Emission Factor Measurements for Two Fires in British Columbia Compared with Results for Oregon and Washington

Darold E. Ward and Ronald A. Susott
Intermountain Research Station, Forest Service, USDA
PO Box 8089
Missoula, MT 59807
and
Alan P. Waggoner, Peter V. Hobbs, and J. David Nance
Department of Atmospheric Sciences
University of Washington
Seattle, WA 98195

ABSTRACT

Wildland fires produce smoke emissions dependent on fuel and weather factors affecting their combustion efficiency. Flaming combustion is highly efficient converting a high percentage of the carbon released during the combustion process to CO_2. In comparison to flaming, smoldering combustion releases a lower proportion of the total carbon as CO_2 and a higher proportion of products of incomplete combustion (CO, CH_4, NMHC, and particulate matter). Forest management strategies for prescribed burning that favor flaming over smoldering combustion decrease emission factors for the primary pollutants and air toxic compounds. For the British Columbia measurements, fire-averaged emission factors are computed based on the proportion of fuel consumed during the flaming and smoldering phases of combustion. Models for evaluating emission factors for different combustion efficiency fires are developed for the British Columbia fires using the combined set of airborne and tower-based emissions data.

KEYWORDS: Biomass fires, smoke, emission factors, particulate matter, methane

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1. INTRODUCTION

Emissions of smoke from wildland fires consist of a high percentage of products of incomplete combustion. Without adequate smoke management precautions, the products of incomplete combustion may concentrate in "smoke sensitive areas" and compromise air quality. High concentrations of smoke from biomass fires are thought to have an adverse effect on human health [Ward and Hao, 1992; Reinhardt, this conference]. Generally, smoke management systems require a method for estimating the rate of release of emissions and heat (source strength for the specific fire) to provide for adequate dispersion of the smoke. Emission factors for smoke from prescribed fires burned in British Columbia, Canada are discussed in this paper. Comparisons are made of emission factors measured a few meters above fires using tower-based systems with those sampled within a few kilometers using airborne systems.

In addition to the concern for human health resulting from exposure to excessive amounts of smoke, the particles and gases released from wildland fires can affect the radiation transfer through the atmosphere. Models of Penner et al. [1992] demonstrate the potential for particles from biomass fires to cool the earth, thus partially reducing the impact of the "greenhouse effect." For the Amazon Region of Brazil, Kaufman et al. [1992] made measurements of the optical properties of the atmosphere to estimate the concentration of particulate matter and trace gases resulting from the large amount of biomass burning. Recently, the impact of smoke from fires consuming biomass fuels has been suggested as having a major impact on global atmospheric chemistry and to be one of the contributors to global climate change [Seiler and Crutzen 1980, Crutzen and Andreae, 1990].

Models for estimating emission factors have been developed by Ward and Hardy [1991], Ward et al. [1992], and Hao and Ward [in preparation]. They found different models for estimating emission factors for several hydrocarbons and particulate matter dependent on fuel type (savanna, deforestation, and burning of wastes following the harvesting of trees). This paper focuses on information needed for estimating the source strength of open fires and data needed to demonstrate reductions in the release of air pollutants from prescribed fires.

The ratio of carbon released by a fire as CO_2 is defined as combustion efficiency (η). The η varies over the cycle of a fire from very high (> 0.9) during the flaming phase to $\approx$0.7 to 0.8 during the smoldering combustion phase. The physical and chemical properties of forest fuels are known to affect this ratio [Ward and Hardy 1991, Lobert et al., 1991; Ward et al, 1992]. Studies of the release of emissions of products of incomplete combustion were shown by Ward and Hardy [1991] and Laursen et al. [in press] to correlate with η. The ratio of CO/CO_2 was used as a measure of η by Radke et al. [1988] and Laursen et al. [1992]. The ratio of $CO_2/ (CO + CO_2)$ was defined as modified combustion efficiency ($\tilde{n}$) by Ward and Hao [1991]. Ward and Hardy [1991] derived algorithms for estimating the emission factors for CO, CH_4, non methane hydrocarbons (NMHC), particulate matter without regard to size (PM), and particles with aerodynamic diameters of less than 2.5 μm (PM2.5) as a function of η based on measurements made

for 38 fires in Washington, Oregon, and California. They used tower systems for supporting sampling equipment within the smoke plume from prescribed fires.

The University of Washington Cloud and Aerosol Research Group has sampled many fires across North America including 14 prescribed fires and 3 wildfires [Radke et al., 1991; Laursen et al., 1992]. The smoke plumes from these fires were sampled using equipment mounted in a C-131A research aircraft. Instrumentation on board the aircraft was used for measuring the size and nature of aerosol particles, trace gas concentrations, and meteorological properties of the atmosphere. Laursen et al. [1992] used the ratio of CO/CO_2 to model emission factors for several emissions and used estimates of biomass consumption world-wide to project total emissions from biomass burning. Their results largely agree with those of Ward and Hao [1991] who used η and $\hat{\eta}$ as independent variables.

2. METHODS

The University of Washington performed airborne studies of plumes from two prescribed fires in British Columbia during 1991. The Intermountain Research Station deployed three of the Fire Atmosphere Sampling System (FASS) packages *(Fig. 1)* on one of these fires. Samples of the emissions and dynamics of the fire were collected concurrently with the airborne samples using the tower-based FASS packages. The combined data set is reported here since it is one of the few observations where similar sets of data have been collected over a large spatial scale–from a few meters above the flames (using the FASS) to 10's of kilometers downwind (airborne system).

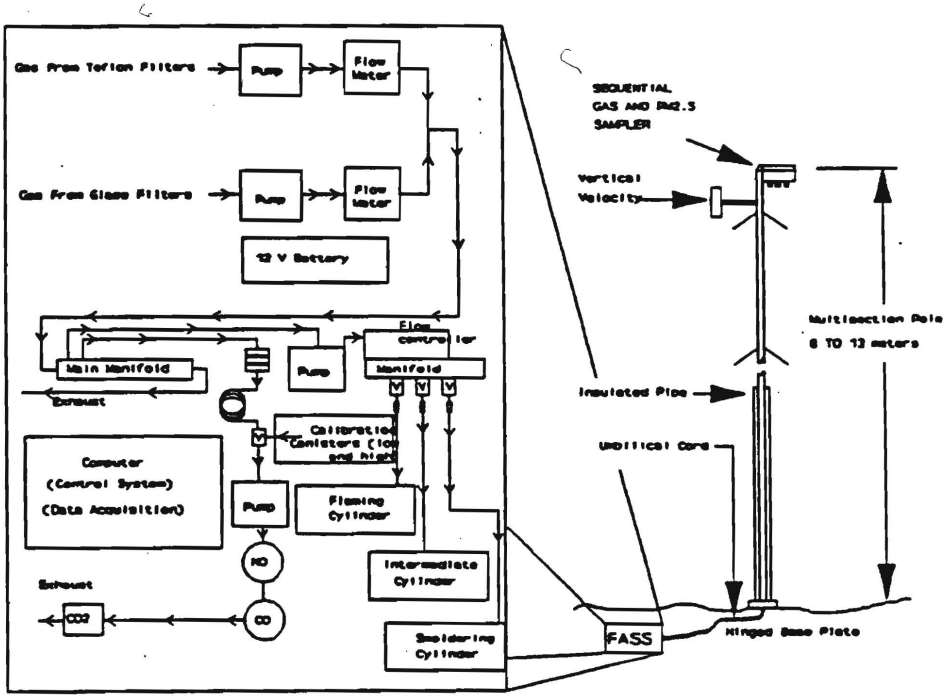

Figure 1. Fire Atmosphere Sampling System used for measuring emissions of CO_2, CO, and NO in real time while measuring fire dynamics variables (vector component of wind) and collecting grab samples of gases and particulate matter

The fires were located near Clearwater, British Columbia at 51.682° N/120.109° W and 51.823° N/120.153° W at an elevation of 1200 and 1350 meters above mean sea level, respectively. The University of Washington performed airborne smoke sampling on both fires with the FASS units deployed on only the first of the two fires. The first fire fuels inventory indicated that the slash from the harvesting of timber was about 49% western red cedar, 22% Douglas fir, and 25% subalpine fir. The other fire burned in a similar fuel complex.

The aircraft flew through the smoke plume at different distances downwind from the source and collected samples of the emissions on filters and in stainless steel canisters for subsequent analyses using standard gravimetric and analytical techniques. The aerosol sampling and characterization systems were described by Radke [1988] and the trace gas instrumentation by Hegg et al. [1987]. Laursen et al. [1992] discussed recent advances in the airborne system and protocols for data reduction. The airborne samples were collected sequentially by making multiple passes through the smoke plume from immediately after ignition (the emissions originated primarily from the flaming phase) to the time when the fire was dying (the emissions were being released predominantly from the smoldering combustion phase).

The general performance of the FASS packages has been described by Susott et al. [1991]. The FASS packages were configured for the British Columbia fire to collect samples of the gases and particulate matter in canisters and on filters for three periods of time (a ten minute flaming phase, a 20 minute first smoldering phase, and a 30 minute second smoldering phase). Additional data were collected in real time with the sensors for CO_2, CO, vector wind velocity, and temperature. The concentrations of CO_2 and CO from the canisters from both the airborne and FASS were compared with the onboard real time instruments for measuring CO_2 and CO. Gravimetric analyses of the filter samples collected using both systems were performed using similar microbalances with overall accuracy's of at least +/- 10 μg.

The method of using the carbon mass balance for computing emission factors was described in detail by Ward et al. [1979] and Radke et al. [1988]. The carbon contained with all chemical compounds (above background) is used to calculate the fuel consumed per unit volume:

$$W_v = \frac{\sum^{c} n}{R}$$

where,
- W_v = fuel consumed, g/m^3,
- C_n = the mass of carbon in emission n, g/m^3,
- n = CO_2, CO, PM, CH_4, and
- R = the carbon fraction of the fuel.

An emission factor (EF_n) for a specific emission (n) is computed by dividing the mass of the emission, n, by the total fuel consumed in producing the emissions in that volume:

$$EF_n = \frac{E_n}{W_v}$$

where, E_n = concentration of emission n, mg/m^3.

For the FASS packages, the rate of fuel consumption was computed by multiplying the concentration of carbon of the CO_2 and CO above background by the vertical vector of the wind field and this function integrated over the periods of time of collection of the flaming and two smoldering phase samples.

The η is calculated by dividing the measured $EFCO_2$ by the theoretically largest $EFCO_2$ possible (1833 g/kg) were all the carbon oxidized to CO_2. Generally, measurements of the carbon fraction of wildland fuels, R in equation 1, average 50% [Susott et al., 1991; Susott and Olbu, in preparation].

3. RESULTS AND DISCUSSION

Concentrations of the dominant combustion products were measured in real time using the FASS packages and the airborne sampling system. Grab samples were collected on filters and in canisters. In the following sections, we present the concentration of various primary products of combustion (section 3.1) and their emission factors (section 3.2). Then, the emission factors are plotted as a function of combustion efficiency and the regression models compared with the results from previous research (section 3.3). Based on the fuel consumption by phase of combustion (section 3.4), we develop weighted emission factors for the total smoke released from the fire (section 3.5).

3.1 Concentrations of Emissions

Concentrations of the primary products of combustion (above background) were about a factor of 50 higher for the samples collected using the FASS a few meters above the flames than those collected at a kilometer or more from the fire using airborne systems (Tables I and II). The background concentrations from canister samples collected both using airborne and ground systems averaged 355 ppmv CO_2, 0.3 ppmv CO, 1.7 ppmv CH_4, and 0.5 ppmv NMHC. The particulate matter concentrations were measured with the FASS system near the fire for the flaming and smoldering combustion phases and ranged from 6.8 to 41.0 mg/m^3. Concentrations of the particulate matter averaged 22 and 0.6 mg/m^3 for the ground and airborne sampling, respectively.

3.2 Emission Factors and Combustion Efficiency

Emission factors were calculated using equations 1 and 2 for both the airborne and ground-based measurements of concentrations (section 3.1). The calculated η and emission factors for $PM_{2.5}$, $PM_{3.5}$, CO, CO_2, CH_4, and NMHC are listed in Tables III and IV. Note that the cut point for the cyclone used with the FASS package was nominally 2.5 μm, whereas that for the airborne system was 3.5 μm. From data presented

by Radke et al. [1991], the difference between a cut point of 2.5μm and 3.5μm would be expected to be very small, certainly <5%. The differences between averages for individual emission factors for the airborne and ground data for the products of incomplete combustion averaged 16, 40, 35, and 24%, for EFPM2.5 (EFPM3.5 for airborne), EFCO, $EFCH_4$, and EFNMHC, respectively. In the following sections, we will show the importance of computing emission factors for the entire fire based on a fuel consumption weighting procedure.

3.3 Emission factor models

Emission factor and η data from Tables III and IV are plotted in *Fig. 2.* Best-fit linear regression models were calculated for the emission factors as a function of η (*Fig. 2*) and the models are listed in Table V. The linear regression models of Ward and Hardy [1991] for emission factors for fires in the Oregon, Washington, and California are plotted with the models shown for British Columbia. Data collected using the FASS packages encompass the range of data from the airborne samples. Because of the mixing of emissions from flaming and smoldering combustion phases, the airborne samples are composite samples of both phases of combustion (η ranges from 0.84 to 0.94). The η for the FASS measurements ranged from 0.67 to 0.96 (see *Fig. 2*).

For the data presented in this paper, statistically, there is no difference between the models developed from data collected using the ground-based FASS as compared to the models for the data collected from airborne sampling. The standard errors of the estimate overlap for both sets of models. The slope coefficients are significantly different, however, this appears to be a result of the range of data of the airborne samples (η = 0.84-0.94) rather than a distinctly different response function. Based on the lack of evidence suggesting that the data are different, we have combined the data and present one set of models in Table V and *Fig. 2.* However, the BC models derived for the two fires have independent slope coefficients relative to the models presented by Ward and Hardy [1991] for the Pacific Northwest, USA. For $EFCH_4$ models, Hao and Ward [in

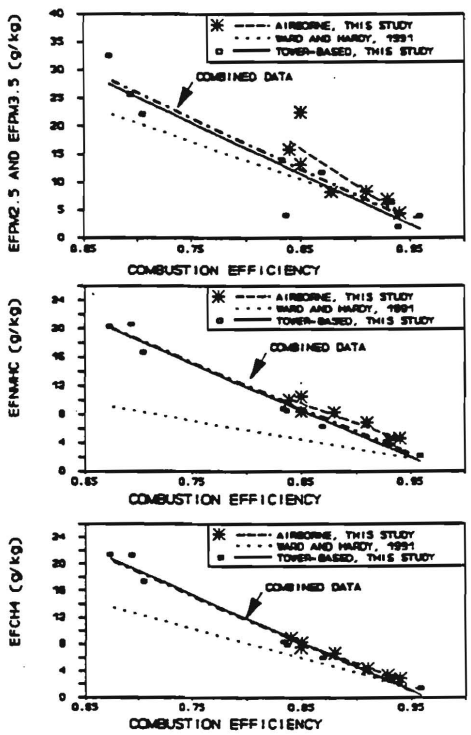

Figure 2. Emission factor models for emissions from prescribed fires in British Columbia using airborne and tower-based sampling methods. The models are compared with those of Ward and Hardy [1991].

preparation] have found different sloped regression models dependent on broad fuel type stratifications. Additional research is needed to learn if the BC models are different because of the fuel type variation between the two BC fires and those used for the Ward and Hardy models. The BC fires consumed fuels consisting of a high percentage of western red cedar. The fires sampled by Ward and Hardy [1991] consumed primarily Douglas-fir, western hemlock, true firs, and coastal hardwood species.

3.4 Real Time Measurements Using FASS

Measurements of CO_2 and CO concentrations (*Fig. 3A and 3B*) and the vertical vector of the wind field (*Fig. 3D*) are used over the duration of the fire to compute the fuel consumption *(Fig. 3E*). The concentration of CO_2 reached 10,000 ppmv during the peak of the flaming phase. As the fire changed from flaming to smoldering, the CO concentration increased to nearly 800 ppmv before declining. The computed η (actually modified combustion efficiency, $\hat{\eta}$) declined as the CO_2 decreased and CO production increased (*Fig. 3C*). As the fire progressed from flaming to smoldering (approximately from 30 to 100 minutes into the fire, *Fig. 3*), the $\hat{\eta}$ showed much larger deviations probably because of intermittent flaming during this period.

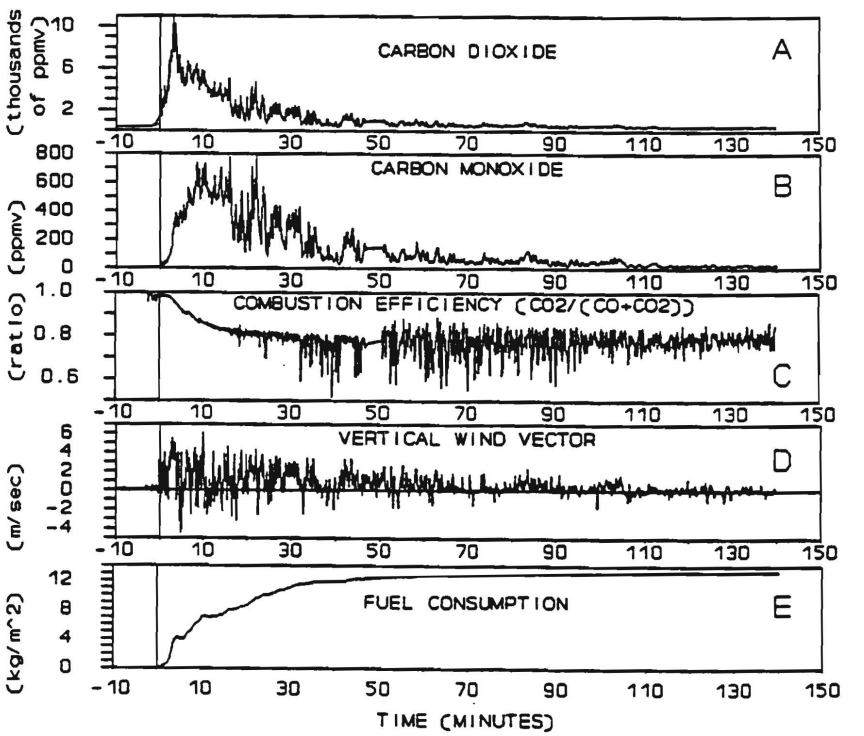

Figure 3. Real time measurements of CO_2, CO, and vertical wind vector using the Fire Atmosphere Sampling System (FASS) for package 15. The values are used for computing the combustion efficiency and fuel consumption.

By multiplying the vertical component of the windfield by the carbon contained with the CO_2 and CO, the rate of release of carbon from the site was computed. *Fig. 3E* illustrates for FASS15 the integrated rate of fuel consumption curve and provides the total fuel

consumption over the duration of the fire (FASS12, 10.4 kg m^{-2}; FASS14, 16.2 kg m^{-2}; and FASS15, 13.3 kg m^{-2}). An average of 36.1% of the fuel (4.8 kg/m^2) was consumed through flaming combustion during the first 10 minutes of sampling with 32.7% (4.3 kg/m^2) over the next 20 minutes, 23.8% (3.2 kg/m^2) during the next 30 minutes, and 7.4% (1.0 kg/m^2) during the final 80 minutes.

3.5 Weighting of Emission Factors

Ward and Hardy [1991] demonstrated that between 30 and 70% of the fuel consumption occurs during the flaming phase of combustion. The measurements presented in Section 3.4 show approximately 36.1% of the fuel consumption occurring during the flaming phase of combustion, 32.7% during the first smoldering phase, and 31.2% during the remainder of the fire (Normally, a much greater difference would be observed for the fuel consumption by phase of combustion over the three periods of sampling). The percent fuel consumption by phase of combustion are multiplied by the average emission factors from the 3 FASS packages for the 3 sample periods to compute a weighted emission factor for the entire fire. Hence, the weighted emission factors are 1528, 142, 9.5, 9.7, and 13.2 g/kg for $EFCO_2$, EFCO, $EFCH_4$, EFNMHC, and EFPM2.5, respectively. The weighted η for the fire and the three FASS packages was 0.833. In this case, the percent fuel consumption by sample period was nearly equal. The fuel consumption was divided approximately 33% flaming and 67% smoldering for this fire. The average emission factors from the airborne data as compared to the weighted emission factors based on the FASS samples are different by 5.9%, -37.6%, -36.7%, -21.3%, and -13.2% for $EFCO_2$, EFCO, $EFCH_4$, EFNMHC, and EFPM2.5, respectively. The η based on the fuel-weighted averages is 0.833 and 0.886 for the FASS and airborne samples, respectively. This suggests that the airborne samples may have been biased through collecting a higher proportion of emissions from the flaming combustion phase. For the airborne and FASS samples, this documentation shows minor differences between emission factors as a function of η (see *Fig. 2*). However, the average emission factors for the products of incomplete combustion were lower than the emission factors weighted proportional to fuel consumption for the FASS samples by -21.3 to -37.6% for the gases and -13.2% for the fine particles. There is a strong likelihood that the more buoyant plumes generated during periods of flaming combustion were sampled more frequently by the airborne system.

4. CONCLUSIONS

The research results presented here show measurements made using airborne and tower-based instruments are compatible and the best-fit linear regression models developed using combustion efficiency (η) as the independent variable fit the combined data very well. Sampling emissions proportional to the carbon released (fuel consumed) is not practical using airborne methods, but when supplemented with ground measurements of the proportion of emissions generated from flaming and smoldering combustion, the airborne data can be fit to the weighted average for the fire.

Weighted emission factors were developed for the fire in British Columbia of 1528,

142, 9.5, 9.7, and 13.2 g/kg for $EFCO_2$, EFCO, $EFCH_4$, EFNMHC, and EFPM2.5, respectively. The airborne derived average emission factors ranged from -21.3 to -37.6% lower for the gases and -13.2% lower for the fine particles.

Linear regression models were developed for the combined data with slope coefficients more responsive to η than the models presented by Ward and Hardy [1991]. This suggests that there are fuel differences affecting the combustion process that contribute to the higher rate of release of products of incomplete combustion than observed for the test fires in the Pacific Northwest, USA.

5. ACKNOWLEDGMENTS

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Table I. Concentrations of primary combustion gases and particulate matter. Samples collected using the Fire Atmosphere Sampling System (FASS) packages for a prescribed fire in British Columbia.

ID	CO_2	CO	CH_4	NMHC	PM2.5
	(ppmv)	(ppmv)	(ppmv)	(ppmv)	(mg/m^3)
BC12F	2168	95	8.5	11.9	12.3
BC12I	3020	297	27.8	32.0	35.8
BC12S	890	179	25.5	26.4	25.3
BC14F	5634	168	11.9	20.1	21.8
BC14I	2847	367	37.7	43.4	41.0
BC14S	929	175	21.2	22.2	17.7
BC15F	3576	172	10.7	17.1	6.8
BC15I	3759	538	48.2	57.2	16.5
BC15S	1098	225	34.2	36.2	27.0

Table II. Concentrations of primary combustion gases and particulate matter. Samples collected from the University of Washington C-131A Research Aircraft for two separate fires in British Columbia.

SAMPLE TYPE	TIME	CO_2	CO	CH_4	TNMHC	PM3.5
		(ppmv)	(ppmv)	(ppmv)	(ppmv-C)	(mg/m^3)
COLUMN	1516	390	4.45	2.32	0.97	0.63
COLUMN	1526	431	10.20	3.02	1.92	1.58
PLUME	1541	376	2.48	2.08	0.50	0.65
COLUMN	1627	378	2.36	2.06	0.52	0.28
COLUMN	1434	412	2.74	2.04	0.69	0.34
COLUMN	1442	421	4.69	2.30	1.14	0.73
POST-CLOUD	1517	392	2.23	2.02	0.47	0.35

Table III. Emission factors and combustion efficiency (η) for the primary products of combustion using data from Table I for the tower-based samples collected using the Fire Atmosphere Sampling System (FASS).

ID	η	$EFCO_2$	EFCO	$EFCH_4$	EFNMHC	EFPM2.5
	(ratio)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
BC12F	0.93	1712	57	2.9	3.7	6.4
BC12I	0.87	1595	113	6.0	6.4	11.9
BC12S	0.67	1236	263	21.4	20.3	32.6
BC14F	0.96	1759	36	1.4	2.2	4.0
BC14I	0.83	1528	143	8.4	8.9	14.0
BC14S	0.70	1293	250	17.4	16.7	22.2
BC15F	0.94	1722	58	2.1	3.1	2.0
BC15I	0.84	1534	154	7.9	8.6	4.1
BC15S	0.69	1272	245	21.3	20.6	25.7

Table I. Concentrations of primary combustion gases and particulate matter. Samples collected using the Fire Atmosphere Sampling System (FASS) packages for a prescribed fire in British Columbia.

ID	CO_2	CO	CH_4	NMHC	PM2.5
	(ppmv)	(ppmv)	(ppmv)	(ppmv)	(mg/m^3)
BC12F	2168	95	8.5	11.9	12.3
BC12I	3020	297	27.8	32.0	35.8
BC12S	890	179	25.5	26.4	25.3
BC14F	5634	168	11.9	20.1	21.8
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COLUMN	1526	431	10.20	3.02	1.92	1.58
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COLUMN	1627	378	2.36	2.06	0.52	0.28
COLUMN	1434	412	2.74	2.04	0.69	0.34
COLUMN	1442	421	4.69	2.30	1.14	0.73
POST-CLOUD	1517	392	2.23	2.02	0.47	0.35

Table III. Emission factors and combustion efficiency (η) for the primary products of combustion using data from Table I for the tower-based samples collected using the Fire Atmosphere Sampling System (FASS).

ID	η	$EFCO_2$	EFCO	$EFCH_4$	EFNMHC	EFPM2.5
	(ratio)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
BC12F	0.93	1712	57	2.9	3.7	6.4
BC12I	0.87	1595	113	6.0	6.4	11.9
BC12S	0.67	1236	263	21.4	20.3	32.6
BC14F	0.96	1759	36	1.4	2.2	4.0
BC14I	0.83	1528	143	8.4	8.9	14.0
BC14S	0.70	1293	250	17.4	16.7	22.2
BC15F	0.94	1722	58	2.1	3.1	2.0
BC15I	0.84	1534	154	7.9	8.6	4.1
BC15S	0.69	1272	245	21.3	20.6	25.7

Table IV. Emission factors and combustion efficiency (η) for the primary products of combustion using data from Table II for the airborne samples collected using the University of Washington C131-A Research Aircraft.

ID	TIME	η	$EFCO_2$	EFCO	$EFCH_4$	EFNMHC	EFPM3.5
		(ratio)	(g/kg)	(g/kg)	(g/kg)	(g/kg)	(g/kg)
COLUMN	15 16	0.85	1551	118	8.3	10.5	13.3
COLUMN	15 26	0.84	1532	127	8.9	10	15.9
PLUME	15 41	0.85	1562	106	7.6	8.5	22.5
COLUMN	16 27	0.88	1608	95	6.7	8.3	8.6
COLUMN	14 34	0.94	1715	48	2.6	4.7	4.4
COLUMN	14 42	0.91	1660	69	4.4	6.9	8.5
POST-CLOUD	15 17	0.93	1696	56	3.4	4.4	6.7

Table V. Linear regression models for data in Tables III and IV for the FASS (IFSL) and airborne (UofW) data separate and combined (BC) as compared to models of Ward and Hardy [1991] (W&H).

GROUP	DEP. VAR.	IND. VAR.	CON-STANT	SLOPE	R^2	S.E. of Y	S.E. of b
IFSL	EFCH4	CE	69.10	-71.62	0.980	1.21	3.83
UofW	EFCH4	CE	59.49	-60.41	0.986	0.32	3.17
BC	EFCH4	CE	67.94	-70.09	0.980	0.93	2.65
W&H	EFCH4	CE	42.70	-43.20	0.770		
IFSL	EFNMHC	CE	63.82	-65.01	0.980	1.11	3.51
UofW	EFNMHC	CE	56.86	-55.60	0.909	0.80	7.88
BC	EFNMHC	CE	61.55	-61.65	0.962	1.16	3.29
W&H	EFNMHC	EFCH4	0.76	0.62	0.690		
IFSL	EFPM2.5	CE	88.97	-91.05	0.868	4.24	13.43
UofW	EFPM2.5	CE	125.71	-129.04	0.723	3.61	35.75
BC	$EFPM_{FINE}$	CE	88.04	-61.65	0.799	4.16	11.85
W&H	EFPM2.5	CE	67.40	-66.80	0.740		