

Characteristics of Smoke Emissions from Biomass Fires of the Amazon Region—BASE-A Experiment

Darold E. Ward, Alberto W. Setzer, Yoram J. Kaufman,
and Rei A. Rasmussen

Biomass burning is a major source of emissions of "greenhouse gases" and particulate matter to the atmosphere (Seiler and Crutzen, 1980; Crutzen et al., 1985; Mooney et al., 1987; Radke, 1989). The net effect on global climate is not well quantified (Mooney et al., 1987; Houghton and Woodwell, 1989), and there is a need for better source information regarding the total biomass consumed globally and the quantity and time of release of the important emissions. Measurements of particulate matter emissions are important due to their effect on cloud microphysics and reflectivity (Radke et al., 1988; Radke, 1989). Furthermore, fires and emitted particulate matter are the only components of biomass burning that can be monitored from satellites (Malingreau and Tucker, 1988; Holben et al., 1990; Setzer et al., 1990). Remote sensing of particulate matter and fires from Advanced Very High Resolution Radiometer (AVHRR) was used to estimate the emissions of trace gases and particulate matter from deforestation in the Amazon Basin (Kaufman et al., 1990). This estimate uses measured emission ratios of trace gases and particulate matter.

Global emissions of gases and particles from biomass burning are usually estimated based on extrapolations from work performed in North America (Ward and Hardy, 1984) or Europe (Hao et al., 1990). A few measurements of both gas concentrations and particulate matter concentrations were taken for fires in the Amazon region by Andreae et al. (1988). Artaxo et al. (1988) studied the inorganic fraction of aerosols collected from ground monitoring stations. Several have studied the gaseous composition of the atmosphere relative to biomass burning in Brazil (Crutzen et al., 1979; Greenberg et al., 1984; Crutzen et al., 1985; Andreae et al., 1988). The Biomass Burning Airborne and Spaceborne Experiment—Amazonia (BASE-A) was designed to study both aerosol and gaseous emissions from fires in the Amazon region of Brazil from an airborne sampling platform. There were many fires observed during the several days of the experiment. One of the objectives

of BASE-A was to validate estimates of deforestation burning made using satellite imagery (Setzer et al., 1990).

Previous research by Kaufman et al. (1990) demonstrated the feasibility of sensing the concentration of atmospheric aerosol from space. The ratios of smoke aerosol concentration to the concentration of specific gases were needed to improve the measurements of concentrations of gases important from a greenhouse gas standpoint (Holben et al., 1990). This chapter describes the airborne measurements of PM_{2.5} and trace gases in the *cerrado* and tropical forested areas of Brazil and relates them to those made for fires in North America.

Algorithms for emissions of total particulate matter (PM), particulate matter containing particles less than 2.5 μm diameter (PM_{2.5}), CO, CO₂, CH₄, and nonmethane hydrocarbons (NMHC) for logging residue fires burned in the Pacific Northwest were shown to be functions of combustion efficiency (Ward and Hardy, 1991). They used towers to support sample packages above prescribed fires and sampled for a wide range of combustion conditions. Combustion efficiency depends on fuel characteristics and fire conditions, which are often different in the tropical areas of the Amazon Basin from those in North America. As a result, it is important to measure the combustion products from burning of biomass in the tropics (e.g., Brazil). In addition to the emission measurements, the chemical composition of the forest biomass burned by one fire in Brazil is compared to the fuel chemical composition for biomass burned in North America.

Methods

Sample Collection

An airborne sampling system was employed to collect grab samples of smoke for analysis of both in-plume smoke characteristics and the ambient air. The sampling system was transported from the United States and installed on the Instituto de Pesquisas Espaciais

(INPE) aircraft while at San Jose dos Campos, Brazil (Figure 48.1). Two types of samples were needed that involved installing different systems for collecting samples of gases through a stainless steel tube from outside the aircraft and samples from high concentration plumes over a limited spatial region of the plume.

In-plume sampling was done using a system consisting of a plastic polyvinyl chloride (PVC) pickup tube, 38 millimeters (mm) in diameter, that extended from outside the aircraft to a large sample bag in the aircraft. The tube was designed to sample from under the fuselage approximately 25 cm from the fuselage and well in front of any possible influence from the engine exhaust or wings of the aircraft. A valving system was used for directing a sample of "ram air" from outside the aircraft through an exhaust port or into the large 1.5 cubic meters (m^3) polyethylene sampling bag. The bag was protected by a heavy cloth cover that was used to suspend the bag from the ceiling of the airplane. The bag required approximately 10 seconds to fill and integrated the sample over approximately a 500 meter (m) path length. After each sample, the large bag was flushed with ambient air and evacuated before repeating the sampling protocol. Cross-sectional penetrations of plumes were made and samples extracted from portions of the plume considered to contain high concentrations of smoke from the biomass fires. Similar systems have been used for airborne studies in the United States (Einfield et al., 1990; Radke et al., 1990).

Subsampling was accomplished onto pairs of 37 mm filters (one Teflon and one glass fiber filter) from the large bag through a cyclone (mean mass cutpoint diameter of 2.5 μm). These filters were used for determining the mass concentration of PM_{2.5} and the

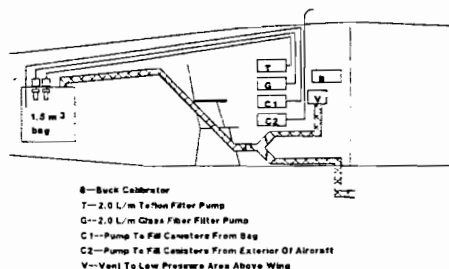


Figure 48.1 Schematic of sampling apparatus used on board the INPE aircraft for sampling emissions from biomass fires in Brazil.

content of the particles for inorganic and organic fractions. The aerosol samples were sampled at a rate of 2 liters per minute over 15 to 20 minute periods. A soap bubble calibrator was used at each altitude to sample the volume flow of the pumps, and these were corrected for temperature and pressure.

In addition, CO₂, CO, and CH₄ concentrations were determined from canister samples collected from the large bag. These canisters were pumped to 2 atmospheres pressure and returned to the United States for analysis using gas chromatography procedures.

Ambient gas samples were collected using a separate sampling system for collecting canister samples from outside the aircraft through the stainless steel sample tube that extended directly out of the cabin through a side port of the fuselage. A separate pump was used for sampling directly into canisters and these were pumped to approximately 2 atmospheres pressure. The pressurized canisters were returned to the United States for gas analyses for CO₂, CO, and CH₄.

Calculations

Emission factors were calculated using the carbon mass balance (CMB) method to compute the mass of fuel consumed in producing the emissions. The technique was first used by Ward et al. (1979) and later perfected by Ward et al. (1982) with laboratory testing by Nelson (1982). The method is based on the stoichiometric partial oxidation of fuel (C_xH_yO_z) to CO₂ and incomplete combustion products. The carbon contained in the fuel is about 50% of the mass of the fuel (Byram, 1959). The measured carbon contained in the combustion products is multiplied by 2 to calculate the mass of fuel consumed in producing the combustion products. Emission factors for specific emission components are calculated by dividing the mass of the emission by the fuel consumed and are expressed in units of grams of emission released per kilogram of fuel consumed (g/kg).

Here *combustion efficiency* is defined as the mass of carbon released in the form of CO₂ divided by the total mass of carbon released. It is expressed as a ratio or percentage of total carbon. In practice, combustion efficiency can be approximated by dividing the sum of the molar concentrations of CO and CO₂ into the molar concentration of CO₂. Generally, the molar concentration of CH₄, and the methane equivalent molar concentration of the carbon contained in both the nonmethane hydrocarbon and particulate matter fractions, are added to that of CO and CO₂. The carbon released in the form of compounds and particulate matter other than CO and CO₂ makes up less

than 5% of the total. Hence, the ratio of CO to the sum of CO plus CO₂ is an excellent first-order approximation of combustion efficiency.

Sample Collection and Concentrations

The INPE aircraft was flown from San Jose dos Campos to Brasilia and northward to Alta Florista (Figure 48.2). One sample was collected from a *cerrado* (savanna-like area) during this flight segment. The second and third plume penetrations of smoke from tropical deforestation burns were made during flight missions out of Alta Florista on 2 and 3 September 1989. After flying from Alta Florista to Manaus and while in flight to Curitiba, a fourth penetration of

a plume from a tropical deforestation fire was accomplished. In addition, many ambient air samples were collected, and these were examined as a function of time and altitude. Three spirals were flown to collect samples for profiling the atmosphere from near the surface to over 3600 m (see Figure 48.2 for locations on 4, 6, and 7 September). The profiles sampled on 4 and 6 September are discussed in this chapter.

In-plume Samples

The net concentrations of gases and particulate matter (after subtracting the background concentrations) are presented in Table 48.1. Background concentration data were averaged for a number of samples collected near the same altitude of the plume penetrations. Unlike the aged plumes sampled by Andreae et al. (1988) at concentrations near that of background, the particulate matter concentration of the ambient air was considered to be low relative to the in-plume concentrations.

On 2 September 1989 the airborne sampling system was first tested flying out of Brasilia for Alta Florista in an active clean-burn fire of mostly grass and low shrubs and trees (*cerrado* fuel type). A sample was collected at 1058 Local Standard Time (LST) using the large-bag sampling apparatus on the second penetration of the plume at about 500 m above terrain. There were no clouds, with surface winds from the southwest at no more than 2 meters per second (m/s). There was little turbulence.

A series of background samples were collected prior to the plume penetration and indicated an average background concentration of 362, 0.192, and 1.721 ppmv of CO₂, CO, and CH₄, respectively. The PM_{2.5} concentration in the plume was measured from an average of the Teflon and glass fiber filter mats of 399 μg/m³.

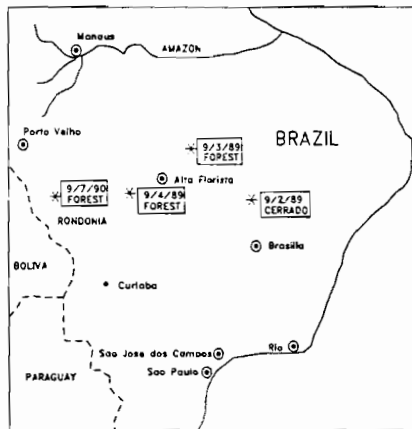


Figure 48.2 General base map showing the time of sample collection and approximate relative locations of major events during the BASE-A experiment.

Table 48.1 Net concentration of gases and PM_{2.5} for one *cerrado* (low trees, brush, and grass fuel type) and three tropical deforestation fires sampled from the INPE aircraft using grab sampling techniques

Sample date	Time	Vegetation type	Concentrations			
			CO ₂ ^a	CO ^a	CH ₄ ^a	PM _{2.5} ^b
2 Sept. 89	1058	<i>Cerrado</i>	91	1.96	0.08	339
3 Sept. 89	1256	Deforestation	129	1.88	1.04	
4 Sept. 89	1500	Deforestation	35	1.47	0.14	193
7 Sept. 89	1358	Deforestation	10	1.20	0.13	177

a. Parts per million by volume (ppmv).

b. Micrograms per cubic meter (μg/m³).

On 3 September 1989 a second plume penetration was made of a fire near Alta Florista at 1256 UT for a deforestation burn. The meteorological conditions of the atmosphere were conditionally stable with a condensation level near 2000 m. The wind speed was light with scattered clouds. The gas concentrations inside the plume were higher than measured for the *cerrado* fire. The particulate matter sampling system became detached during the rough ride through the plume and no sample was collected.

On 4 September 1989 a third plume penetration was made at 1500 LST of a fire near Alta Florista. This was a planned deforestation fire that was carefully observed from the ground by two of our research team members. Surface winds were less than 2 m/s with air temperature of 31° to 36° C and an unstable atmospheric layer to at least 3000 m. A cumulus cloud formed along the top boundary of the smoke plume.

The gas concentrations inside the plume were low as compared to those needed for performing accurate carbon mass-balance calculations of the fuel consumed in releasing the emissions. The gas concentrations in the plume averaged 390, 1.972, and 1.901 ppmv with the background concentrations of 355, 0.498, and 1.764 ppmv for CO₂, CO, and CH₄, respectively. The particulate matter concentration averaged 193 µg/m³.

In addition, nine samples of the more common fuels consumed by the fire were returned to the United States for C, H, and N analysis. (Oxygen was estimated by subtracting the percent C, H, and N from 100%. All results were corrected for water and mineral content.) The fuels consisted of stems, twigs, and leaves, which had an average elemental composition of 53.4 ± 1.8, 5.9 ± 0.1, 1.6 ± 0.7, and 39.1 ± 2.3% C, H, N, and O, respectively. The C and H composition is similar to fuels of North America with the N content being a factor of 2 higher than measurements for the boreal forest of Canada (Susott et al., 1990). The results suggest that the carbon mass balance technique described in the methods section of this report should be equally valid for the tropical forests of South America.

On 7 September 1989 a fourth plume penetration was made at 1358 UT of a plume from a deforestation fire near the state of Rondonia while flying from Porto Velho to Curitiba (Table 48.1). There were numerous towering cumulus clouds resulting from the heat generated from the higher intensity fires. The cloud condensation level was near 3000 m. It was not possible to estimate surface conditions at the time of sample collection. The gas concentrations inside the plume were

373, 1.840, and 1.887 ppmv with a background concentration of 363, 0.643, and 1.762 ppmv, respectively. The particulate matter concentration from the glass fiber filter was 177 µg/m³.

Spiral Profiles

While ascending and descending through the atmosphere, profiles were made of the concentrations of CO₂, CO, and CH₄ through the inversion layer from within 150 m of terrain to over 3500 m altitude. In a companion paper (Holben et al., this volume, Chapter 49), the concentration data are compared with the sun photometer measurements taken from the aircraft.

On 4 September 1989 between 1100 and 1200 hours, a vertical profile of the atmosphere was sampled 50 km to the west of Alta Florista from 150 m above terrain to an altitude of 3600 m. Scattered cumulus clouds were present with a lower condensation level of 3000 m. The CO concentration near the surface to 2000 m averaged 350 ppbv and then decreased to 100 ppbv after passing through the top of the mixing layer located at an altitude of between 2000 and 2600 m. The CH₄ concentration paralleled that of CO, ranging from a high of 1773 ppbv near the surface to 1695 ppbv at 3600 m.

On 6 September 1989 between 0830 and 0930 hours, a vertical profile of the atmosphere was sampled again about 50 km west of Alta Florista from 150 m above terrain to 3600 m altitude. The atmosphere was reasonably stable with a noticeable smoke pall near the surface within 500 m of the surface. The CO concentrations near the surface close to Alta Florista were as high as 600 ppbv, and from 1000 m to 1500 m the concentration was near 300 ppbv. At approximately 2000 m, the concentration decreased to 100 ppbv and reached a low of 67 ppbv at 3300 m.

Results and Discussion

Emission Factors and Combustion Efficiency

The emission factors were calculated using the CMB technique for the smoke emissions released from the *cerrado* and tropical deforestation burns. The data are presented in Table 48.2. Emission factors for CO averaged 88 ± 30 g/kg for the three samples collected of smoke from fires for deforestation purposes. The emission factor for CO can be compared with the measurements made by Hegg et al. (1989) of 91 ± 21 g/kg, the calculated emission factors of 91.4 g/kg from data of Andreae et al. (1988), and those of Ward et al. (1989) from tower sampling of logging slash fires of

Table 48.2 Emission factors for PM_{2.5}, CO₂, CO, and CH₄ for one *cerrado* and three deforestation fires in Brazil during September 1989

Sample date	Time	Vegetation type	Emission factors (g/kg)				Combustion efficiency (%)
			CO ₂	CO	CH ₄	PM _{2.5}	
2 Sept. 89	1058	<i>Cerrado</i>	1783	24.5	0.56	4.4	97.2%
3 Sept. 89	1256	Deforestation	1666	97.7	4.90	—	90.8
4 Sept. 89	1500	Deforestation	1741	46.6	2.48	5.3	94.9
7 Sept. 89	1358	Deforestation	1586	120.9	7.18	15.6	86.4

156 ± 37 g/kg for Douglas fir slash and 128 ± 22 g/kg for hardwood species slash. The samples of Hegg et al. (1989) were collected similarly to this study. The measurements by Ward et al. (1989) were for the flaming and smoldering combustion phases and weighted for the entire fire based on the fuel consumed during each of the combustion phases. Of major concern is the possibility of not collecting samples that are representative of the fire producing the emissions. Ward and Hardy (1991) discuss the fire buoyancy effect on lofting the emissions from the flaming phase and releasing these emissions in a stratum of the atmosphere higher than those emissions from the smoldering phase.

Emission factors for CH₄ averaged 4.8 ± 2.0 g/kg compared to the average by Hegg et al. (1989) of 2.9 ± 0.66 and that of Ward et al. (1989) of 5.5 ± 2.0 for Douglas fir logging slash.

Particulate matter emission factors require a sample with a weighable mass of particles from a sample space concurrent with the collection of a sample of the gases. The gas concentrations must be accurately measured to differentiate them from the background concentrations. The large-bag sampling system enhances the collection from portions of the smoke plumes where the concentrations are differentiable from background. PM_{2.5} emission factors ranged from 4.4 for the *cerrado* sample to 15.6 g/kg for one of the tropical deforestation fires.

The measured emission factors are plotted against the algorithms of Ward and Hardy (1991) as a function of combustion efficiency (Figure 48.3). The algorithms were developed from 38 test fires in the western United States and include numerous samples from both the flaming and smoldering combustion phases. The combustion efficiency for the *cerrado* fire was 97% and for the three tropical deforestation fires averaged 90.7% ± 4.3%. This compares to the measurements of Hegg et al. (1989) of 89.6% ± 2.0%, of Andreae et al. (1988) of 92% as calculated from the

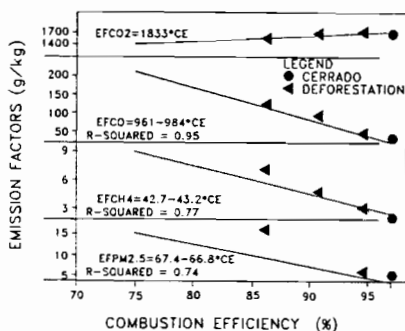


Figure 48.3 Emission factors for CO₂, CO, PM_{2.5}, and CH₄ as functions of combustion efficiency. The data for the *cerrado* and tropical deforestation fires are superimposed. The similarity of emission factors for various emissions for different combustion efficiencies fit well on the data derived for logging slash fires in the United States (Ward and Hardy, 1991).

CO/CO₂ molar ratio, and to the measurements of Ward et al. (1989) of 84% to 89% dependent on fuel type and burning conditions. The measurements for emissions from fires in tropical fuel types agree well with the measurements of fires in North America if the combustion efficiency effect is factored into the analysis.

The ratios of emission factors as measured in the BASE-A experiment are summarized in Table 48.3 and compared with similar measurements in North America (Ward and Hardy, 1986) and Brazil (Andreae et al., 1988; Greenberg et al., 1984; Crutzen et al., 1985). It was found that although the fire combustion efficiency varied between the three observed fires, and as a result the ratio of CO/CO₂ varied (see the standard deviations in Table 48.3), the ratios of PM_{2.5} to CO or to CH₄ are markedly constant. The constant ratio between PM_{2.5} and trace gas emissions shows that remote sensing of smoke particles from

Table 48.3 Ratio of emission factors as measured in the BASE-A experiment

	BASE-A		Ward (1986)		Andreae et al. (1988)	Greenberg et al. (1984)	Crutzen et al. (1985)
	Cerrado	Forest	Flaming	Smoldering			
CO/CO ₂	1.4%	5.4 ± 2.1%	4.3 ± 1.6%	18.1 ± 9.2%	5.4%	3 to 20%	9%
CH ₄ /CO ₂	0.03%	0.3 ± 0.1%	0.1 ± 0.1%	0.5 ± 0.2%		0.2 to 0.8%	
PM _{2.5} /CO ₂	0.3%	0.6 ± 0.3%	0.4 ± 0.3%	0.8 ± 0.3%			
PM _{2.5} /CO	18.0%	12.1 ± 0.8%	9.6 ± 3.5%	5.6 ± 3.3%			
PM _{2.5} /CH ₄	785.7%	215.5 ± 1.8%	325.5 ± 182.9%	176.6 ± 62.8%			

Note: Percent on a mass basis.

space, in addition to remote sensing of fires themselves, can be a useful tool for regional and global estimates of trace gas emissions from deforestation fires.

Andreae et al. (1988) discuss the difficulty of differentiating background concentrations of particulate matter and CO₂ from in-plume concentrations. None of their measurements show elevations of CO₂ of more than 2 ppmv. The average molar ratio of CO/CO₂ of 0.085 was determined from multiple samples. Individual fires produce ratios of emissions dependent on the burning conditions, fuel type, and method of ignition (Ward, 1991). Often, especially for airborne sampling work, the initial flaming phase burns at a high combustion efficiency with the combustion efficiency decreasing as the products of incomplete combustion from the smoldering phase dominate the emissions released from the fire. The molar ratio of CO/CO₂ can change dramatically from 0.25 to 0.023 over a range of combustion efficiencies of 75% to 95%.

Development of Gas-to-Particulate Matter Mass Ratios

To estimate the emissions of other trace gases from measurements of particulate matter loading on a regional basis requires reliable measurements of the ratio of trace gas to particulate matter. We measured both PM_{2.5} concentrations and the concentrations of trace gases in three plumes during the BASE-A experiment. The multiplier to estimate PM_{2.5} concentration in the background air was derived from the plume penetration data for the three tropical deforestation fires. Samples of PM_{2.5} and gases were collected from only two of the deforestation fires. The ratio of PM_{2.5} to gas concentration for the *cerrado* fire was 0.2032 mg of PM_{2.5} per m³ per ppmv of CO. Figure 48.4 shows a good fit with the ratio data for the

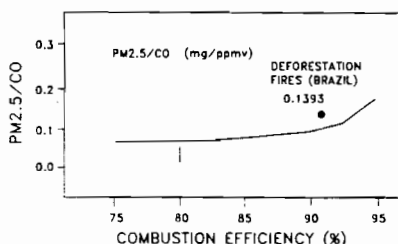


Figure 48.4 The ratio of mass of PM_{2.5} to CO for fires in the United States and the average ratio for the tropical deforestation fires as a function of combustion efficiency.

smoke emissions sampled for prescribed fires in the United States when the effect of combustion efficiency is factored into the comparison. The two deforestation fires averaged 0.1393 mg of PM_{2.5} per m³ per ppmv CO (average combustion efficiency of 90.6%). This also is comparable to measurements for fires in the United States of similar combustion efficiency. The removal of smoke particles from the atmosphere due to scavenging through cloud processing was not factored into these calculations. In fact, the selective removal of particles could have easily exceeded 50% of the mass released for the fires that induced precipitation (Radke, personal communication, 1990).

Calculation of Atmospheric Loading of PM_{2.5}

The PM_{2.5} to CO concentration ratios were used to compute the mass of PM_{2.5} from the surface to 3600 m. This was done by collecting canister samples of the gases at several altitudes and applying the ratio of 0.1393 mg of PM_{2.5} per m³ per ppmv CO for each of the CO concentrations at the different altitudes of measurement. For integration purposes, the concen-

tration was considered constant from midpoint between the sample altitudes. The lowest CO concentration measured at 3600 m was assumed to be above the mixing height for the particles from the deforestation burns, and the CO concentration at this altitude was subtracted from the other measurements before multiplying by the ratio of PM_{2.5} to CO concentration.

Figure 48.5 shows the CO concentration data for 4 and 6 September and the calculated concentration of PM_{2.5} as a function of altitude. The integrated total PM_{2.5} for each height interval is shown as well by the bar diagram superimposed on the line drawings. The total atmospheric PM_{2.5} loading from ground level to 4000 m was determined from this analysis to be 92.8 and 67.5 mg/m² on 4 and 6 September, respectively.

Inorganic and Organic Content of PM_{2.5}

The lightly loaded filters may have contributed to some of the differences between measurements of trace elements for samples collected in the *cerrado*

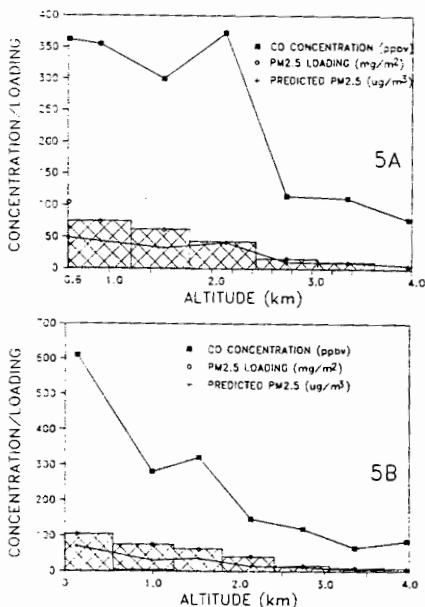


Figure 48.5 Vertical profile of CO was used with ratios shown in Figure 48.4 to compute the mass concentration of PM_{2.5} and the optical thickness of the atmospheric loading of PM_{2.5} for two profiles: (a) 4 September 1989 and (b) 6 September 1989.

and tropical deforestation fires and those for North America. Generally, the filter samples collected in the United States contain upward of 100 µg of sample per filter and often as much as 1 mg. The filter samples for Brazil contained 13 and 14 µg for the two deforestation fires and 29 µg for the *cerrado* fire. The filter weighing was done meticulously with full use of check weights and control filters.

The inorganic content of the PM_{2.5} was determined using X-ray fluorescence techniques by NEA Laboratory in Beaverton, Oregon. The concentrations of a few of the trace elements that are most interesting are shown in Figure 48.6. Of special interest is the absence of lead, generally considered to be a deposition product resulting from leaded gasoline. Mercury was found for the tropical deforestation samples collected in the Amazon tropical forested areas but not the *cerrado*. The presence of mercury with the smoke particles may be a result of the widespread use of mercury to remove gold from ore in this region of Brazil. Of further interest is the high content of Si, Ca, Cl, and K for the *cerrado* area. The same is true in low concentration for the tropical deforestation smoke relative to the smoke from the *cerrado* fires. Future analyses of the elemental composition of the biomass fuels should help explain these differences between the inorganic elemental composition of the fuel types in Brazil as well as the differences between typical smoke samples collected in other parts of the world.

The carbon content of PM_{2.5} was determined using a volatilization/combustion technique first used by Johnson and Hunzicker (1981) and now used commercially by Sunset Laboratory of Beaverton, Oregon. The ratio of graphitic to organic carbon measured with the technique was considered to be a valid measurement even though the absolute values of the mass of carbon lost from the sample was higher

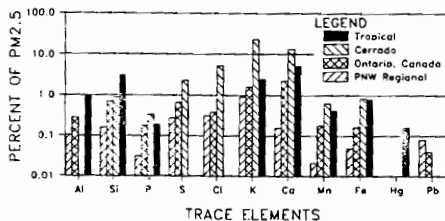


Figure 48.6 Inorganic content of PM_{2.5} for the *cerrado* and tropical deforestation fires as compared to a fire in Canada and the average of 38 test fires in the United States.

Table 48.4 Apportionment of carbon released in the form of particles for the *cerrado* and two deforestation fires sampled in Brazil during September 1989

Vegetation type	Date	Net weight per filter		Net wt PM2.5 (μg)	Ratio of carbon		Percentage carbon	
		Graphitic (μg)	Organic (μg)		Graphitic	Organic	Graphitic (%)	Organic (%)
<i>Cerrado</i>	2 Sept.	0.97	16.78	29	0.054	0.946	3.3%	56.7%
Deforestation	4 Sept.	1.29	6.49	13	0.166	0.834	9.9	
Deforestation	7 Sept.	0.40	3.35	14	0.107	0.893		49.9

Note: The filter loadings were not sufficient to provide true mass loadings of each of the types of carbon. However, the relative proportion of each is thought to be within $\pm 20\%$ of the percentage values listed in the table.

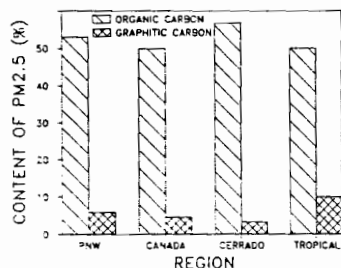


Figure 48.7 Comparison of the organic carbon content of the emissions of PM_{2.5} for fires of the *cerrado* and tropical areas as compared to a fire in Canada and the average of 38 fires in the United States.

than previous samples of smoke from biomass burning. The total carbon contained with the PM_{2.5} was assumed to be similar to that for samples of smoke collected in the United States (60% carbon) and the proportion of graphitic to organic used to apportion the carbon between graphitic and organic fractions (Table 48.4). The ratio of graphitic to organic was lower for the fire in the *cerrado* fuel type than for the tropical deforestation fires by a factor of two. The comparison with other fuels in the United States and Canada is shown in comparison to the *cerrado* and tropical deforestation fires of Brazil (Figure 48.7).

Conclusions

Emission factors for combustion products from four fires suggest that the proportion of carbon released in the form of CO₂ is higher than for fires of logging slash burned in the western United States (higher combustion efficiency). The combustion efficiency was 97% for the *cerrado* test fire and 86% to 94% for the deforestation fires.

Although ratios of PM_{2.5} to CO were measured in the fire plumes, the actual ratios in the ambient air may be lower. The removal of PM_{2.5} due to cloud processing needs to be evaluated and could be a dominant factor in the tropics. Systematic measurements of the ratios of particles to CO₂ concentrations close to the fire and in the aged mixed air could be used to show the removal of smoke particles from the air.

Source characterization needs to account for the mass of biomass consumed relative to the emissions released because wild-land biomass fires have high combustion efficiencies during the flaming phase. (Carbon released in the form of CO₂ exceeds 90% of total carbon released during the flaming phase and typically ranges from 70% to 85% during the smoldering phase.)

The inorganic content of particles from fires in biomass fuels in the tropics may be different from fires of the western United States. This needs further investigation.

This limited data set suggests that tropical biomass combustion may be markedly different than for temperate forest fuels. Combustion efficiencies are higher, as are emission factors for CO₂. These results are consistent with our visual observations of the fuel beds where the small-sized fuels dry quickly and are fully consumed during the flaming combustion process, but the large-diameter fuels dry more slowly and are only partially consumed during the early part of their dry-down. The heavy large-diameter fuels, when wet, are quickly extinguished following the consumption of the fine fuels.

We found that although the combustion efficiency varied between the three observed fires, and as a result the ratio of CO/CO₂ varied from fire to fire, the ratio of PM_{2.5} to CO or to CH₄ remained markedly constant. The smoke particle concentration was measured instantaneously and only in two fires; therefore,