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Smoke and Fire Characteristics for Cerrado and Deforestation Burns in Brazil: BASE-B Experiment

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Fires of the tropical forests and savannas are a major source of particulate matter and trace gases affecting the atmosphere globally. A paucity of quantitative information exists for these ecosystems with respect to fuel biomass, smoke emissions, and fire behavior conditions affecting the release of emissions. Five test fires were performed during August and September 1990 in the cerrado (savannalike region) in central Brazil (three fires) and tropical moist forest (two fires) in the eastern Amazon. This paper details the gases released, the ratios of the gases to each other and to particulate matter, fuel loads and the fraction consumed (combustion factors), and the fire behavior associated with biomass consumption. Models are presented for evaluating emission factors for CH_4, CO_2, CO, H_2, and particles less than 2.5 μm diameter (PM2.5) as a function of combustion efficiency. The ratio of carbon released as CO_2 (combustion efficiency) for the cerrado fires averaged 0.94 and for the deforestation fires it decreased from 0.88 for the flaming phase to <0.80 during the smoldering phase of combustion. For tropical ecosystems, emissions of most products of incomplete combustion are projected to be lower than previous estimates for savanna ecosystems and somewhat higher for fires used for deforestation purposes.

1. INTRODUCTION

Fires in tropical forests and savannas are a major source of particulate matter (PM) and gaseous emissions to the atmosphere. In excess of 80% of the emissions from all sources of biomass burning (estimated to be as much as 5 Pg of carbon per year on a global basis) originate in the tropics [*Hao et al.*, 1990; *Crutzen and Andreae*, 1990]. Some of the emitted gases (CO_2, CH_4, CH_3Cl) participate in the greenhouse effect that heats the atmosphere [*Ramanathan et al.*, 1985]. Other gases (e.g., NO_x, CH_4) affect atmospheric chemistry [*Crutzen*, 1988], causing elevated levels of ozone [*Fishman et al.*, 1979; *Andreae et al.*, 1988, 1990; *Crutzen*, 1988] and acid precipitation [*Crutzen and Andreae*, 1990].

Biomass burning is also a major source of organic hygroscopic particles [*Greenberg et al.*, 1984; *Crutzen et al.*, 1985; *Ward*, 1990; *Andreae et al.*, 1988]. These smoke particles were observed to affect cloud microphysics [*Twomey and Warner*, 1967; *Warner and Twomey*, 1967; *Hobbs and Radke*, 1969] by increasing the available cloud condensation nuclei [*Squires and Twomey*, 1960; *Twomey and Warner*, 1967; *Radke*, 1989] and decreasing the cloud drop size [*Kaufman and Nakajima*, 1992]. These particles can cool the climate by directly reflecting solar radiation to space or by modifying the cloud albedo [*Penner et al.*, 1991]. Biomass burning emits graphitic carbon, a black material, that can increase absorption of solar radiation by the atmosphere [*Ackerman and Toon*, 1981] and by clouds [*Twomey*, 1977], hence affecting climate.

Present estimates of biomass burning and rate of emission of trace gases and PM are based on measurements of the ratio of the trace gases or PM to the concentration of CO_2 [*Andreae et al.*, 1988] and on crude estimates of the rate of deforestation and savanna burning (e.g., using population statistics [*Seiler and Crutzen*, 1980; *Hao et al.*, 1990]). A method for remote sensing of total PM released into the atmosphere from biomass burning, using advanced very high resolution radiometer (AVHRR) imagery, was demonstrated by *Kaufman et al.* [1990]. In order to estimate the emission of trace gases produced from biomass burning in the Amazon region of Brazil, the method used ratios of trace gases to PM measured in the United States [*Ward and Hardy*, 1984]. To improve these estimates of the emissions of trace gases and PM from biomass burning, detailed measurements are required of the relation among the biomass characteristics, rate of burning, and rate of emission of products of incomplete combustion. The BASE-A experiment, provided measurements of emissions from fuel complexes over a wide geographic range in Brazil using airborne sampling methods [*Ward et al.*, 1991; *Holben et al.*, 1991; *Kaufman et al.*, this issue]. The Biomass Burning Airborne and Spaceborne-Brazil (BASE-B) experiment reported in this paper presents the results from detailed ground based measurements of the fire evolution, biomass burning and rate of emission of trace gases, and particulate matter for several deforestation and savanna fires.

The mixture of combustion products and the total amount of smoke released from these fires are not well quantified. Measurement techniques have generally utilized airborne sampling of the smoke emissions, often in extremely dilute smoke plumes [*Ward et al.*, 1991; *Kaufman et al.*, this issue; *Andreae et al.*, 1988; *Crutzen et al.*, 1985]. Few studies have examined fuel loading [*Fearnside*, 1991], fire behavior, or combustion factors (percent of total biomass consumed) in the tropical evergreen forests [*Kauffman and Uhl*, 1990; *Kauffman et al.*, 1988]. We know of no other studies that have examined these variables along with the simultaneous

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measurement of the emissions released. Along with prefire and postfire measurements of the biomass and the fire behavior, this research utilized instruments supported on surface towers to measure smoke from fires burning in the cerrado and Amazonian forests of Brazil.

Here we provide the results from in situ source characterization measurements of ratios of gases to particles for a variety of fire situations in Brazil. New information is presented regarding emission factors for particles ≤ 2.5 μm in diameter (PM2.5), H_2, CO, CH_4, and NO as a function of combustion efficiency for representative fires. An emission factor is defined as the mass of emission released per unit mass of biomass consumed (grams per kilogram). Combustion efficiency is defined as the ratio of carbon released by the fire as CO_2. We discuss the rate of release of carbon from the individual fires and characterize the percent of the total aboveground biomass consumed by the five fires studied (combustion factors).

2. Fire Processes

Combustion efficiency is a fundamental parameter that integrates many of the variables affecting the volatilization and oxidation of biomass fuels [*Ward and Hardy*, 1991]. The chemical and physical features of the ecosystem coupled with environmental parameters (humidity, temperature, wind speed) and the type of ignition affect the combustion factor and combustion efficiency and therefore the consumption of biomass, the composition of the smoke emissions, and the rate of release of emissions. The relative amount of biomass consumed through flaming and smoldering combustion can also vary due to these factors. Flaming and smoldering combustion are processes distinctly different, both in the appearance and in the production of emissions.

Flaming combustion dominates during start-up, with the fine fuels supplying the volatile fuel required for sustaining the rapid oxidation reactions. Flaming typically lasts for only a few minutes. The combustion efficiency of the flaming combustion phase has been measured for a wide range of fires and is normally greater than 0.90. Savanna and grassland ecosystems, where the majority of the fuel load consists of fine fuels, would be expected to support fires of a high combustion efficiency and to produce less emissions of products of incomplete combustion [*Ward and Hao*, 1991]. Literature values generally use a constant emission factor which translates to a lower combustion efficiency for fires used for deforestation purposes [*Crutzen and Andreae*, 1990; *Hegg et al.*, 1989].

As the flaming combustion ends, the large and compact fine fuels are left smoldering and the combustion efficiency decreases very abruptly into the 0.75 to 0.85 range. The smoldering combustion phase is a very low intensity process that produces high emissions of PM, CO, and other products of incomplete combustion [*Lobert et al.*, 1991; *Ward and Hardy*, 1991; *Cofer et al.*, 1989]. *Ward and Hardy* [1991] studied the emissions released from a large number of fires in forest and fuel scenarios of the Pacific Northwest in the United States. They presented emission factor models as a function of combustion efficiency for PM (total PM with no size segregation), PM2.5, CO, CH_4, and nonmethane hydrocarbons (NMHCs). Their models are widely used in the United States for evaluating the quantity of smoke emissions from both planned prescribed fires and unplanned wildfires. In this study, the emission factors measured in Brazil for the flaming and smoldering combustion phases are compared with their models and with the measurements made by others.

3. Methods

In section 3 we describe the ecological study areas (section 3.1), methods for characterizing the biomass (section 3.2), methods for characterizing the emissions (section 3.3), analytical protocols used for speciation of the emissions (section 3.4), and computational methods used for emission factors and fuel consumption (section 3.5). It is helpful to study the characteristics of the emissions simultaneously with the characteristics of the biomass to develop an understanding of factors contributing to the release of mixes of combustion products. Plant species alone would not be expected to explain all differences in the mix of primary products of combustion. The arrangement, moisture content, wind, humidity, and temperature also affect the efficiency of the combustion process. During this study we measured emissions from the cerrado (savannalike) region of central Brazil and areas of deforestation in the Brazilian Amazon basin.

3.1. *Study Areas*

The cerrado vegetation zone encompasses approximately 1.8 million km^2 in Brazil [*Goodland*, 1971; *Coutinho*, 1982, 1990]. The physiognomy of the cerrado is diverse, consisting of tropical grasslands, savannas, and semideciduous forests. The vegetation has been characterized as a continuum along a soil fertility and fire gradient from open tropical grassland or Campo limpo (C1) to forest or Cerradâo (C5) (Figure 1) [*Coutinho*, 1978]. Between this grassland and forest are two savanna and one grassland formation: Campo sujo (C2), Campo cerrado (C3), and Cerrado sensu stricto (C4). In-depth descriptions of these plant communities can be found in the work of *Goodland* [1971] and *Coutinho* [1978, 1990]. In contrast to the savannas and grasslands, fire is not a common occurrence in the Cerradâo forests [*Goodland*, 1971]. Biomass and emissions were only examined in the four grassland/savanna formations of the gradient.

The cerrado study area was located 35 km south of Brasilia D.F. on lands administered as ecological and research preserves (The Reserva Ecologica) by the Instituto Brasileiro de Geografia e Estatistica (IBGE) (15°51'S, 47°53'W) (Figure 2). Mean annual precipitation is 1470 mm with the majority occurring from October to March or April. A distinct dry season occurs from April to September. The majority of burning occurs during August and September. The annual maximum and minimum temperature is 25° and 16°C, respectively. Mean relative humidity is 72% (climate data are from the Reserva Ecologica, IBGE, 1980–1989).

The tropical moist forest study sites were located in the eastern Amazon north of Marabá, Para (04°3.25'S, 49°0.25'W) (Figure 2). We sampled two common burn scenarios practiced by local agriculturalists in this ecosystem. The first investigated was a primary forest (PF) slashed for shifting agriculture. The other scenario was a 15-yr-old second-growth forest (SF) that had been slashed for reformation to cattle pasture. These study sites were located in rural areas in which reliable climatic data do not exist. The closest weather data available were from the city of Marabá

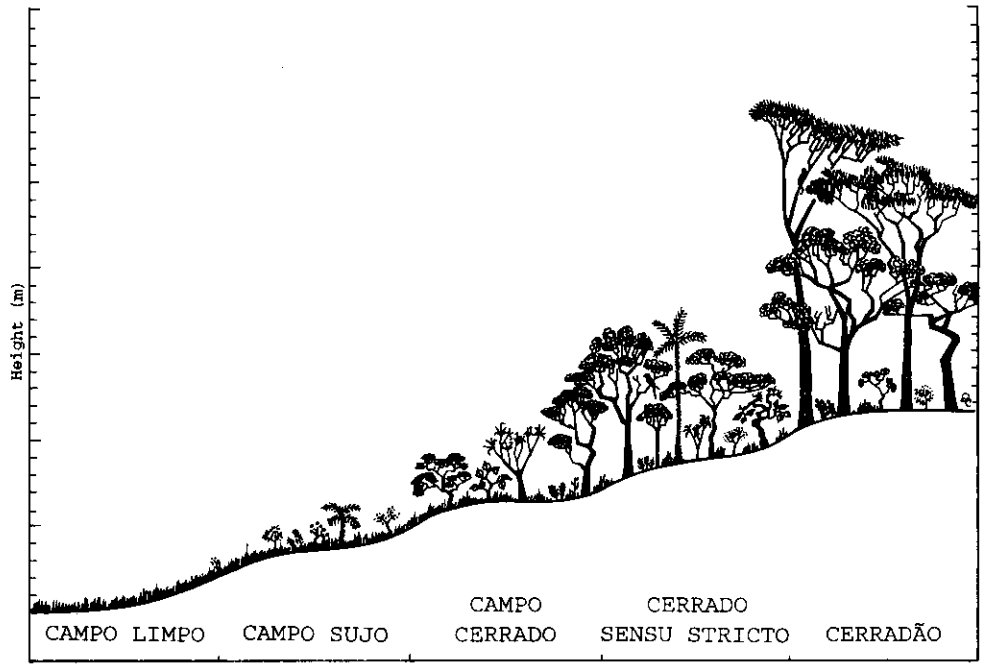

Fig. 1. Plant communities of the cerrado vegetation type of central Brazil. Fires are a common occurrence in the savanna and grassland associations (that is, the gradient from Campo limpo (C1) to cerrado sensu stricto (C4). Average tree height (based on data from this study and *Goodland* [1971] is 1–5 m for Campo sujo (C2), 3–6 m for Campo cerrado (C3), and 4–8 m for Cerrado sensu stricto (C4). Density of trees >2 m in height is 600 ha^{-1} in Campo cerrado (C3) and 833 ha^{-1} in Cerrado sensu stricto (C4). The Cerradâo is a closed-canopy forest (C5).

located approximately 75 km south of the study areas. In Marabá, mean annual precipitation is 1426 mm yr^{-1}, with the months of July to September receiving less than 20 mm per month. The mean maximum and minimum temperatures are 30.6° and 23.4°C, respectively. Average relative humidity is 79% [*Diniz and Bastos*, 1974].

Fig. 2. General locations of study areas within Brazil near Brasilia (cerrado study areas) and Marabà (primary forest and second-growth study areas).

3.2. *Measurements of Fuels, Biomass Consumption, and Fire Behavior*

Fuels in the tropical moist forest sites included slashed wood debris, attached foliage, the litter layer of the forest floor, and live dicot seedlings and sprouts. To estimate the biomass and consumption of wood debris, we used planar intersect models modified specifically for the PF and SF slashed fuels of this study. Prior to burning we established 30 transect lines in the PF and 15 transect lines in the SF. Transect lines were established in a systematic manner to insure sampling throughout the slashed areas. Wood debris were partitioned by diameter class following the methods of *Van Wagner* [1968] and *Brown and Roussopoulos* [1974]. Following burning, these same transect lines were remeasured to quantify the residual mass of wood debris. In addition, the ash depth was measured at 100 points in each of the burned areas. Ten ash samples of a known volume and weight were collected to determine the mean bulk density. Ash mass was then determined by multiplying depth by the mean bulk density.

In the four cerrado plant communities (Figure 1), fuels were defined as all living or dead vegetation less than 2 m in height above the soil surface (excluding trunks of large trees or shrubs). To estimate the biomass of fuels, we established a series of 10 transect lines in the C3 and C4 ecological communities. Five transect lines were established in each of the grassland communities (C1 and C2). Each transect was 15 m in length with five 25- × 25-cm plots established at 3-m intervals along each transect. The biomass within each plot was clipped to ground level and placed in a paper bag, oven dried for 48 hours at 60°C, and weighed. The percent of the total mass consisting of dicot (hardwood) litter, dicot seed-

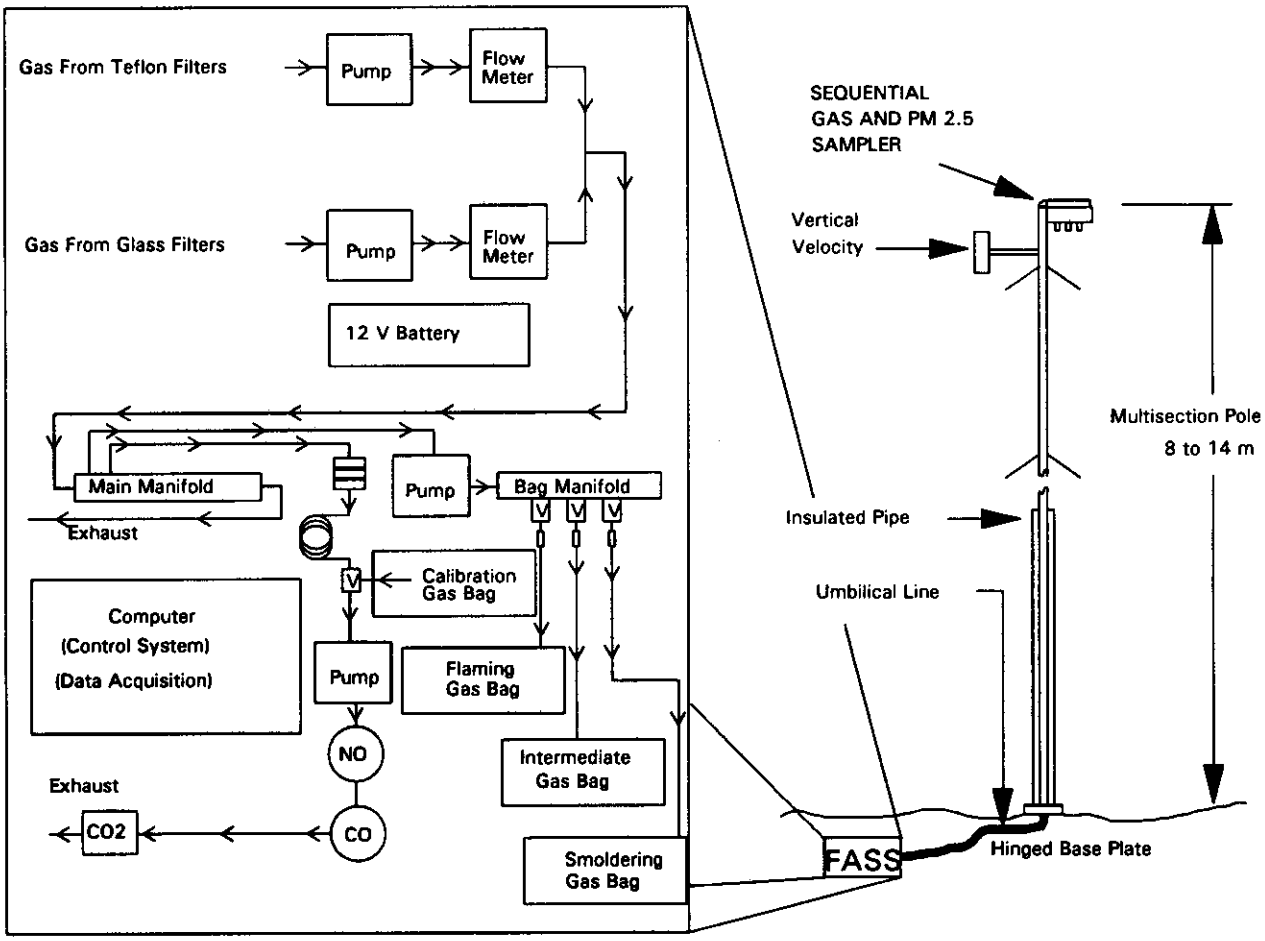

Fig. 3. Schematic of fire atmosphere sampling system (FASS) with mast for supporting the sequential filter sampling head and the computer-driven data logger module positioned at the base of the mast containing real-time analyzers for measuring the concentration of CO_2, CO, NO, and for collecting samples of the gases concurrently with the filter samples.

lings, green grass, and dormant (cured) grass were separated and weighed for each community type. Prefire and postfire dead woody debris were measured along the same transect utilizing the planar intersect technique [*Van Wagner*, 1968; *Brown and Roussopoulos*, 1974]. Following the fire, ash and residual unburned materials were collected in plots placed along the transect 1 m away from the prefire plots.

Prior to and during the flaming phase of combustion, environmental and fire behavior measurements were monitored. The date and time of burning, air temperature, relative humidity, and in-stand (midflame) wind speed were recorded at all sites. The moisture content of selected fuel particles were also sampled at the time of ignition. Flame length, flame depth, flame angle, and flame height were measured from the head fires during each fire [*Alexander*, 1982]. In addition, the rate of spread and the residence time of flaming combustion were measured. Fire line intensity, which is defined as the rate of heat release per unit length of fire line (kW m^{-1}), was calculated through equations utilizing flame length as described by *Byram* [1959].

3.3 *Emission Sampling Protocols*

A special fire atmosphere sampling system (FASS) was used for measuring the carbon emissions and fire parameters in real time [*Susott et al.*, 1991]. The FASS units were controlled independently with individual on-board computers and data acquisition systems. Each contained real-time sensors for measuring the concentration of CO_2, CO, and NO along with temperature and the vertical vector of wind. The CO_2 sensors were nondispersive infrared gas monitors manufactured by Valtronics (model 2015 BMC) with a specified accuracy of 3% of full scale. (The use of trade or firm names is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.) The CO and NO sensors were electrolytic cells manufactured by Citicells with a specified accuracy of 2% of full scale. All gas sensors had response times of ≈20 s to reach 90% of full scale.

A schematic of the FASS package shows the flow of gases, airflow controllers, and computerized data logging systems (Figure 3). Typically, the real-time sensor data were logged once each second. The PM2.5 sampling was accomplished using individual cyclones to fractionate the particles less than 2.5 μm from the larger particles. The filters were positioned inside a special insulated metal container located between 8 and 13 m above the ground depending on expected fire conditions. Valves in the insulated container and in the main FASS control system directed sampling to

TABLE 1. Length of Time for the Collection of Each Set of Grab Samples

Test Area	Sampling Time, min				
	Pretest	F	S1	S2	S3
C4(11)	10	6	30.5		42.8
C4(16)	10	6	30.5		30.7
C3(11)	10	6	20.5		1.2
C3(16)	10	6	20.5		27.9
C1(11)	10	6	20.5		63.8
C1(16)	10	6	20.5		25.2
PF(11)	10	10	10	30.5	434
PF(16)	...	...	...	...	...
SF(11)	10	10	10	30.5	21.3
SF(16)	10	10	10	30.5	18.6

F, flaming; S, smoldering. PF, primary forest; SF, second-growth forest.

sequential pairs of filters and filled sequentially 2.5-L bags with gases coincident with the PM2.5 filter samples. The temperature of the combustion gases was measured using a type K thermocouple near the sample port height coincident with the FASS packages.

The general sampling protocol involved setting up two FASS packages for each test fire. Pretared Teflon and glass fiber filter mats were attached to the sampling ports for collecting samples of the PM2.5. Multilayered sampling bags were filled with samples of the gases downstream of a splitter valve. Paired samples of PM2.5 and gases were collected simultaneously from the same sample space for the flaming (F), first 10 min of smoldering (S1), and the next 20–30 min of smoldering (S2) combustion phases. The sampling times used by phase of combustion are listed in Table 1. Samples of the combustion gases collected in the multilayered bags by phase of combustion were transferred to evacuated 750-ml stainless steel canisters within 8 hours following the tests.

Sampling of emissions was performed for the C1, C3, and C4 vegetation types. In addition, the FASS packages were used for smoke emission sampling from slash fires in PF and SF types. In the field the FASS packages were positioned from 70 to 200 m from the line of ignition to avoid edge effects. The sampling protocol was triggered when the temperature at a point 50 m from the FASS exceeded 67°C. Each FASS package was triggered independently and switched from a background monitoring mode to a sampling mode tailored for the expected fire residence time in the specific fuel complex (Table 1).

3.4. *Analytical Protocols*

The analytical work on samples of gases, particles, and biomass was accomplished in laboratories at the Intermountain Fire Sciences Laboratory, Oregon State University, the Oregon Graduate Institute of Science and Technology, Sunset Laboratory, and NEA Laboratory. The 37-mm filters used for the collection of samples of particles were weighed before and after exposure using a Cahn model C-32 electrobalance (±10 μg in the 1- to 200-mg range). Standardized weighing procedures were followed with both field-control blanks and standard check weights weighed with the exposed filters in a controlled humidity and temperature clean room environment. Teflon filters were analyzed for trace metals using an X ray fluorescence method and the glass fiber filter mats sampled in parallel with the Teflon were used for determining the graphitic and organic carbon content using a ramped temperature volatilization method [*Huntzicker et al.*, 1982].

Nondispersive infrared (NDIR) gas analyzers were used to measure the concentrations of CO and CO_2 gas in sample bags to accuracies of ±0.3 and ±0.4%, respectively. The CH_4 and NMHC fractions were analyzed using a Carle gas chromatographic system equipped with packed columns and a FID (accuracy of ±3%). All analytical instruments were calibrated using multipoint calibrations with certified and traceable standards. Calibrations were intercompared with other laboratories. The FASS sample packages were calibrated using span gases (Scott gases, certified to ±2%, 496 parts per million by volume (ppmv) CO and 9800 ppmv CO_2 in air and 50 ppmv NO in air). Calibrations were performed automatically preceding the fire, following S1, and again after the sampling was completed. The NO calibrations were only made at the time of prefire and postfire deployment and retrieval. Other trace gases, including CO, CO_2, H_2, CH_4, and other hydrocarbons, were analyzed at the Oregon Graduate Institute of Science and Technology using techniques of gas chromatography and mass spectrometry [*Rasmussen et al.*, 1974; *Rasmussen and Khalil* [1981].

3.5. *Emission Factors and Rate of Fuel Consumption*

Emission factors were calculated using the carbon mass balance method [*Ward et al.*, 1979; *Radke et al.*, 1990]. The method is based on the partial oxidation of fuel (typically represented by the formula $C_6H_9O_4$) to CO_2 and products of incomplete combustion. The analysis of carbon content of slash from the boreal forest area in the Province of Ontario, Canada, provided carbon concentrations of 50–55% on an ash-free basis [*Susott et al.*, 1991]. Other analyses of carbon for fuels from the BASE-B study confirm the use of a value of 50% carbon (R. Susott and G. Olbu, unpublished data, 1992). *Fearnside* [1991] used a value of 50% carbon for biomass of Amazonia. By accounting for the carbon contained with the CO_2, CO, hydrocarbons, and particulate matter, the equivalent amount of fuel consumed can be estimated. In practice, the CO_2 and CO account for 95 to 99% of the carbon released from the fuel [*Ward and Hardy*, 1991].

An emission factor (grams per gram or grams per kilogram) is computed by dividing the concentration of the emission above background (grams per cubic meter) by the total carbon concentration (after subtracting the background) multiplied by 2, the ratio of fuel mass to carbon mass. The FASS units were specifically designed to make the measurements needed by phase of combustion so that these calculations could be made for the F, S1, and S2 combustion phases.

Rate of fuel consumption calculations were made by multiplying the carbon concentration above background as measured using the CO_2 and CO real-time sensors (grams per cubic meter) by the vertical velocity (meters per second) and this by the ratio of fuel to carbon. The error associated with not measuring the particulate matter and hydrocarbons in real time is less than 5%. Individual source strengths for emissions can be calculated by multiplying the concentration (grams per cubic meter) by the vertical velocity (meters per second).

TABLE 2. Aboveground Biomass (Fuel Loads) Before and After Fire (kg m^{-2}) and the Combustion Factor (%) Along a Vegetation Gradient From Tropical Grassland (Campo Limpo, C1) to Tropical Dry Evergreen Forest (Cerrado Sensu Stricto, C4) Near Brasilia, Brazil (August to September, 1990)

	Campo Limpo, C1		Campo Sujo, C2		Campo Cerrado, C3		Cerrado Sensu Stricto, C4	
Component	Prefire	Combustion Factor, %	Prefire	Combustion Factor, %	Prefire	Combustion Factor, %	Prefire	Combustion Factor, %
Dicot litter	<0.1 (0.0)	···	0.04 (0.01)	100 (0.0)	0.13 (0.01)	100 (0.0)	0.37 (0.01)	100 (0.0)
Grass dormant	0.55 (0.04)	···	0.58 (0.04)	···	0.29 (0.02)	···	0.25 (0.01)	···
Grass, green	0.12 (0.01)	···	0.08 (0.01)	···	0.06 (<.01)	···	0.02 (<.01)	···
Total grass	0.67 (0.05)	100 (0.0)	0.66 (0.04)	98 (0.6)	0.35 (0.02)	99 (0.2)	0.27 (0.01)	99 (0.3)
Dicot seedlings	0.04 (0.01)	100 (0.1)	0.03 (0.01)	71 (62.5)	0.24 (0.02)	49 (26.8)	0.17 (0.01)	71 (13.0)
Shrub leaves					<.01 (<.01)	84 (16.0)	0.01 (<.01)	34 (16.1)
Wood debris, cm diameter								
0–0.64	···	···	···	···	0.02 (<.01)	59 (11.7)	0.01 (<.01)	33 (14.0)
0.64–2.54	···	···	···	···	0.07 (0.02)	33 (13.1)	0.07 (0.01)	17 (11.1)
>2.54	···	···	···	···	0.04 (0.04)	0 (0)	0.10 (0.06)	57 (10.7)
Total wood debris	···	···	···	···	0.13 (0.06)	26 (11.7)	0.18 (0.06)	40 (10.4)
Total	0.71 (0.05)	100 (0.0)	0.73 (0.05)	97 (0.9)	0.86 (0.08)	72 (8.2)	1.00 (0.05)	84 (4.9)

Numbers are mean and standard error (in parentheses).

4. RESULTS AND DISCUSSION

In section 4 the data and initial analyses are presented for the cerrado and deforestation test fires. This is followed by a presentation of an analysis of emissions from the burning of biomass in tropical ecosystems.

4.1. *Biomass, Fire Behavior, and Combustion Factors*

4.1.1. *Cerrado ecosystems.* The cerrado of Brazil is one of the most extensive tropical vegetation types in South America [*Coutinho*, 1990]. Fire-return intervals in cerrado ecosystems are as frequent as 1–3 years [*Eiten*, 1972]. Because the composition and structure of the cerrado varies from closed-canopy forest to open grassland, fuel composition and loads are also variable. Differences in the composition and structure of fuels were important in affecting fire behavior, biomass consumption, and smoke composition.

Along the vegetation gradient from C1 to C4, fuel loads increased from 0.71 to 1.00 kg m^{-2} (Table 2). In addition to variability in mass there were large compositional differences. The C1 and C2 were essentially treeless grasslands and the fuel loads were primarily composed of grasses (or grasslike). In these grasslands the fuel loads were equivalent to the total aboveground biomass. In contrast, semideciduous trees, at a density of 600–800 ha^{-1} and a mean height of 3–5 m, dominated the C3 and C4 sites. The boles and canopies of the trees were relatively resistant to the intense, short-duration pulse of heat produced during fires in these communities. In the C3 and C4 communities, dicot litter was the most abundant component (0.37 kg m^{-2}). There was also a significant quantity (0.13–0.18 kg m^{-2}) of wood debris and dicot seedlings (0.17–0.24 kg m^{-2}). The dead and downed wood debris fuel component has seldom been considered in fire studies of tropical savanna ecosystems.

All of the experimental fires in the cerrado occurred between August 28, 1990, and September 4, 1990. Relative humidity during the burns ranged from 41 to 54% and temperature ranged from 28°–34°C. Winds were moderate in intensity (6–15 km h^{-1}). All fires were wind-driven head fires. They were ignited with kerosene-soaked rags on the upwind side of the burned areas. Slope of all sampled areas was <10%.

Moisture content on a dry weight basis of the dead fine fuels (that is, litter, small wood debris, and dormant grass) ranged from 13 to 29%. Live fuel moisture content (that is, dicot seedlings and green grass) ranged from 104 to 146%. From these data the quantity of water in fuels at the time of burning was calculated: 0.31 kg m^{-2} in C1, 0.29 kg m^{-2} in C2, 0.51 kg m^{-2} in C3, and 0.46 kg m^{-2} in C4.

As virtually all fuels were fine textured grasses in these tropical grasslands (C1 and C2), the fire spread was much more efficient than the two woodland-dominated communities (C3 and C4). Flame depth, flame height, and flame length were greatest for the grasslands. Average fireline intensity in the tropical grasslands (C1 and C2) exceeded 16,000 kW m^{-1} compared to measurements of <4000 kW m^{-1} for fires in areas dominated by trees (C3 and C4).

The total amount of biomass consumed by the fires (that is, the combustion factor) was 100 and 97% in the two tropical grasslands (C1 and C2) (Table 2). In the savanna types, combustion factors were 72% for C3 and 84% for C4. Even though the total combustion factor was significantly lower for these two savanna types, there was no difference in the combustion factor of the grass component among all communities. In all communities the combustion factor of the grass component and dicot litter exceeded 98%. However, in C3 and C4 the percentage of wood debris consumed during fires was lower than for the grass components; combustion factors of wood debris were 26 and 40%, respectively.

4.1.2. *Tropical moist forest.* The fuel biomass of the tropical moist forest was approximately 30-fold greater than that of the cerrado vegetation types. Total fuel loads of SF and PF were 12.1 and 29.2 kg m^{-2}, respectively (Table 3). The biomass estimate of SF is equivalent to total aboveground biomass as all vegetation had been cut prior to burning. However, in the PF there were many uncut trees of the Lecythidaceae (Brazil nut) family standing as well as numerous trees that had been cut but did not fall. Therefore our estimate of the fuel mass in PF is somewhat less than the total aboveground biomass for this ecosystem.

Our fuel loading estimate for PF is similar to that reported for other primary forest sites of the eastern Amazon [*Nep-*

TABLE 3. Total Mass (kg m^{-2}) Prior to Fire and Following Slash Fires in PF and SF Tropical Moist Forest Near Maraba Brazil, September 1990

Component	SF		PF	
	Prefire	Combustion Factor, %	Prefire	Combustion Factor, %
Attached foliage	0.12 (0.03)	88.91 (3.62)	0.28 (0.03)	78.34 (16.59)
Litter	1.10 (0.17)	98.92 (1.08)	1.18 (0.16)	100.00 (0.00)
Dicot seedlings	0.02 (0.01)	100.0 (0.00)	0.11 (0.04)	100.00 (0.00)
Wood debris, diam cm				
0.64	0.23 (0.05)	88.91 (3.63)	0.35 (0.04)	78.34 (16.59)
0.64–2.54	1.36 (0.24)	67.41 (6.58)	1.88 (0.20)	77.56 (4.97)
2.54–7.6	1.35 (0.23)	27.13 (7.21)	3.16 (0.31)	55.31 (8.84)
7.6–20.3	5.20 (0.90)	28.33 (11.06)	6.78 (0.64)	25.30 (5.83)
>20.3	2.76 (1.33)	13.97 (5.48)	15.50 (3.45)	44.43 (10.76)
Total wood debris	10.90 (1.69)	36.87 (2.45)	27.67 (3.62)	49.47 (3.87)
Total	12.14 (1.68)	42.87 (2.93)	29.24 (3.58)	52.56 (3.61)

Numbers are mean and standard error (in parentheses).

stad, 1989; *Uhl and Kauffman*, 1990; *Uhl et al.*, 1988]. These authors reported total aboveground biomass of the primary forest to be ≈31.9–36.3 kg m^{-2} which is close to our fuel-loading estimate of 29.2 kg m^{-2}. In a global comparison of tropical moist evergreen forests these forests are above average, although not exceedingly so [*Brown et al.*, 1989]. In a review of aboveground biomass of tropical moist forests, *Kauffman and Uhl* [1990] reported a range of 18.1–40.6 kg m^{-2}.

In both forest ecosystems (SF and PF), biomass of fine fuels (that is, wood debris ≤0.64 cm diameter, attached foliage and litter) exceeded 1.4 kg m^{-2}. The fine fuels carry the fire through the slashed areas and are totally consumed during the flaming combustion phase.

The PF site was burned on September 9, 1990, under clear skies with a temperature of 40°C and relative humidity of 41%. The SF site was burned on September 13, 1990, with an ambient temperature of 37°C and relative humidity of 59%. Winds were light (0–10 km h^{-1}) and the sky was completely overcast on both days. Local agriculturalists who performed the burning operations for the PF and SF sites stated that conditions were ideal for burning. For the SF site, a significant precipitation event occurred ≈1 hour following ignition which likely lowered the combustion factor. Nevertheless, the property owner was satisfied with the level of biomass consumption.

Virtually all fine fuels (stems, leaves, litter) were consumed during these slash fires in Amazonia (Table 3). Lesser quantities of coarse woody debris were consumed. Combustion factors for the total fuel consumed in this study were 43% for the SF and 53% for the PF. These are substantially higher than the 30% combustion factor reported by *Fearnside* [1985]. In addition, these combustion factors are substantially higher than those utilized by *Seiler and Crutzen* [1980] and *Hao et al.* [1990] in their estimates of global emissions from biomass burning (25 and 30%, respectively). However, the combustion factors of fires in this study were lower than that observed by *Kauffman et al.* [1992] for other slash fires in the eastern Amazon. Precipitation in the eastern Amazon is lower than that of many tropical moist forests and this may contribute to the higher combustion factors observed for slashed tropical ecosystems. However, in comparison to the tropical dry deciduous forests of northeastern Brazil these combustion factors were quite low. *Kauffman et al.* [1991] reported combustion factors of slash fires in tropical dry forest ranged from 78 to 95%. Fuel biomass in these ecosystems was ≈7.4 kg m^{-2}. Additional research is needed to further quantify the range of variability in both biomass and combustion factors among tropical slash fires.

4.2. *Emission Measurements*

The characteristics of emissions generated from the five experimental fires conducted in the cerrado and forested areas of Brazil are presented in the following sections. The analysis of grab samples that were collected by phase of combustion using FASS are presented in section 4.2.1 along with the real-time measurements of the background preceding the fire and continuing with measurements of the emissions through the F, S1, and S2 combustion phases. The particulate matter concentration and content data are presented in section 4.2.2, with the ratios of emissions presented in section 4.2.3, the carbon flux and biomass consumption by phase of combustion in section 4.2.4, and the calculation of combustion efficiency and emission factors in section 4.2.5.

4.2.1. *Concentrations of gaseous emissions.* Table 4 lists the concentration data for the trace gases for the F phase cerrado samples; F, S1, and S2 for the PF fire; and F and S1 phases for the SF fire for each of the two FASS packages used (FASS 11 and 16). The background sample concentrations are listed in Table 4. The integrated gas samples collected for the cerrado areas exhibited high concentrations of all combustion-generated gases for the F phase samples and then decreased to near-background levels for the S1 samples. This is reflected in the high average concentrations of 1262, 58, 4.1, 5.8, and 9.3 ppmv for CO_2, CO, CH_4, NMHC, and H_2, respectively. The average concentrations for the same gases for the S1 combustion phase were 354, 0.8, 2.2, 5.1, and 4.7 ppmv, respectively. The background samples for all gases were from canister samples, whereas the analysis of the NMHC component was performed from the bag samples [*Olbu et al.*, 1991]. Undoubtedly, the background of the bags swamped the low concentrations from the cerrado tests; therefore we do not report the NMHC emission factors or ratios of emissions for the cerrado tests (Table 4).

TABLE 4. CO_2, CO, CH_4, and H_2 Concentrations From Grab Samples Collected and Transferred From Sample Bags to Evacuated Canisters for Three Fuel Types in Brazil

	CO_2 ppmv	CO ppmv	NMHC ppmv-C	CH_4 ppmv	H_2 ppmv	η Ratio
C4/11F	1076	55.7		3.70	11.5	0.93
C4/16F	1562	74.0		4.01	11.4	0.94
C4/background	356	0.28		2.02	.89	
C3/11F	1088	64.4		3.79	9.8	0.93
C3/16F	742	33.8		2.99	6.7	0.92
C3/background	336	0.11		2.10	1.0	
C1/11F	1240	46.3		3.72	6.2	0.95
C1/16F	1861	75.5		6.14	10.4	0.95
C1/background	345	0.13		2.10	0.90	
PF/11F	2762	272.8	15.8	29.99	99.8	0.88
PF/11S1	1730	208.9	13.1	23.56	80.3	0.85
PF/11S2	946	90.4	7.7	14.29	45.7	0.84
PF/background	359	0.26	2	2.00	0.90	
SF/11F	552	14.7	2.4	3.53	6.9	0.92
SF/11S1	1238	94.0	3.1	11.19	37.0	0.90
SF/16F	744	39.2	3.2	5.63	13.8	0.89
SF/16S1	1000	61.1	6.1	9.35	29.2	0.89
SF/background	345	0.20	2	2.02	0.89	

Nonmethane hydrocarbon (NMHC) concentrations are determined directly from sample bags. Background samples were collected into evacuated canisters. Combustion efficiency (η) is listed in the right-hand column; ppmv is parts per million by volume.

Concentrations of the primary gases were measured using real-time CO_2, CO, and NO sensors on board the FASS packages (Table 5). The measurements included a period of time preceding and following the fire (see Table 1) as well as a complete concentration profile during the fire. The average concentration measured by the real-time sensors should equal the concentrations of gases in the canister samples over the same collection periods ($+4 \pm 17\%$ and $-5 \pm 7.5\%$ for CO and CO_2, respectively). Figure 4 shows the real-time response of the FASS 11 instrument on area C1, as compared to the same measurements for the PF area. The real-time data collection before and after the fires was of variable length. The mass ratio of CO/CO_2 increases as the fire progresses from the flaming phase to the smoldering phase. This ratio has been found to correlate well with the release of other products of combustion [*Ward and Hardy*, 1991] and is used here as an indicator of combustion efficiency. The calculated combustion efficiency (CE) based on the ratio of carbon released as CO_2 divided by the carbon released in the form of all carbon-containing products of combustion correlates well with the ratio of CO to CO_2 ($CE = 0.99–1.03*(CO/CO_2)$, $R^2 = 0.99$).

The NO concentrations ranged to 7 ppmv for the PF test and averaged close to a peak concentration of 4 ppmv for the cerrado tests. The integrated average values were higher during the F phase than for the S1 phase. For example, for PF the concentration decreased from 2.7 ppmv during the F phase to less than 1 ppmv late in the S2 phase (Figure 4). The dominant emissions of nitrogen species should be expected during the period of combustion of the fuels with the highest nitrogen content. Higher ratios of NO_x would be expected during the F phase with reduced nitrogen species dominating during the S combustion phase [*Hao et al.*, 1990; *Lobert et al.*, 1991].

4.2.2. *Concentrations of PM2.5 emissions.* PM2.5 was collected for each phase of combustion on both glass fiber and Teflon filter mats (37-mm filters). The volume of gas through each filter was measured and this value divided into the mass of PM2.5 collected on each filter (Table 5). Both filters were averaged for each phase of combustion and the average used for the emission factor calculations. The concentration of PM2.5 for the cerrado test areas was low (3.4 mg m^{-3}) as compared to the PF area (12.2 mg m^{-3}). The difference in indicated mass concentration between the glass fiber and Teflon filter mats is likely a result of losing fibers from the glass fiber filters. Field controls, check weights, and a very sensitive microbalance were used; however, the fires were of a very short duration for the cerrado areas and PM2.5 concentrations were relatively low. The glass fiber filter mats were analyzed for organic and graphitic carbon content [*Huntzicker et al.*, 1982]. The organic carbon content of the PM2.5 for the cerrado fires ($57.9 \pm 37.9\%$) was higher than for the PF fire (42.5%). For the graphitic carbon content of the PM2.5 the cerrado fires averaged $4.6 \pm 3.4\%$ as compared to 4.1% for the PF fire.

Trace element composition was measured from the Teflon filter mats collected in parallel with the glass fiber filters. For the PF site, a lower inorganic fraction was measured for the PM2.5 with a corresponding increase in the organic carbon fraction between the flaming and the two smoldering phases

TABLE 5. Average Gas Concentrations Measured Using Real-Time Gas Analyzers On Board the FASS Packages Located in the Fire Zone of Three Different Fuel Types in Brazil

	FASS CO ppmv	FASS CO_2 ppmv	FASS NO ppmv	PM2.5, G mg m^{-3}	PM2.5, T mg m^{-3}	Average mg m^{-3}
C4/11F	41.1	1060	0.62	1.17	5.44	3.31
C4/16F	61.1	1646		4.28	7.40	5.89
C3/11F	52.5	1148	0.61	1.51	5.62	3.56
C3/16F	30.8	826		1.21	3.31	2.26
C1/11F	35.7	1201	0.84	1.26	1.14	1.20
C1/16F	72.4	1901		2.83	5.91	4.37
PF/11F	251.1	2668	2.69	19.28	15.89	17.58
PF/11S1	195.1	1713	2.25	14.42	13.59	14.00
PF/11S2	99.4	993	1.03	5.66	4.50	5.08
SF/11F	14.9	569	0.44	1.50	3.10	2.30
SF/11S1	99.5	1498	1.64	12.76	10.10	11.43
SF/16F	39.6	789		4.78	5.23	5.00
SF/16S1	86.7	1192		7.67	5.43	6.55

FASS, fire atmosphere sampling system; PM, particulate matter; G, glass fiber; T, Teflon.

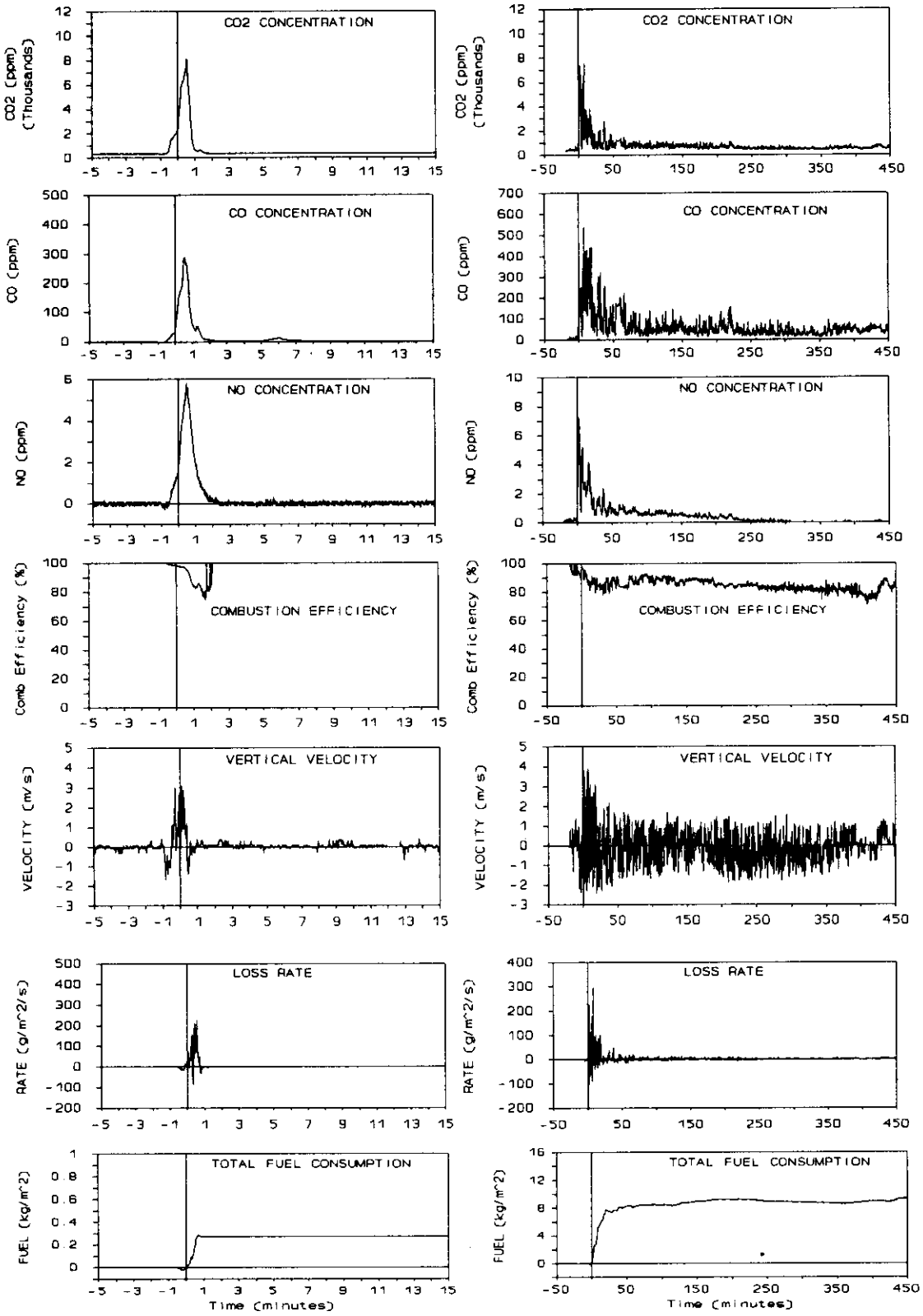

Fig. 4. Real-time measurements of gas concentrations and vertical velocity for a cerrado area burn (on the left) and a fire in a primary slashed forest site using the FASS.

of combustion. The S, Cl, K, and Ca concentrations of the PM2.5 are of particular significance (Figures 5*a*–5*c*). The general profile of trace elements for the Brazil smoke samples are similar to profiles for fires in the United States [*Ward and Hardy*, 1991]. Pb and Hg were both below the detection limit for the X ray fluorescence techniques utilized for analyzing the filters. The apparent reversal of the percent inorganic content of the PM2.5 of S, Cl, K, and Ca for the SF

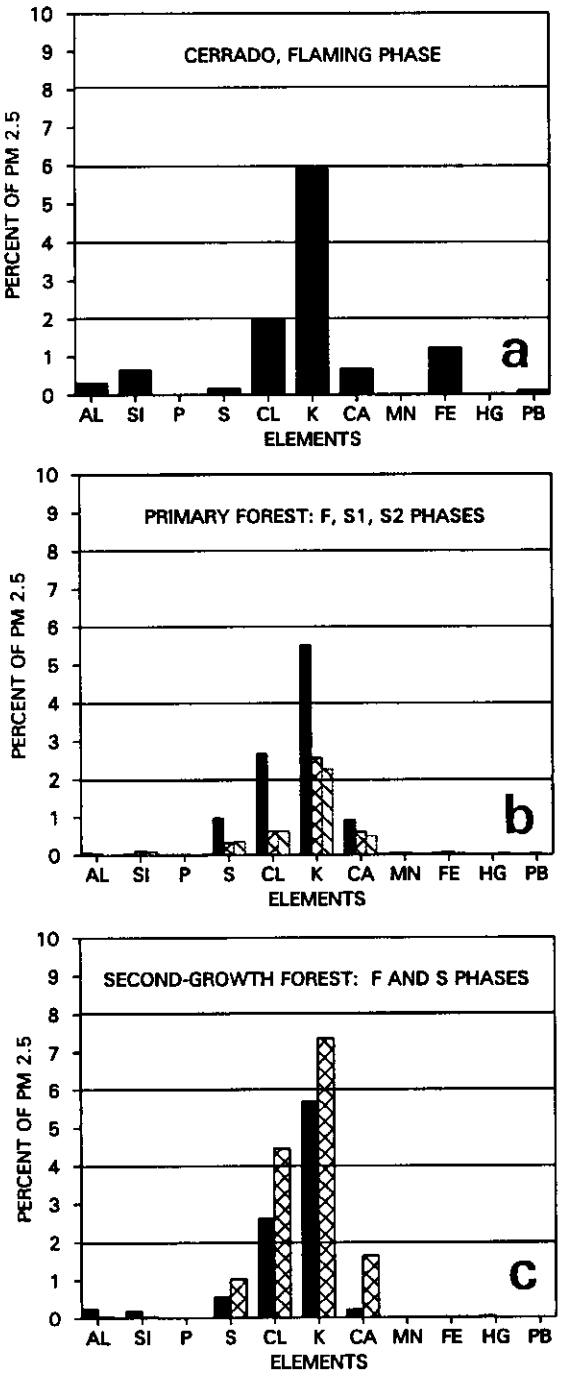

Fig. 5. Trace element composition of PM2.5 for smoke particles from three different burn scenarios in Brazil: (*a*) cerrado, (*b*) primary forest, and (*c*) second-growth forest.

fire (Figure 5*c*) is thought to be a result of the fire spreading slowly and having a poorly defined (and delayed) transition from flaming to smoldering. The ratio of K to "black carbon" content of the aerosol is often used as a tracer for particulate matter from biomass burning [*Artaxo et al.*, 1988; *Cooper*, 1980]. *Artaxo et al.* [1988] found ratios of K to total particulate matter of 0.0030 which they deduced resulted from a minor contribution of biomass burning to the measured loading of particulate matter. Our measurements of K to PM2.5 collected at the source of the biomass fires are an order of magnitude larger, ranging from 0.02 to 0.075.

4.2.3. *Ratios of emissions.* The concentrations of trace gases (CO, CH_4, and H_2) are well correlated with PM2.5 (Figure 6). The cross-correlation coefficients for concentrations of products of incomplete combustion show high correlation coefficients among CO, PM2.5, CH_4, and H_2 of $r \geq 0.93$. However, the correlation of these same compounds with CO_2 exhibits r values between 0.69 and 0.81 (Table 6). As we will demonstrate in the following sections, the ratios of products of incomplete combustion should be relatively constant over a wide range of combustion efficiency. On the other hand, the ratio of products of incomplete combustion to CO_2 should be much less stable.

Kaufman et al. [this issue] used ratios of gases to PM for evaluating the release of trace gases to the atmosphere. If these ratios are constant over the range of combustion conditions (from high to low combustion efficiency), then the overall estimates made by *Kaufman et al.* [1990] of trace gas emissions released to the atmosphere should be good. We have tested this range of ratios over the range of combustion efficiencies sampled (0.84 to 0.95, from Table 4). The combined data for the cerrado and forest areas provide ratios of PM2.5/CO, PM2.5/CH_4, and PM2.5/H_2 of 0.061, 0.161, and 3.00 with relative standard deviations of 50, 45, and 38%, respectively (Table 7). This suggests for these data that the ratios over the broad range of combustion conditions from the cerrado to the PF have a standard deviation of 50% or less of the mean. Using the ratios of PM2.5 to trace gases of CO, CH_4, or H_2 should yield results with error bars slightly larger than the technique used to estimate the PM2.5 emissions.

Several investigators [*Crutzen and Andreae*, 1990; *Andreae*, 1991; *Hegg et al.*, 1989] have used the molar ratios of gases to CO_2 for evaluating the gases produced globally. We show this ratio to be highly variable and dependent on the combustion efficiency as well as the chemical composition of the biomass. Our data presented here and those of *Ward and Hardy* [1991] demonstrate the magnitude of the errors that may result when using ratios of products of incomplete combustion to CO_2 for evaluating the global release of emissions [*Ward and Hao*, 1991]. Different ecosystems have physical and chemical characteristics affecting the combustion efficiency for fires and therefore the ratio of products of incomplete combustion to CO_2. For example, for the cerrado ecosystem the residence time of the flame zone was of the order of 15 to 30 s with nearly 100% of the fine fuels consumed by the flaming fire front (Table 2). In contrast, the PF fire was believed to have a much longer residence time for the flame front (of the order of minutes) with a very large percent of the total fuel consumed through the smoldering combustion process. Because of the abundance of the large diameter classes of fuels (Table 3) and the compactness of the biomass near the ground the fire smoldered for a very long period of time, 5 days (Figure 4, ≈6–7 hours of sampling). Hence the fire exhibited a low combustion efficiency (Table 8) and high emissions of products of incomplete combustion. The use of constant emission factors for different ecosystems with dissimilar fire environments will lead to sizable errors.

One of the principal objectives for both BASE-A and BASE-B research was to improve the overall accuracy of methods using satellite imagery for quantifying and characterizing the emissions from biomass burning in the tropical regions. *Kaufman et al.* [1990] used 3.7 μm and 11 μm

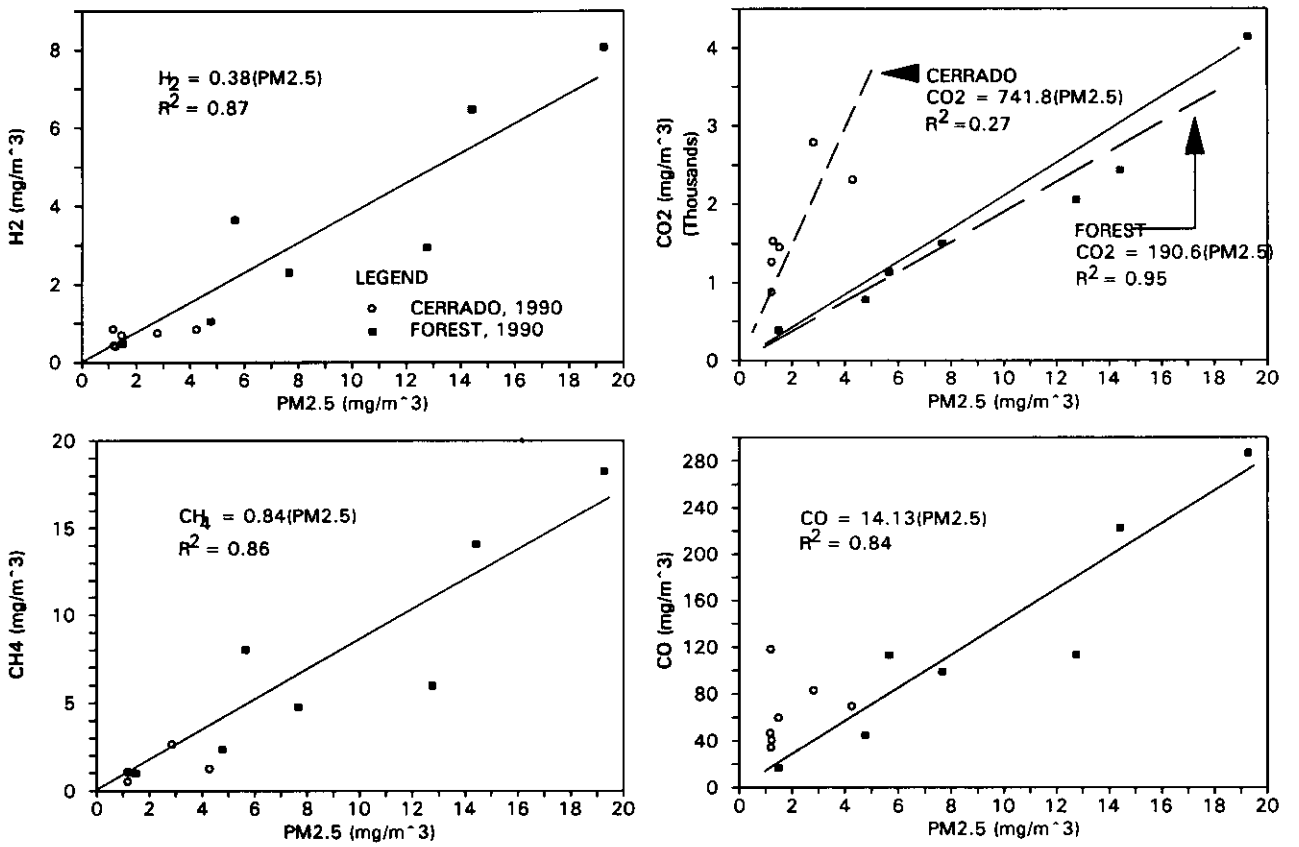

Fig. 6. General correlation of concentrations (mass to volume) of emissions of H_2, CO_2, CH_4, and CO and PM2.5. The data are for the cerrado, primary forest, and second-growth forest tests in Brazil.

imagery from the AVHRR satellite to identify and count the number of fires burning in Brazil (in a limited area between 6.5°–15.5°S and 55°–67°W) during 3 months of the dry season (July 1 to September 30). Satellite imagery for the visible and near-IR portions of the spectrum were used to derive the aerosol optical thickness and other parameters. Using this technique, an estimate was derived of the total mass of particulate matter released by the fires. One of the principal assumptions of the study was that ratios of gases to particulate matter measured in temperate areas [*Ward and Hardy*, 1984] apply to emissions from fires in the tropics. The average ratios used by *Kaufman et al.* [1990] were 1.73, 0.06, and 0.01 for PM2.5/CH_4, PM2.5/CO, and PM2.5/CO_2, respectively. These ratios are compared to those measured for the PF and SF fire tests of this study of 1.44, 0.081, and 0.005. The results show a difference of 17, −26, and 100%, respectively. We think the agreement for the PM2.5/CH_4 and PM2.5/CO ratios is acceptable; however, with our present knowledge of combustion efficiency, improvements are possible for the PM2.5/CO_2 ratio. In reviewing the work of *Kaufman et al.* [1990], it is evident that calculations of emissions were based on the smoldering combustion ratio of PM2.5/CO_2 (0.01). The ratio of PM2.5/CO_2 for the carbon release weighted average was reported by *Ward and Hardy* [1984] to be 0.007 with a fire-weighted average combustion efficiency of 0.83. The average combustion efficiency for the analysis of *Kaufman et al.* [1990] was 0.76. This would account for the difference in ratios of PM2.5/CO_2 among this work, the work of *Ward and Hardy* [1991], and the work of *Kaufman et al.* [1990]. The combustion efficiency for the PF and SF fires ranged from 0.84 to 0.92. The combination of PF, SF, and pasture burns would suggest a higher combustion efficiency than the scenario described by *Kaufman et al.* [1990].

TABLE 6. Correlation Matrix for the Concentration of Gaseous (Table 4) and PM2.5 (Table 5) Emissions From Fires in the Cerrado, Deforestation, and Second-Growth Areas of Brazil

Emission	CO_2	CO	CH_4	H_2
PM2.5	0.72	0.93	0.93	0.94
CO_2		0.81	0.71	0.69
CO			0.98	0.98
CH_4				0.99

For estimating emissions on a regional or global scale, potential error can develop if ratios of products of incomplete combustion to CO_2 are used without considering the combustion efficiency for the different ecosystems. For the data of *Kaufman et al.* [1990] the CO_2 emissions are a factor of 2 larger when measurements made during this study are used for expanding the data. This can be expected from the results of *Ward and Hardy* [1991] which demonstrates particulate matter emission factors changing from 0.06 to 0.02, while the emission factors for CO_2 increase from 2.5 to 3.0 over the range of combustion efficiency from 0.75 to 0.90. Hence the ratio of PM2.5/CO_2 would change from 0.024 to 0.006 or by a factor of 4. The ratios of PM2.5/CO and PM2.5/CH_4 only change from 0.0010 to 0.0011 and 0.025 to

TABLE 7. Ratios of Compounds on a Mass-to-Mass Basis for the Cerrado, PF and SF Fires of Brazil

	PM2.5/CO	PM2.5/CH_4	PM2.5/H_2	PM2.5/CO_2	CH_4/CO	H_2/CO	H_2/CH_4
Cerrado							
avg	0.035	1.677	2.936	0.001	0.023	0.013	0.600
s.d.	0.014	0.875	1.269	0.0004	0.006	0.003	0.206
r.s.d.	38%	52%	43%	33%	26%	25%	34%
Forest							
avg	0.081	1.439	3.057	0.005	0.059	0.027	0.468
s.d.	0.023	0.534	1.099	0.001	0.008	0.003	0.022
r.s.d.	28%	37%	36%	16%	13%	12%	5%
Both							
avg	0.060	1.549	3.001	0.003	0.042	0.021	0.529
s.d.	0.030	0.690	1.131	0.002	0.020	0.008	0.150
r.s.d.	50%	45%	38%	66%	47%	40%	28%

The ratios are the emission factor of one compound divided by the emission factor of another compound. Values are averages (avg), standard deviations (s.d.), and relative standard deviation (r.s.d.) for each set of ratios. The r.s.d. is the s.d. divided by the avg.

0.0265, respectively, over the same range of combustion efficiency. If ratios of emissions are being used based on CO_2, then the combustion efficiency of the fires of interest is extremely important when computing the release of CO_2 to the atmosphere and in developing the ratios of products of incomplete combustion to CO_2. When multiplying particulate matter emissions by ratios of products of incomplete combustion to particulate matter, then the combustion efficiency of the fire is not critical. However, when evaluating emissions released based on the biomass consumed and when emission factors are used, it is extremely important to consider the combustion efficiency of the fire or the class of fires for the ecosystem of interest.

4.2.4. *Biomass consumption and carbon flux measurements.* In developing emission ratios and emission factors that are representative of the entire fire from ignition to the end of the smoldering combustion phase, it is important to weight the emission ratios or emission factors by the carbon released by phase of combustion. This is accomplished by multiplying the emission ratio for the flaming phase by the ratio of carbon released during the flaming phase and adding to this the product of the smoldering phase emission ratio and the ratio of carbon released during the smoldering phase. Probably the methods employed during this project and those reported by *Ward and Hardy* [1991] are the only ones that have provided these measurements for field research.

Generally, samples have been extracted from flaming or smoldering or flaming and smoldering environments with no measurement of the fuel consumed by phase of combustion [*Crutzen et al.*, 1985; *Greenberg et al.*, 1984; *Bonsang et al.*, 1991; *Radke et al.*, 1991]. If consideration is given for a difference in emissions by phase of combustion, it is generally assumed to be a mixture of flaming and smoldering with no definition of the percentage of either.

For this study, the flux of carbon is computed by multiplying the sum of the concentrations of CO_2-C and CO-C (milligrams per cubic meter) by the vertical flow velocity (vector mass flow component, meters per second), as discussed in section 2.5. The carbon from the CO_2 and CO constitutes more than 95% of the carbon released [*Ward and Hardy*, 1991], hence any error would be expected to be less than 5% as a result of not accounting for carbon associated with particulate matter, CH_4, and the NMHC fractions. Eddy correlation techniques are useful for measuring the flux of materials through the atmosphere, generally where the rate of deposition or release from the surface are of

TABLE 8. Emission Factors (EFs) for PM2.5, CO_2, CO, CH_4, NO, and H_2 and Combustion Efficiency for the Three Differnet Fuel Types Sampled in Brazil

	EFPM2.5 g kg^{-1}	EFCO_2 g kg^{-1}	EFCO g kg^{-1}	EFCH_4 g kg^{-1}	EFNO-N g kg^{-1}	EFH_2 g kg^{-1}	CE Ratio
C4/11F	4.5	1713	63	1.6	0.5	1.2	0.93
C4/16F	4.4	1732	52	1.0		0.6	0.94
C3/11F	4.2	1705	70	1.3	0.4	0.8	0.93
C3/16F	4.4	1690	68	1.1		0.9	0.92
C1/11F	1.4	1749	46	1.2	0.6	0.5	0.95
C1/16F	2.7	1740	51	1.6		0.5	0.95
PF/11F	6.8	1612	112	7.1	0.6	3.1	0.88
PF/11S1	8.9	1551	142	9.0	0.8	4.1	0.85
PF/11S2	6.8	1531	152	10.8	0.8	4.9	0.84
SF/11F	10.0	1692	73	4.3	1.1	2.1	0.92
SF/11S1	9.2	1652	91	4.8	0.8	2.4	0.90
SF/16F	10.4	1637	94	4.9		2.2	0.89
SF/16S1	7.1	1625	107	5.2		2.5	0.89

Same identification parameters as used for Tables 2 and 3. The emission factors are on a mass of compound to mass of fuel-consumed basis except for NO (mass of nitrogen per mass of fuel-consumed basis).

TABLE 9. Biomass Consumption From Measurements of the Flux of Carbon Contained With the CO_2 and CO As Measured Using the Real-Time Gas Analyzers On Board the FASS Packages for the Three Different Fuel Types Sampled in Brazil

	Cerrado, C1, C2, C3 kg m^{-2}	PF kg m^{-2}	SF kg m^{-2}
Prefire	0.025	1.96	0.01
F	0.415	2.64	0.03
S1	0.000	1.01	0.18
S2	0.005	0.60	3.25
S3	0.010	1.76	2.77
Avg	0.460	7.97	6.23

interest [*Zeller et al.*, 1990]. Several conditions must be satisfied to improve the reliability of eddy correlation methods for flux calculations, including level surface, homogeneous turbulence, sufficient averaging time, and others. We use a simple computation of the vertical smoke vector multiplied by the concentration to compute the flux. This works well for most long duration fires (flaming phase >10 min and smoldering phase >1 hour) on reasonably level terrain with low horizontal wind speeds [*Susott et al.*, 1991]. The technique was used for estimating the fuel consumption by phase of combustion and the total for each set of measurements on each fire (Table 9). The fuel consumption on a unit area basis for the cerrado fires was complete within 3 to 4 min following ignition. A very minor amount of biomass was consumed during the smoldering combustion phase for these tests.

The fuel consumption based on the carbon flux method averaged 0.46 kg m^{-2} for the three cerrado areas. This was ≈61% of the inventory measurement of fuel consumption (Table 2). Nevertheless, the relative rate of carbon release shows in excess of 97% of the carbon released during the F phase (6 min). The real-time measurements (see Figure 4) show the carbon release rate to occur even more rapidly with virtually all of the carbon being released within the first 2 min after arrival of the fire front. For the PF test, we measured the rate of carbon flux from the test area over the first 7 hours of the burn. The results for the PF fire (Figure 4) demonstrate the exponential die down of the smoldering combustion phase similar to the model of *Ward and Hardy* [1991] for fires of the Pacific Northwest (United States) but with a much longer time constant. The smoldering combustion was still not complete after 5 days.

The fine fuels on both the cerrado and the deforestation sites (those fuels <0.64 cm diameter) were actively consumed during the first few minutes of the fire (high concentrations of CO_2 and vertical flow of gases, Figure 4) which created a high-intensity flame front moving through the areas of the FASS units. The measured fuel consumption for the PF site using the carbon mass flux method was 8 kg m^{-2}, which represents 52% of the inventoried carbon released from the site. This is a reasonable measurement of the consumption since nearly all of the fine fuels and materials to about 7.6 cm in diameter (or ≈6 kg m^{-2}) would be consumed during the 7 hours of sampling. Considering that the diameter reduction and smoldering consumption of the larger diameter fuels was well under way by this time, the measurement of carbon release for PF agrees well with the site conditions. For the SF site, the FASS measurement of carbon flux was approximately 20% larger than the inventoried values (Tables 3 and 9). The SF fire lasted less than 2 hours with 90% of the carbon release occurring during the S2 and S3 phases (Tables 1 and 9) due to the early triggering of the FASS units.

4.2.5. *Emission factors and relation to combustion efficiency.* On the basis of many measurements of combustion efficiency [*Ward and Hardy*, 1991] we have found the parameter to be a good integrator of the fire response to the combined fuel arrangement and weather influence on the behavior of the fire and the measured combustion products. Others have used the ratio of CO/CO_2 (usually as a molar ratio or as a ratio of carbon to carbon) to correlate with other products of incomplete combustion. This ratio is nonlinearly correlated with combustion efficiency. A normalized parameter, modified combustion efficiency (MCE), $(CO_2/(CO + CO_2))$ can be linearly correlated with other products and is correlated for this study with combustion efficiency (MCE = 0.197 + 0.801*CE, $R^2 = 0.994$). MCE is independent of the PM2.5, CH_4, and NMHC. We use the more fundamental parameter for defining the combustion efficiency of the fires in the emission factor models presented below.

An emission factor (EF_n) is an important parameter used to define the efficiency of converting fuel to individual chemical species. It is expressed as a ratio of the mass of a species released to the fuel consumed (on an oven dry weight basis). The source strength and the total release of effluent, Q_n, can be defined as:

$$Q_n = A \cdot B \cdot \alpha \cdot \beta \cdot EF_n \quad (1)$$

where n = CO, CO_2, CH_4, NMHC, PM2.5, N_2O, $\cdots$, where A is a region or ecosystem of defined extent, B is a total loading of biomass fuel, α is the fraction of the biomass aboveground, and β is the combustion factor. Others have estimated A, B, α, and β on an ecosystem basis [*Hao et al.*, 1990; *Crutzen and Andreae*, 1990; *Ward and Hao*, 1991]. Through this research, we have provided additional data for the aboveground biomass, combustion factors, and EF_n. Over a finite period of time, A, B, and α can be assumed to be constant, whereas β and EF_n are variables dependent on the climate history over the preceding days to weeks and the immediate influence at the time of the fire. The factors B and α may have a more pronounced weather dependency for savanna ecosystems. The overall production of biomass between fire-return intervals can be influenced by the rainfall and temperature history for the ecosystem. The proportion of aboveground biomass (α) consumed (β) by a fire may have a very different emission factor (EF_n) under dry burning conditions than during a wet period. We have been able to characterize or integrate these effects on EF_n through modeling against combustion efficiency.

Using data from Tables 4 and 5 and the carbon mass balance technique, emission factors were calculated (Table 8). The combustion efficiency averaged 0.94, 0.86, and 0.90 for the cerrado, PF, and SF sites, respectively. Linear regression methods were used to develop the following models as a function of combustion efficiency for the combined data sets (cerrado, PF, SF):

$$EFPM2.5 = 69.9–70.9(CE), \quad R^2 = 0.59; \quad (2)$$

$$EFCO = 896–892(CE), \quad R^2 = 0.99; \quad (3)$$

TABLE 10. Linear Regression Models for Predicting Emission Factors for PM2.5, CO, CH_4, and H_2

Parameter	Intercept	Slope	R^2	CE = 0.90 g kg^{-1}	Reported EFs* g kg^{-1}	Difference %
This study						
PM2.5	69.9	−70.9	0.59	6.0		
CO	896	−892	0.99	92.9	105	13
CH_4	78.6	−82.1	0.92	4.8	6	26
H_2	35.1	−36.5	0.95	2.3	2.0	−10
Ward and Hardy [1991]						
PM	93.3	−90.5	0.54	11.8	15	27
PM2.5	67.4	−66.8	0.74	7.3		
CO	961	−984	0.95	75.4	105	39
CH_4	42.7	−43.2	0.77	3.8	6	57

The models are compared with those developed by *Ward and Hardy* [1991].
*Emission factors adapted from *Crutzen and Andreae* [1990].

$$EFCH_4 = 78.6–82.1(CE), \quad R^2 = 0.92; \quad (4)$$

$$EFH_2 = 35.1–36.5(CE), \quad R^2 = 0.95; \quad (5)$$

$$EFCO_2 = 1833(CE). \quad (6)$$

Equation (6) is based on the definition for combustion efficiency. If 100% of the carbon (CE = 1.0) in a kilogram of fuel is oxidized to CO_2, then $EFCO_2$ = 1833 g kg^{-1}.

As we will demonstrate, a clear case can be made for developing different response functions for CH_4 production from fires in cerrado and deforestation types. The data base is too limited to make a separation for PM2.5, H_2, or CO at this time. We compared the models for this study with the Pacific Northwest (United States) models [*Ward and Hardy*, 1991]. In applying their models, the PM2.5 and CH_4 emissions are overestimated and the CO emissions are underestimated at 0.95 combustion efficiency. However, for the range of combustion efficiencies from 0.85 to 0.90 the performance is similar between models (Table 10).

In Figure 7, good agreement is demonstrated with the reported emission data from *Crutzen and Andreae* [1990]. All of their emission ratios are for a combustion efficiency of ≈0.90. We calculated emission factors of CO_2, PM2.5, CO, CH_4, and H_2 from our data and for PM from those of *Ward and Hardy* [1991] and compared these values of 1650, 6.08, 93, 4.8, 2.3, and 11.8 g kg^{-1}, respectively, with the computed values from *Crutzen and Andreae* [1990] of 1650 (not given), 105, 6.0, 2.0, and 15.0 g kg^{-1}, respectively. The calculated differences based on the Brazil models are 0 (not given), 13%, 26.1%, −10.4%, and 26.6%, respectively. The emission factors at 0.90 combustion efficiency are valid for many fires of the temperate forest zone and may represent the tropical forested areas but based on this research give much poorer estimates for the grassland vegetation types. The average combustion efficiency for the cerrado fires was 0.94 and that for the PF, 0.86. From past work [*Kaufman et al.*, this issue] the combustion efficiency of the tropical regions can be high (0.97) and is dependent on the conditions of the fuel and weather at the time of the fire.

4.3. *Comparative Analysis of PM2.5 and CH_4 Emissions From Fires in Biomass Fuels of the Tropics*

Emission models for ecosystems of the tropical regions have been difficult to develop because of a lack of sufficient data. Research completed during the last decade by *Bonsang et al.* [1991], *Greenberg et al.* [1984], *Crutzen et al.* [1985], *Ward and Hardy* [1991], and *Kaufman et al.* [this issue] has provided additional support for the modeling work presented in this paper. The evidence strongly suggests two models for CH_4: one for fires in the cerrado and savanna regions and a second for the deforestation fires.

Bonsang et al. [1991] reported measurements of emissions of gases including CO_2, CO, CH_4, and NMHC for a range of fires in savanna fuels of Africa. They did not measure the PM emissions released with the gaseous emissions. In using their data (one point was an outlier and excluded from the analysis), we have estimated the carbon contribution of the PM2.5 based on (2) (the carbon contribution of the PM2.5 is about 1% of the total). We used an iterative process to estimate the overall combustion efficiency and through this process adjusted the emission factors based on the total carbon released. The same general procedure was used for computing particulate matter emissions for data of *Crutzen et al.* [1985], *Greenberg et al.* [1984], and *Crutzen and Andreae* [1990]. *Greenberg et al.* [1984] calculated geometric means for the cerrado data separately from the selva types of Brazil but did not list the individual data points. *Crutzen et al.* [1985] calculated arithmetic and geometric means for the combined selva and cerrado data for both airborne and surface measurements but did not separate the cerrado and selva data. We have plotted both the geometric averages for the selva and cerrado and the arithmetic average of *Crutzen et al.* [1985] from the airborne samples but have not used these points in the development of the regression models (Figure 8). The geometric mean is always less than or equal to the arithmetic mean. One would expect the variance of the data for the selva tests to be greater than that for the cerrado. This could be one reason for the geometric mean value plotted in Figure 8 to lie below the regression line for the deforestation model. The agreement of the data point from *Greenberg et al.* [1984] with the

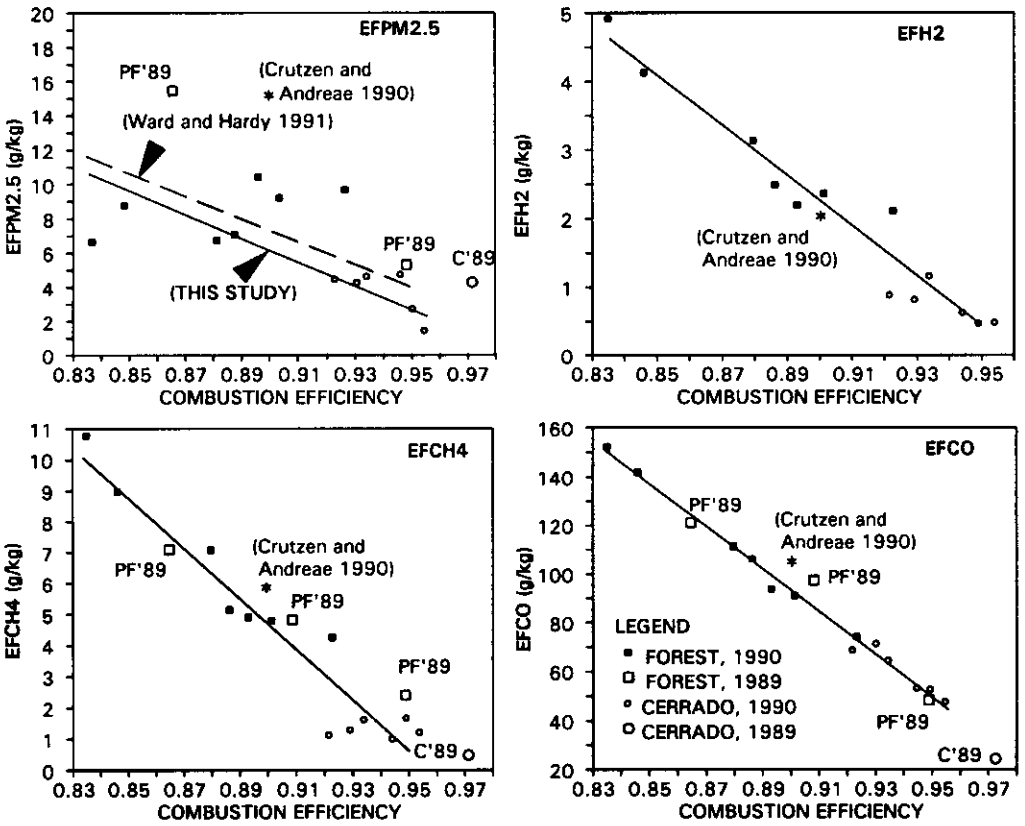

Fig. 7. Emission factor models for PM2.5, CH_4, H_2, and CO for the combined cerrado, primary forest, and second-growth forest emission data. The independent variable is combustion efficiency or the percent of carbon released in the form of CO_2.

regression model for the cerrado is close. The airborne data from *Kaufman et al.* [this issue] and *Bonsang et al.* [1984] were used with the data from this study to develop the regression models presented in Figure 8 for cerrado and savanna and deforestation ecosystems as follows:

Cerrado

$$EFCH_4 = 32.05–32.53(CE), \qquad R^2 = 0.87 \qquad (7)$$

Deforestation

$$EFCH_4 = 63.41–64.69(CE), \qquad R^2 = 0.91, \qquad (8)$$

with standard error of the estimates for $EFCH_4$ values of ± 0.75 and ± 0.54 and of the slope coefficients of ± 6.31 and ± 3.21, respectively. It is clear that the two regression models are independent. The chemical properties of the fuel complexes must in some way affect the release of CH_4 emissions differently for the savanna ecosystems relative to the forest biomass fires.

5. Application to Global Emissions

We can use the algorithms developed through this research (equations (2)–(8)) and the combustion factors for the cerrado and tropical forest ecosystems to improve the overall estimates of emissions from biomass burning in the tropical ecosystems. To do this, we summarized the biomass consumption and emissions reported by *Crutzen and Andreae* [1990] for tropical ecosystems: (1) forest burning, which included shifting agriculture, was combined with permanent deforestation (700–1700 Tg C y^{-1}) and (2) savanna burning (300–1600 Tg C y^{-1}).

The regression models (equations (2), (3), and (5)–(8)) were applied to the reported biomass consumption, adjusted for carbon content, and used to calculate the emissions released. *Crutzen and Andreae* [1990] made assumptions regarding the uncertainty associated with emission factors and combustion factors. We factored in our levels of uncertainty for combustion efficiency ($\pm 1\%$) and accepted the assumption of *Crutzen and Andreae* [1990] for biomass consumption (except we used 95% combustion factors for the upper level of consumption for the savanna ecosystems, based on Table 2). The lower limit of 50% combustion factor for the deforestation burning agrees well with our findings during this study (Table 3). The upper limit of 85% is reasonable considering other measurements of combustion factors reported by *Kauffman et al.* [1991]. The model of *Ward and Hardy* [1991] is used for calculating emission factors for total particulate matter and these total emissions compared to the estimates of *Crutzen and Andreae* [1990]. Emissions of PM2.5 were approximately 50% of the calculated PM emissions for both the savanna and the deforestation conditions.

Figure 9 illustrates the difference between the estimates of emissions based on results from this study and the estimates derived for the forest and savanna emissions from the work of *Crutzen and Andreae* [1990]. Both the minimum and the

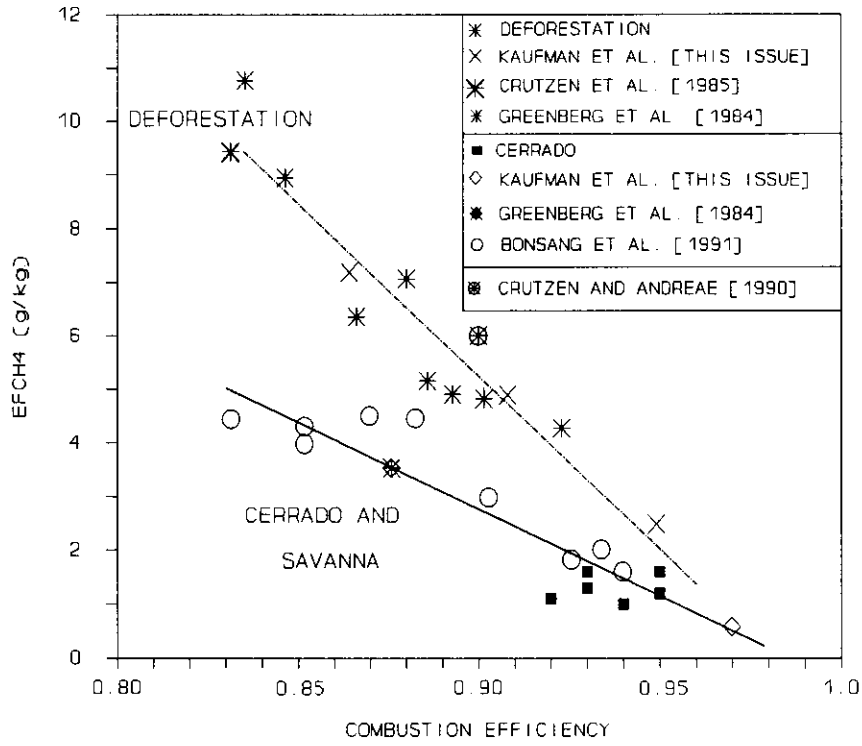

Fig. 8. Two models for estimating emission factors for CH_4 as a function of combustion efficiency. The solid line is based on data for fires in grassland and savanna vegetation types of Brazil and Africa, where the dashed line is based on data from deforestation fires.

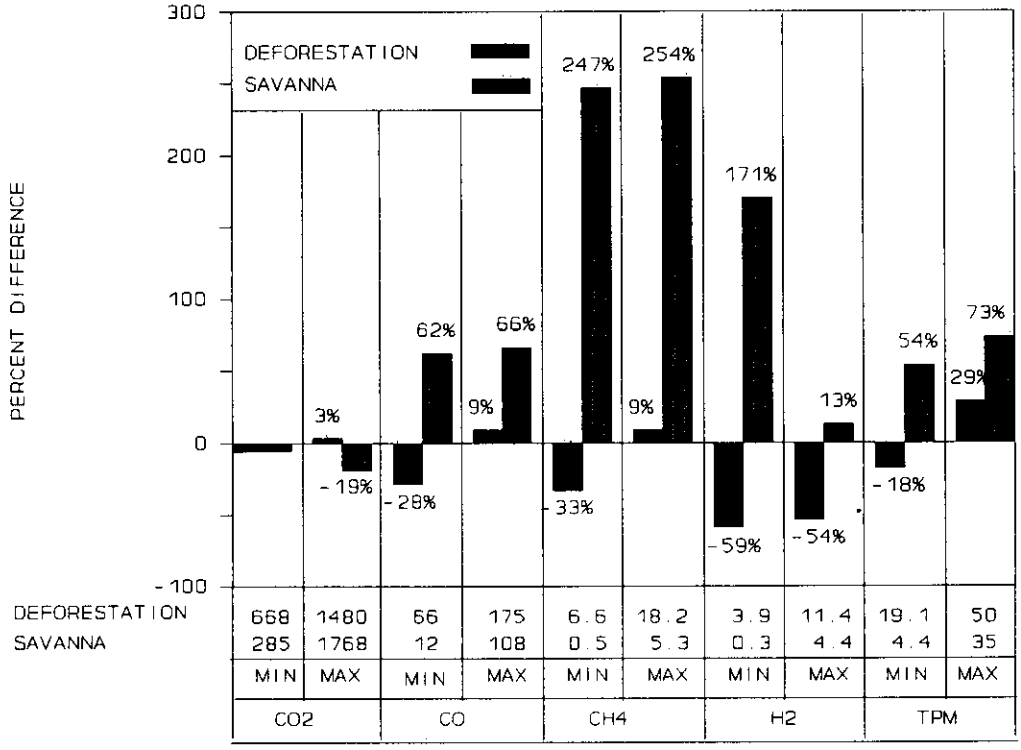

Fig. 9. Tabular values are estimates of the emissions released from fires in tropical ecosystems based on the emission factor models presented in this paper (Teragram (Tg) of carbon per year, 1 Tg = 10^{12} g). The results are compared with those of *Crutzen and Andreae* [1990].

maximum scenarios selected reflect much lower emissions of CH_4 for the tropical savanna ecosystems than projected by *Crutzen and Andreae* [1990]. Their values are 2.5 times larger than the emissions we project based on identical fuel consumption scenarios. On the other hand, the emissions of CH_4 and other products of incomplete combustion from the combustion of tropical forest materials are larger than projected by *Crutzen and Andreae* [1990].

6. Conclusions

The combination of improved estimates of total biomass and biomass consumption (combustion factors) coupled with new emission factor models and ratios of emissions should enhance the prediction of trace emissions to the atmosphere from fire sources of the tropics. Even though we selected the areas and fires to be representative of the cerrado and Amazon regions, more tests are needed and are under way to strengthen the relations presented here.

Verification and extension of the work are needed to cover the range of combustion conditions encountered in the cerrado and Amazon regions and, to a wider extent, deforestation and savanna burning in Africa and deforestation biomass burning in Asia. Field research in the tropical regions using sophisticated instrumentation is difficult and the results from this study and those of *Kaufman et al.* [this issue] show promise in explaining the variance of a wide range of measurements of other research. Data from field research projects are needed to answer the questions concerning the combustion factors and the combustion efficiency for full-scale fires. During 1991, six additional fires were sampled in Brazil and plans are progressing to sample more fires, both in Brazil and in southern Africa during 1992. With the new information, greater confidence will be possible in modeling the release of emissions from the tropical regions. The BASE-A and BASE-B experiments successfully characterized the major emissions of combustion gases from the burning of two very prominent vegetation types; fires in grassland cerrado vegetation and deforestation of the tropical moist primary forests (PF) of Brazil. Measurements for the second-growth forest (SF) field maintenance burn were not as successful due to high humidity and poor burning conditions. This research demonstrated a very high combustion efficiency of 0.94 or higher for the cerrado region with the combustion efficiency decreasing to 0.84–0.90 for the PF and SF fires.

Emission factors for the cerrado (grassland) region averaged 3.6, 1721, 58, 1.31, 0.48, 0.75 g kg^{-1} for PM2.5, CO_2, CO, CH_4, NO, and H_2, respectively. A preliminary set of models was developed for estimating emission factors as a function of combustion efficiency for several emissions, including PM2.5 (particles less than 2.5 μm diameter), CO_2, CO, CH_4, and H_2. Separate CH_4 emission factor models were developed for the grassland and deforestation. The combustion efficiency of fires burning in different ecosystems and under different weather patterns must be considered when estimating the production of emissions from individual fires or for composite fires on regional and global scales.

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