

Emission Factors for CO₂, CO and Main Hydrocarbon Gases, and Biomass Consumption in an Amazonian Forest Clearing Fire

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ABSTRACT

Emission factors for CO₂, CO and main hydrocarbon gases, as well as biomass consumption in an Amazonian forest clearing fire are presented and discussed. The experiment was conducted in the Western Amazon region, near the city of Cruzeiro do Sul, Acre state, 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 on the ground before burning was estimated as 583 ton ha⁻¹ for larger parts of biomass with characteristic diameters larger than 10 cm. The small parts with characteristic diameters lower than 10 cm were quantified before burning on the ground and represented a value of 105 ton ha⁻¹ with 17.1% humidity. The carbon content on the ground before burning was estimated to be 191 ton ha⁻¹. The overall biomass consumption for the experiment was calculated as 22.5% and 89.2% for larger and small parts of biomass, respectively. Excess mixing ratios were measured for CO₂, CO, CH₄, C₂-C₃ aliphatic hydrocarbons, and PM_{2.5}. Excess mixing ratios of CH₄ and C₂-C₃ hydrocarbons were linearly correlated with those of CO. The average emission factors of CO₂, CO, CH₄, NMHC, and PM_{2.5} for 3 sampling hours were 1,513, 157.3, 8.17, 3.89, and 1.86 g kg⁻¹ of burned dry biomass, respectively. Thus one hectare of burned forest released about 232,115 kg of CO₂, 24,141 kg of CO, 1,254 kg of CH₄, 596 kg of NMHC and 285 kg of PM_{2.5}.

INTRODUCTION

Biomass burning is the second largest source of trace gases and the largest source of primary fine carbonaceous particles in the global troposphere. Biomass burning can be broadly defined as open or quasi-open combustion of any non-fossilized vegetative or organic fuel. Examples range from open fires in forests, savannas, crop residues, semi-fossilized peat lands, etc. to biofuel burning (e.g. cooking fires, dung burning, charcoal or brick making, etc.). Savanna fires, domestic and industrial biofuel use, tropical forest fires, extra tropical (mostly boreal) forest fires, and crop residue burning are thought to account for the most global biomass consumption (in the order given) ¹.

Biomass burning as live or dead vegetation has been common practice for decades and is a significant source of gas and particulate atmospheric pollutants. These emissions are an effective source of several greenhouse gases such as CO₂, CH₄ and N₂O, as well as other pollutants such as NO_x, CO and volatile carbon compounds ².

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 land³.

According to Ito and Penner⁴, approximately 2,290 Tg C/year are released to the atmosphere by biomass burning, while, according to Mieville et al.⁵, the average total annual emissions of carbon dioxide as a result of biomass burning are estimated to be 2,714 Tg C/year over the 1997 to 2005 period. These values can be compared to approximately 8,180 Tg C/year by fossil fuel combustion, cement production, and gas flaring. CO₂ release by biomass combustion is equivalent to about 12% of the CO₂ emitted by fossil fuel use⁶.

In Brazil, an average of 17,000 km² yr⁻¹ of primary forests is burned⁷. The average deforestation rate of the legal Amazonian region was 15,815 km² yr⁻¹ during the 2000 to 2011 period⁸.

An extensive set of field data in experiments of biomass burning on Amazon was provided by Soares Neto et al.⁹. This data will be compared with the results obtained in this experiment. 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 western Amazon region, near the city of Cruzeiro do Sul, Acre state, Brazil, b) determine, at ground level, the emission factor of the main gases generated during the burn, c) compare results with those obtained by Soares Neto et al.⁹ in experiment conducted in the arc of deforestation, near the city of Alta Floresta, state of Mato Grosso, Brazil. This research is part of a project to quantify the main emission and consumption parameters of Amazonian forest clearing fires. Most recent research within the project includes CO₂, CO and CH₄ emission in laboratory (Soares Neto et al.⁹) and in the field (Soares Neto et al.¹⁰), natural forest regeneration (d'Oliveira et al.¹¹), under-story fire propagation (Carvalho et al.¹²), mercury emission (Michelazzo et al.¹³), and particulate emission (Costa et al.¹⁴).

METHODOLOGY

Aboveground biomass

All the methodology for quantification of biomass is described in detail by Carvalho et al.¹⁵ and it will be repeated here for the purpose of clarity.

Test site

Figure 1 shows the location of the test site. Cruzeiro do Sul is on the Western part of the Brazilian state of Acre. The main road that passes in the region is interstate BR-364, which links the region to the state capital, Rio Branco, located in the Eastern part of Acre, approximately 700 km from Cruzeiro do Sul. In 2010, when the combustion test was conducted, the road was precariously paved and several rivers could be crossed only by ferry boat. For 9 months of the year, during the dry season, the trip from Rio Branco to Cruzeiro do Sul took about 24 hours using a pickup truck; during the 3 months of the rainy season, the road was completely closed.

A square area of 4 ha was selected to conduct the experiment. The entire vegetation was cut and burned in this 4-ha area, but data were considered only for the central hectare. Figure 2 shows the two areas and the exact location of their center.

Forest inventory

The first step, before the cutting of the vegetation, was the conduction of a forest inventory in the central hectare. Each specimen had its main characteristics measured (diameter at breast height (DBH), trunk height, and canopy height). The allometric equation used to estimate the biomass with DBH > 10 cm was that of Santos¹⁶:

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

in which 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 2×2 m² areas described in the next sub-section.

Forest inventory as well as biomass consumption methods followed the general basis utilized by Soares Neto et al.¹⁰, Carvalho et al.¹⁷, and Carvalho et al.¹⁸.

Biomass consumption

The next step was the clearing of the forest. This activity was done at the beginning of the dry season, in July. The burning was performed in September, when the vegetation was sufficiently dry.

Biomass consumption of small size material (DBH < 10 cm) was estimated by weighing the biomass, before and after the burning, in 12 2×2 m² sub areas disposed as shown in Figure 3. Direction A was randomly selected. Small size material is composed of leaves, small bushes and branches, litter, and liana – material with characteristic diameter smaller than 10 cm. 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.

Logs and larger branches (DBH > 10 cm) were considered as medium and large size material. The consumption for this category was estimated based on the procedure by Sandberg and Ottmar¹⁹ and by observations of a total of 81 logs, which were selected and identified before the fire, and catalogued in a GPS. Figure 4 illustrates the procedure: consumption is calculated by determining the cross section area burned by the fire, and considering the log as formed by two trunks of cone and two cylinders.

Gas sampling system

In order to collect combustion gases, a 13 m tower was employed, in which a set of probes, filters and a manifold with 4 electrovalves was installed. This set can be seen more carefully in Figure 5.

From this manifold, a 100 m PFA tube was installed to conduct the gases until the collection system within the forest and the electrical wires, both with thermal protection. All system was buried to avoid any interference from fire and temperature.

The collection system was composed of two filters, one back pressure valve, one flow controller, one vacuum and pressurization pump and rapid fastening for the bottles used to store samples in different combustion phases. This system allowed a constant sampling in every phase at a certain flow (400 mL/min) and pressure (1.5 atm), regulated simultaneously by the flow controller and the back pressure valve. All collection system was fed by a generator. The scheme for the collection system, and command table previously mounted in its field utilization can be visualized in Figures 6 and 7. Figure 8 shows a general view of the tower with the installation of gas collection and particulate system. The results for particulate measures were published by Costa et al¹⁴.

Analytical methods

A PerkinElmer (Auto System Model) gas chromatograph was employed for analyzing CO₂, CO, CH₄, and C₂–C₃ aliphatic compounds in canisters. Adopted parameters are resumed as follows: Haye Sep12 ft column; analysis time equivalent to 53 min; flow of Helium carrier gas (He) of 30 ml/min; injector temperature of 250 °C; flow of H₂ at the FID detector of 45 ml/min; flow of air at the FID detector of 450 ml/min; furnace kept at 45 °C for 25 min, heated until 120 °C at in 3 min, and kept at a final temperature of 120 °C for 25 min.

After separation of the species in the chromatography column, they were burned and detected quantitatively in a Flame Ionizing Type detector (FID) equipped with a methanizer. To quantify the interest gases contained in the collected samples, a calibration curve was constructed for each species. In order to achieve that, analyses of three standards with known concentration were done, certified by Air Liquide. The concentration of these standards in ppmv were as follows: Standard 1 - (CO₂ – 298, CO – 5.4, CH₄ – 5.9, C₂H₄ – 0.49, C₃H₆ – 0.49); Standard 2 – (CO₂ – 1000, CO – 52.8, CH₄ – 18.3, C₂H₄ – 1.6, C₃H₆ – 1.5); Standard 3 – (CO₂ – 3000, CO - 204, CH₄ – 46.9, C₂H₄ – 4.0, C₃H₆ – 3.9).

RESULTS AND DISCUSSION

Aboveground biomass

Forest inventory

The main results of the forest inventory are presented in Table 1¹⁵. The number of individuals in the central hectare was 582, and the total fresh biomass for DBH > 10 cm, calculated using equation (1), was 583 ton ha⁻¹. From the 582 individuals, 374 were in the DBH class 10-20 cm, and they add up to 13.1% of the biomass, while the two largest individuals add up to 12.2% of the biomass. If a mass median DBH is defined as the DBH that divides the biomass in two equal parts, this is 47.1 cm for the test site.

The fresh weight for individuals with DBH < 10 cm and litter was 105 ton ha⁻¹. The total fresh biomass in the test field was, then, 688 ton ha⁻¹. For comparison, Soares Neto et al.¹⁰ and Carvalho et al.¹⁷ estimated 528 and 496 ton ha⁻¹, respectively, for the biomass in the region of Alta Floresta, state of Mato Grosso, while Carvalho et al.¹⁸ estimated 685 ton ha⁻¹ for the biomass in the region of Manaus, state of Amazonas. The results indicate that the forest in Western Acre was as heavy as the one in Central Amazonas, while the one in Northern Mato Grosso is 25% lighter.

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, as reported by Carvalho et al.²⁰. Taking the determined biomass of the test site, 688 ton ha⁻¹, the amount of carbon in aboveground vegetation before burning was estimated as 191 ton ha⁻¹. For comparison, the Amazon rainforest carbon content has been estimated as 151 ± 39 t ha⁻¹ (Fearnside et al.²¹). The value of 191 ton ha⁻¹ for the site in Acre was, then, 1 ton ha⁻¹ above the maximum predicted by Fearnside et al.²¹. If the largest individual were not in the central hectare, then all the calculated values would be 7.6% lower (see Table 1 for the biomass of the largest individual).

Gas and particle emissions

Table 2 presents the total and net (total minus background) concentrations relative to CO₂, CO and CH₄, obtained through chromatographic analysis of combustion products collected in canisters. PM_{2.5} (particulate material with diameter lower than 2.5 mm), obtained by filtering, is also included in this table.

Table 3 presents the net concentrations of C₂ and C₃ 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 CO₂ is emitted during the flaming phase.

The results presented in Tables 2 and 3 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. Figures 9 show that there was a good correlation between the concentrations of CO and the other minority gases. Fig. 9 also presents the concentration of PM_{2.5} versus the concentration of CO, as well as the correlation. In this figure the correlation results obtained by Soares Neto et al.¹⁰ in Alta Floresta are also presented.

Table 4 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 CO₂:

$$C - CO_2 = \frac{[CO_2] \times M_{CO_2} \times 10^3 \text{ mg} \times 12 \text{ g C}}{V_{CO_2} \times 10^{-3} \times m^3 \times 44 \text{ g CO}_2} = 1058.89 \frac{\text{mg C}}{\text{m}^3} \quad (2)$$

where [CO₂] denotes concentration of CO₂ in ppmv (2546/10⁶), V_{CO₂} is 24.5 L for 1 mole of CO₂ at 25 °C and 1 atm, and M is the molecular mass of CO₂.

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 through gas chromatography. 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.^{22,23}. With the total carbon emitted, it was possible to calculate the mass of dry biomass that was burned. Nelson²⁴ 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.²⁵, Ward et al.^{26,27}) 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 CO₂ associated to the dry 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.

$$EF_{CO_2} = \frac{C_1 \times 44 \times 10^3}{12 \times 2 \times C} = 1702 \frac{g CO_2}{Kg} \quad (3)$$

where C_1 is the mass of carbon emitted as CO₂ (1058.89 mg m⁻³) and C is the total mass of carbon (1140.33 mg m⁻³) (Table 4).

Table 5 presents the emission factors calculated from the data of chromatography. 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. Hydrocarbons larger than C₄ were not accounted. According to Ferek et al.²⁸, who measured compounds higher than C₃, the estimated error of neglecting hydrocarbons larger than C₄ is less than 0.2%. The emission factors obtained in Alta Floresta are also presented in this table (Soares Neto et al.¹⁰). When the results obtained in Cruzeiro do Sul for emission factor values for flame, intermediate and the first step of incandescence phases are compared to those of Alta Floresta, it turns out that they are very close. Such values also agree with a table presented by Soares Neto et al.⁹ for the different combustion phases, in tropical forest fire experiments which were mainly realized in the Amazon region.

Table 6 presents calculated values for the combustion efficiency (CE) and the modified combustion efficiency (MCE). The combustion efficiency, as defined in Ward and Hardy²⁹, is the ratio of the carbon emitted as CO₂ to the total carbon emitted (CO₂, CO, HC and PM_{2.5}). The modified combustion efficiency is defined as the ratio between the carbon emitted as CO₂ and the carbon emitted as CO₂ plus CO. Literature reports CE > 0.90 for flaming biomass combustion and 0.75 < CE < 0.85 for smoldering (Babbitt et al.³⁰). The CE data from Table 8 are in good agreement with those. For comparison, results obtained in Soares Neto et al.¹⁰ are also presented.

Table 7 presents average values for the emission factor, pondered for different periods of the sampling procedure, for which the first 24 min correspond to the initial phase, the following 24 min to the flame phase, the following 24 min intermediate phase, and the last 96 min to the smoldering phase. This table also presents average emission factors for each gas per hectare burned. These values were obtained taking the following into account: the estimated carbon average for dry biomass was 48% and the humidity value was 42%. It was also estimated the quantity of mass with diameters larger than 10 cm, as being 583 t/ha. The smaller trunks with diameters smaller than 10 cm were estimated to be 105 ton/ha with an average humidity of 17.1%. The calculated rate of biomass consumption was 22.5% for larger trunks and 89.2% for fine trunks. Considering the total consumption of dry biomass, we have an average consumption of 36.11%. The average emission factors for de CO₂, CO, CH₄, NMHC, and PM_{2.5} for about 3 h of sampling was respectively 1,513, 157.3, 8.17, 3.89, and 1.86 g per kg of burned biomass.

The following average emission factors of CO₂, CO, CH₄, 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 were obtained in Alta Floresta.

It can be observed a larger value of CO₂ emission and a smaller value for CO emission due to the fact that sampling in Alta Floresta only lasted 1 h (Soares Neto et al.)¹⁰, while smoke was sampled for 3 h in Cruzeiro do Sul. Taking this fact into account, the total average consumption of 36.11% dry biomass, one hectare of burned forest in Cruzeiro do Sul released about 232,115 kg of CO₂, 24,141 kg of CO, 1,254 kg of CH₄, 596 kg of NMHC and 285 kg of PM_{2.5}.

If a biomass consumption of 50% is taken as an estimate for the situation with no rain prior to the burn, as determined by Carvalho et al.¹⁷ for areas larger than 4 ha, the emission factors becomes 321,400 kg of CO₂, 33,427 kg of CO, 1,736 kg of CH₄, 825 kg of NMHC and 395 kg of PM_{2.5}. It is more reasonable to use the consumption of 50%, instead of that of 36.11%, because most of the burns in the region are conducted after a long period of draught. 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.⁶). From Table 7, the average emission factor for CO₂ is 1513 g kg⁻¹, while for CH₄ is 8.17 g kg⁻¹. Multiplying the latter by 21, the emission factor for CO₂ equivalent to the emitted CH₄ is 171.57 g kg⁻¹, which is 11.3 0% of the original 1513 g kg⁻¹. The contribution of CH₄ to the CO₂ equivalent is about 11.33%. Therefore, the total amount of CO₂ equivalent released to the atmosphere by an Amazonian forest clearing process will be, for an average of 15,815 km² year⁻¹ of deforestation (period 2000-2011) and 50% combustion consumption will be 567 Mt year⁻¹ (15,815 x 321,4 x 100 x 1.1133 Mt year⁻¹). The CO₂ emission rate of 567 Mt year⁻¹ for the Amazonian forest represents 1.13% of the global GHG emissions as reported by Barker et al.⁶.

CONCLUSION

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

(a) Fresh weight for individuals with DBH \geq 10 cm was 583 t ha⁻¹. Fresh weight for individuals with DBH < 10 cm and litter was 105 t ha⁻¹. The aboveground biomass of the test site was 688 t ha⁻¹.

(b) The results of the forest inventory indicate that the forest in Western Acre was as heavy as the one in Central Amazonas, while the one in Northern Mato Grosso is 25% lighter.

(c) The overall biomass consumption for the test was 36.11%, which is near the value of 40% determined by Carvalho et al.¹⁷, in a series of burns conducted in the same farm for test areas of the same size (4 ha).

(c) The emission factors for CO₂, CO, CH₄, C₂–C₃ 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, 1 ha burned release to atmosphere about 321,400 kg of CO₂, 33,427 kg of CO, 1,736 kg of CH₄, 825 kg of NMHC and 395 kg of PM_{2.5}. Transforming this emission in CO₂ equivalent and extrapolating for the average rate of annual deforestation of 15,815 km² yr⁻¹ during the 2000 to 2011 period⁸, the CO₂ equivalent emission rate of 567 Mt year⁻¹ for the Amazonian forest represents 1.13% of the global GHG emissions as reported by Barker et al.⁶.

Results presented in this paper should not be regarded as definitive values. They were obtained in the particular experiment conducted in the region near the city of Cruzeiro do Sul, Acre state, Brazil. These figures may vary from place to place for different densities of vegetation and meteorological conditions prior to the burns.

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KEY WORDS

Biomass consumption; Gas emission; emission factors; Amazonian forest fires.

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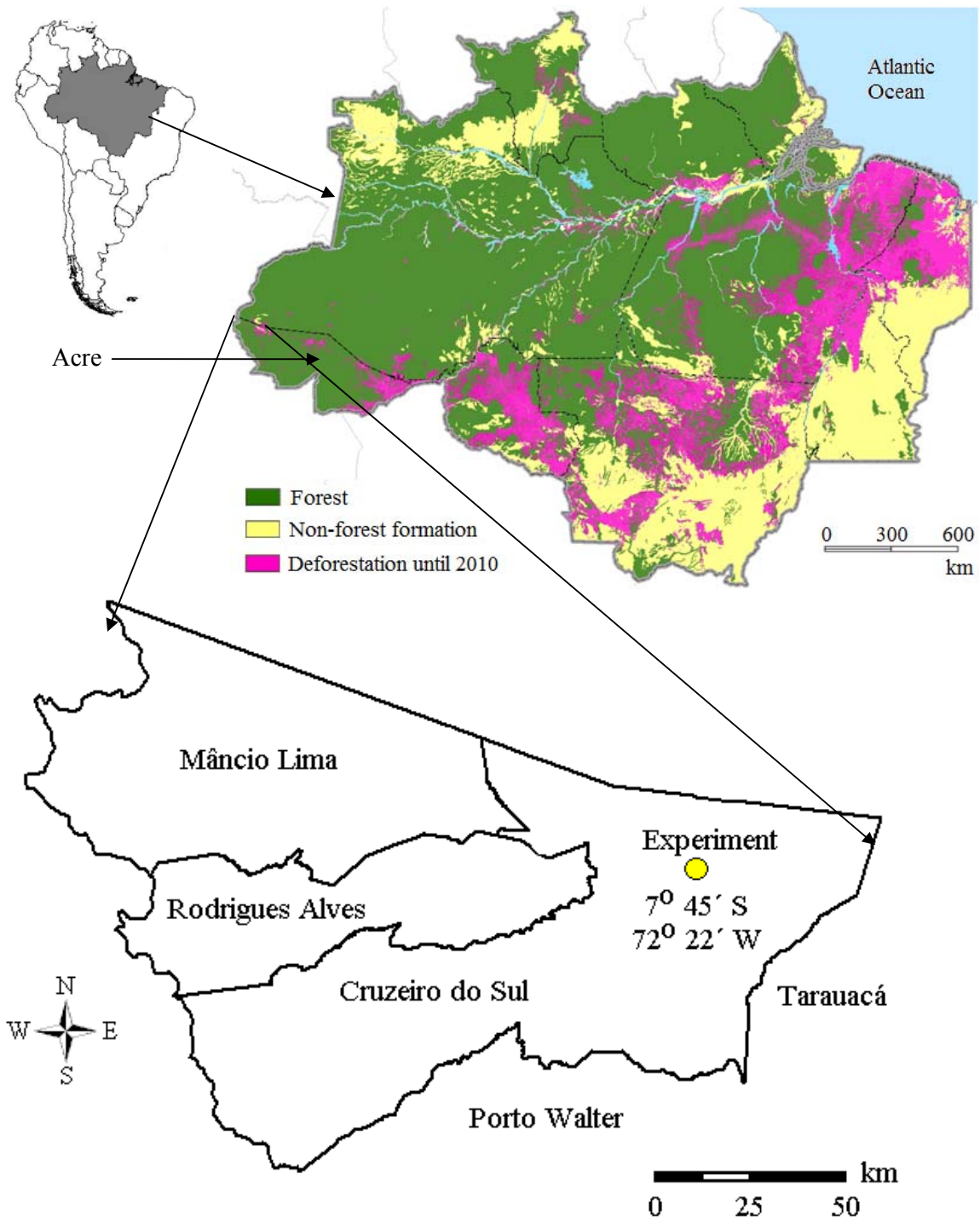


Figure 1. The Amazonian and the location of test site near the city Cruzeiro do Sul, Acre state, Brazil.

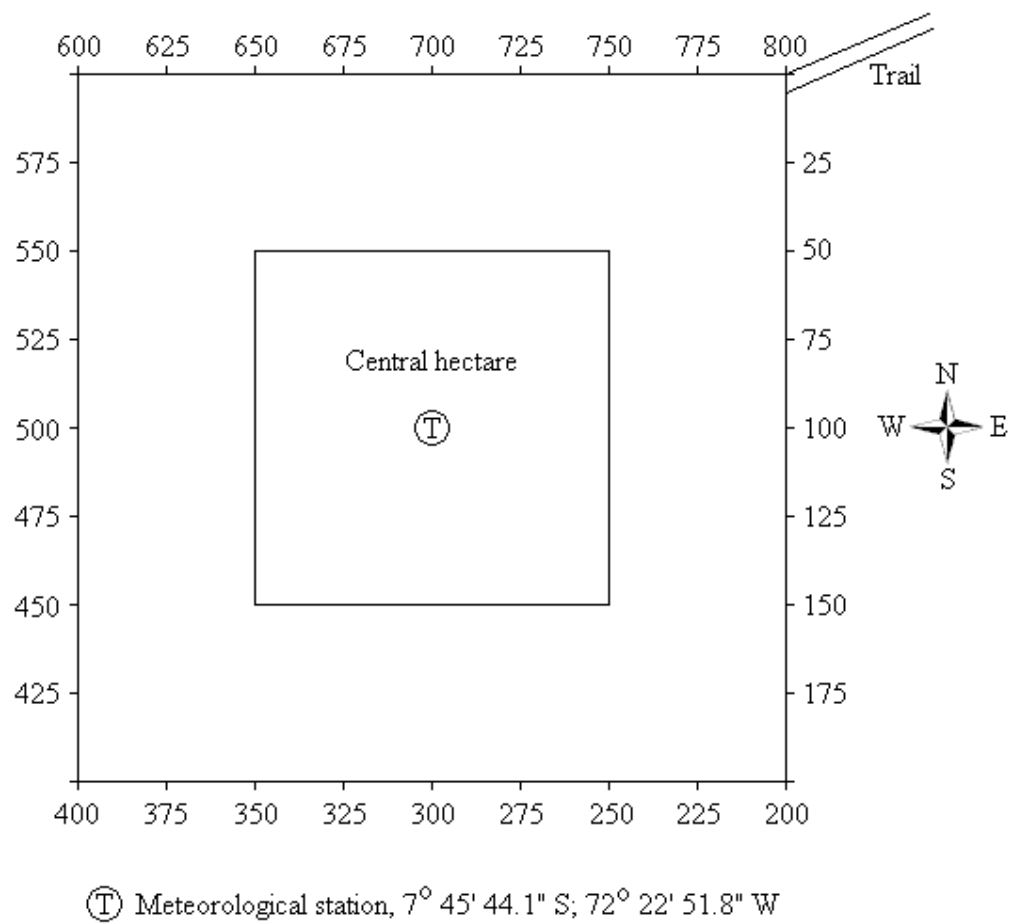


Figure 2 – Location of the two areas.

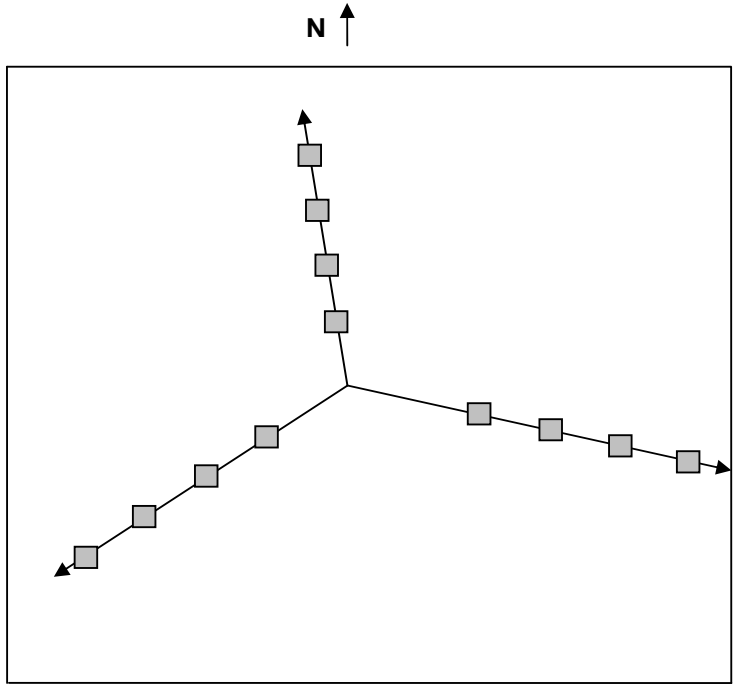


Figure 3. The localization of 12 “2x2” m² sub areas.

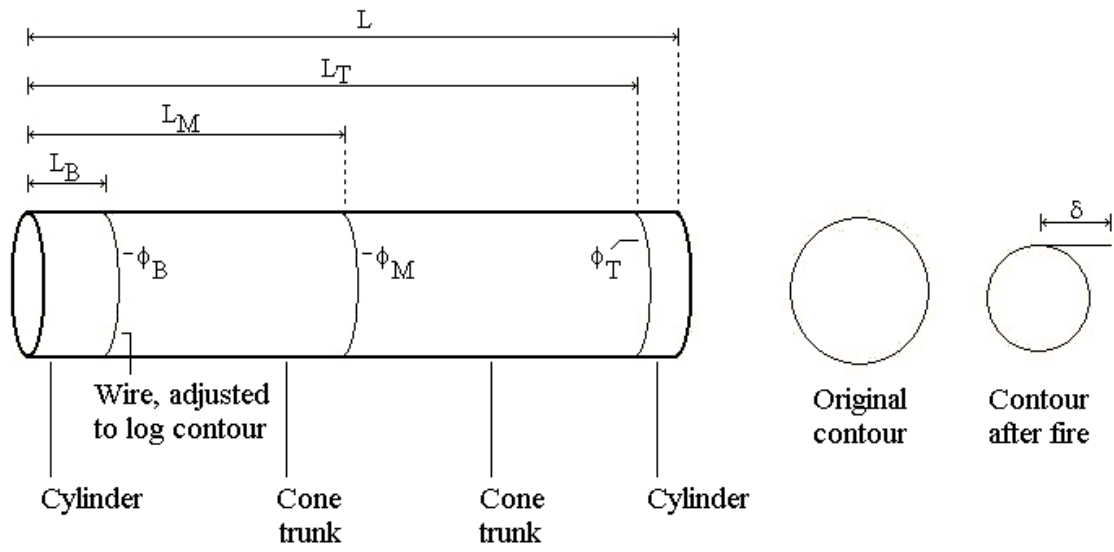


Figure 4 . Illustration of trunk consumption calculations.



Figure 5 – Shelter Box installed in the top of the tower: manifold, electrovalves, filters, pre-filters for retention of particulate materials.

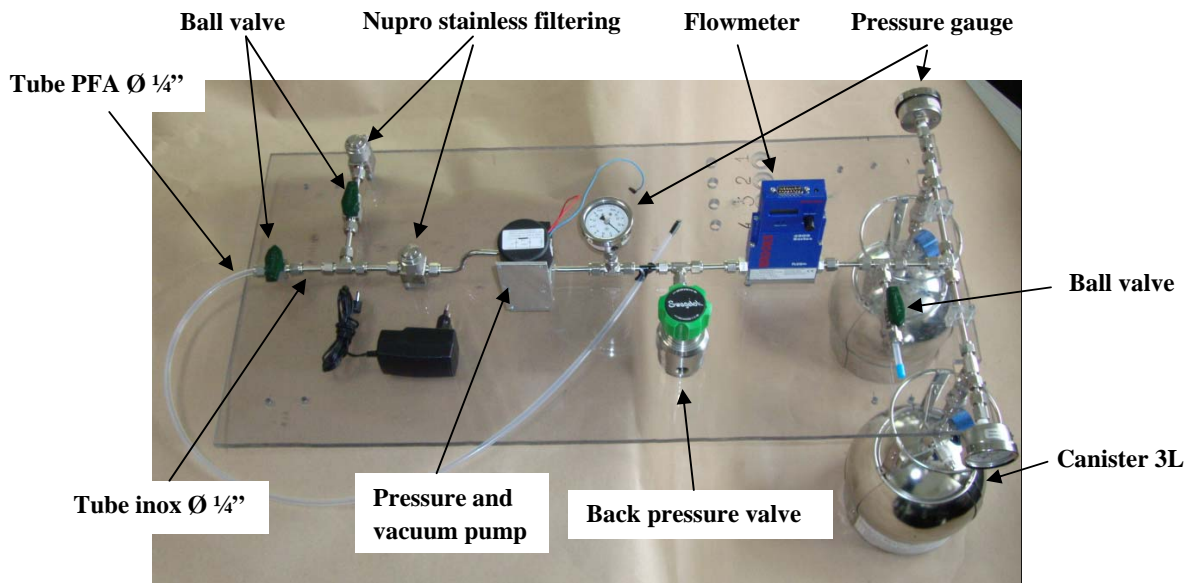


Figure 6 – System of gas sampling mounted and fixed in acrylic table.



Figure 7 – Installation of system for field sampling.



Figure 8 – General view of installed tower.

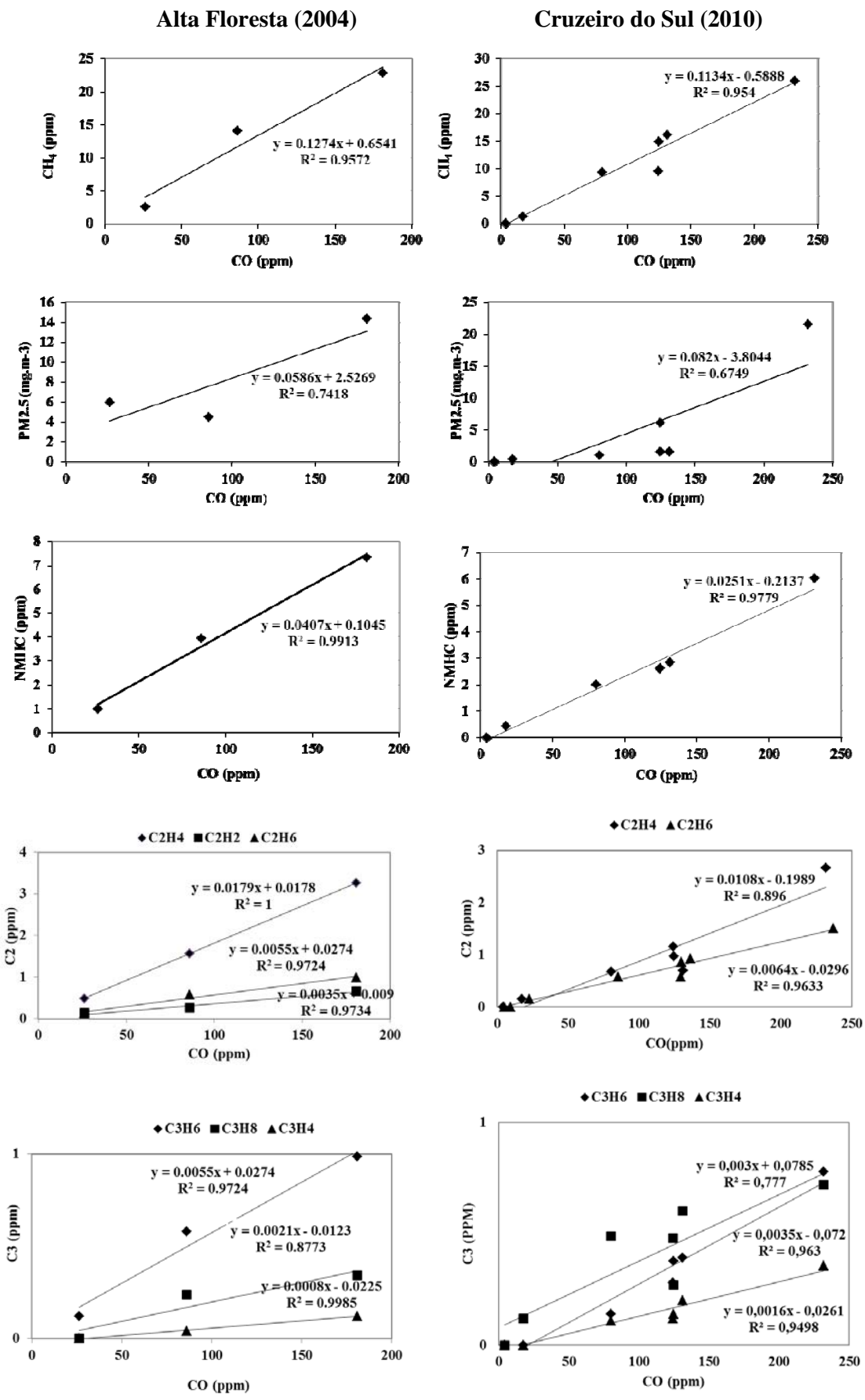


Figure 9 - Correlation between CH₄, NMHC, PM_{2.5} and CO concentrations obtained by chromatographic analysis of product gases collected in canisters from Alta Floresta (Soares Neto et al¹⁰) and Cruzeiro do Sul (this work).

Table 1 - Results of the forest inventory.

Diameter	Individuals	Class	Mass (t)	% Mass
10 - 15 cm	232	10	31.43	5.4%
15 - 20 cm	142	15	44.73	7.7%
20 - 25 cm	81	20	49.07	8.4%
25 - 30 cm	37	25	38.64	6.6%
30 - 35 cm	31	30	48.44	8.3%
35 - 40 cm	9	35	19.49	3.3%
40 - 45 cm	13	40	40.85	7.0%
45 - 50 cm	10	45	40.77	7.0%
50 - 55 cm	8	50	41.06	7.0%
55 - 60 cm	6	55	40.20	6.9%
60 - 65 cm	6	60	49.98	8.6%
65 - 70 cm	0	65	0.00	0.0%
70 - 75 cm	3	70	37.85	6.5%
75 - 80 cm	2	75	28.96	5.0%
80 - 85 cm	0	80	0.00	0.0%
85 - 90 cm	0	85	0.00	0.0%
90 - 95 cm	0	90	0.00	0.0%
95 - 100 cm	1	95	27.04	4.6%
> 100 cm	1	100	44.60	7.6%
Total	582		583.11	

Table 2 - PM_{2.5}, CO₂, CO and CH₄ total concentrations and CO₂, CO and CH₄ net concentrations.

Phase ^a	PM _{2.5} (mg m ⁻³)	Total concentrations (ppmv)			Net concentrations (ppmv) ^b		
		CO	CH ₄	CO ₂	CO	CH ₄	CO ₂
B	0.00	5.1	1.79	382			
I	6.09	9.4	1.82	405	4.3	0.03	23
F	21.45	130	11.25	2546	125	9.46	2164
In	1.50	237	27.67	2085	232	25.88	1703
S	1.50	130	16.65	1135	125	14.46	753
S	1.00	137	17.93	1095	132	16.14	713
S	0.40	86	11.09	824	81	9.3	442
S	0.40	22.7	3.02	451	17.6	1.23	69

^a B: background; , I: initial, F: flame, In: intermediate; S: smoldering.

^b Net concentrations refer to the measurements during the burning (total) minus background concentrations.

Table 3 - Net concentrations for C₂ and C₃ hydrocarbons (ppmv).

Phase ^a	C ₂ H ₄ + C ₂ H ₂	C ₂ H ₆	C ₃ H ₆	C ₃ H ₄	C ₃ H ₈	NMHC ^b
B	0.0	0.0	0.0	0.0	0.0	0,0
I	0.0	0.0	0.0	0.0	0.0	0.0
F	1.15	0.57	0.28	0.12	0.48	2,60
In	2.66	1.50	0.78	0.36	0.70	6.00
S	0.97	0.86	0.38	0.14	0.27	2.62
S	0.70	0.93	0.39	0.20	0.60	2,82
S	0.67	0.58	0.14	0.11	0.49	1.99
S	0.15	0.15	0.00	0.00	0.12	0.42

^a B: background; I: initial, In: intermediate; F: flame, S: smoldering.

^b Total hydrocarbons other than methane.

Table 4- Emitted carbon, associated to each of the analyzed gases.

Canister	Phase ^a	Total C emitted (mg m ⁻³)					
		C-CO ₂	C-CO	C-CH ₄	C-NMHC	C-PM _{2,5}	C-total
1	I	11.27	2.10	0.02	0.00	3.65	17.04
2	F	1058.89	60.96	4.64	2.98	12.87	1140.33
3	In	834.18	113.51	12.68	6.80	0.90	968.07
4	S	368.81	61.15	7.28	2.94	0.90	441.08
5	S	349.52	64.31	7.91	3.35	0.60	413.83
6	S	216.39	39.35	4.56	2.31	0.24	255.74
7	S	33.91	8.59	0.60	0.47	0.24	42.50

^a B: background; I: initial, In: intermediate; F: flame, S: smoldering.

Table 5 - Emission factors (g kg⁻¹).

Canister	Phase	EF ^a CO ₂	EF CO	EF CH ₄	EF NMHC	EF PM _{2.5}
1	I	1213	143.8	0.6	0.00	-
2	F	1702	62.4	2.7	1.60	5.64
-	F ^b	1690	62.7	3.4	2.56	7.45
3	In	1580	136.8	8.7	4.29	0.46
-	In ^b	1625	101.2	7.3	4.72	4.21
4	S	1533	161.7	11.0	4.08	1.02
-	S ^b	1540	140.6	13,1	7.49	3.85
5	S	1548	181.3	12.7	4.95	0.72
6	S	1551	179.5	11.9	5.53	0.47
7	S	1463	235.8	9.5	6.76	2.82

^a values in gram of gas per kg of dry biomass burn.

^b values obtained in Alta Floresta (Soares Neto et al. ¹⁰)

Table 6 - Combustion efficiencies.

Canister	Phase	CE^a	MCE^b	CE^{a1}	MCE^{b1}
1	I	0.661	0.843	-	-
2	F	0.928	0.946	0.922	0.945
3	In	0.861	0.880	0.886	0.911
4	S	0.836	0.858	0.840	0.874
5	S	0.844	0.845	-	-
6	S	0.846	0.846	-	-
7	S	0.798	0.798	-	-
8	S	0.661	0.843	-	-

^a CE – Combustion efficiency; ^{a1} (Alta Floresta, Soares Neto et al. ¹⁰)

^b MCE – Modified combustion efficiency; ^{b1} (Alta Floresta, Soares Neto et al. ¹⁰)

Table 7 - Average emission factors (g kg⁻¹ and kg ha⁻¹).

Average emission factors (g kg⁻¹)^a				
CO ₂	CO	CH ₄	NMHC	PM _{2.5}
1513 ^{a1}	157.3	8.17	3.89	1.86
1599 ^{a2}	111.3	9.2	5.6	4.8
Average emission factors (kg ha⁻¹)^b				
CO ₂	CO	CH ₄	NMHC	PM _{2.5}
232,115 ^c	24,141	1,254	596	285
321,400 ^d	33,427	1,736	825	395

^a values in gram of gas per kg of dry biomass burn.

^{a1} (this work); ^{a2} (Alta Floresta, Soares Neto et al. ¹⁰)

^b values in kg of gas per ha of burned forest.

^c values for overall biomass consumption of 36.11%.

^d values extrapolated to overall biomass consumption of 50%.