedings of the 85th Annual Meeting and Exhibition of the Air and Waste Management Association, Kansas City, Missouri, 1992.

Ward, D.E., Hardy, CC, 1991. Smoke emissions from wildland fires. Environment International 17, 117- 134.

Ward, D.E., Hardy, Ce., Sandberg, D.V., Reinhard, T.E., Emissions characterization, in mitigation of prescribed fire atmospheric pollution through increased utilization of hard-woods, piled residues, and long-needles conifers. Compiled by D.V. Sandberg, D.E. Ward, R.D. Ottmar, et-al., final report to the Bonneville Power and U.S. Department of Energy. Under lAG DE-AI179-85BP18509 (PNW-85-423), july 15,1989.

Ward, D.E., Hardy, Ce., Ottmar, RD., Sandberg, D,V., A sampling system for measuring emissions from west coast prescribed fires, paper presented at the Pacific Northwest International Section of the Air pollution Control Association. p. 10, Vancouver, B.C. Canada, 1982.