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Crown fire emissions of CO_2, CO, H_2, CH_4, and TNMHC from a dense jack pine boreal forest fire

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Abstract. Samples of high-intensity crown fire smoke were collected using a helicopter during the International Crown Fire Modeling Experiment near Fort Providence, Northwest Territories, Canada. The samples were analyzed for carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and total nonmethane hydrocarbons (TNMHC). CO_2-normalized mean emission ratios (ERs) and emission factors (g product/kg fuel burned) were determined for CO_2, CO, H_2, CH_4, and TNMHC. Carbon monoxide production was determined to increase during high-intensity crowning. Unlike CO, a corresponding increase in the production of H_2, CH_4, and TNMHC during crowning was not detected. This represents the first clear indication that we know of where relative increases in CO production from vegetation fires are not positively correlated with corresponding increases in CH_4, H_2, and TNMHC production. These results may be important to the atmospheric carbon budget, and to the potential use of CO as a normalizing parameter for boreal forest fire emissions.

Introduction

It is generally accepted that the higher-temperature flaming stage of combustion in vegetation fires is more efficient (producing higher proportions of carbon dioxide and water and correspondingly less partially oxidized products, e.g., carbon monoxide) than the lower-temperature smoldering phase of combustion (Crutzen and Andreae, 1990; Laursen et al., 1992; Blake et al., 1996). This can readily be explained by considering that the easily ignitable and well-aerated small size (high surface area to volume, thus, excellent heat transfer and combustion properties) fuels burn readily and flame significantly. Conversely, the large-size fuels (high volume to surface, thus, less efficient heat transfer) tend to burn less efficiently and at lower temperatures (i.e., smolder). Measured ratios of carbon monoxide (CO) to carbon dioxide (CO_2) are often used to define combustion efficiency, and to differentiate between flaming and smoldering emissions (Hegg et al., 1990; Ward et al., 1991; Laursen et al., 1992). However, samples we collected, analyzed, and reported from an intensely burning chaparral fire (Cofer et al., 1989) suggested that during extremely intense stages of flaming combustion, a less efficient combustion might occur. To further investigate this possibility, we participated in the Bor Forest Island Fire Experiment, a prescribed high-intensity experimental crown fire in Siberia (see FIRESCAN Science Team, 1996). The Bor Island fire (60°45'N, 89°25'E) was conducted in a live 50 ha stand of 20-m high Scots Pine on July 6, 1993. Our results from this high-intensity crown fire in the Siberian taiga were quite surprising (Cofer et al., 1996). During the vigorous crowning (crowning occurs when surface fires reach sufficient energies to cause the needled tree crowns to erupt into flames) stages of this fire, much larger ratios of CO/CO_2 were measured than is typical of boreal logging-slash or tramp fires (tramp fires are fires in which the timber has no commercial value, therefore, not slashed and harvested, but bull-dozed down and burned) during flaming combustion. However, the accompanying emissions of H_2, CH_4, and nonmethane hydrocarbons (NMHC), relative to CO_2, were consistent with (or even lower) than ratios typically determined for the flaming phase of boreal slash/tramp fires. The same pattern was repeated for the smoldering phase emissions from the Bor Island fire. However, since this fire represented our first collection and analyses of high-intensity crown fire emissions, and since the results were significantly different than for boreal slash/tramp fires that we and others had characterized, we were not sure if these results were typical of crown fire emissions, anomalous, or even spurious (see Cofer et al., 1996). The International Crown Fire Modeling Experiment in the Northwest Territories of Canada, offered another opportunity to study boreal crown fire emissions.

The ICFME

Since high-intensity crown fires account for an overwhelming proportion of the annual area burned in boreal forests (Alexander et al., 1998), the development of a model to predict propagation and spread of crowning forest fires is a high priority of the international boreal forest community, and the Canadian Forest Service. For the same reasons, the need to chemically characterize crown fire emissions released into the atmosphere is also a priority. The Canadian approach to the development of a model has largely been empirical, employing an extensive experimental burning program. In concert with this, the International Crown Fire Modeling Experiment (ICFME) was conducted during June-July, 1997, in the Northwest Territories (NWT). The study area was located about 40 km northeast of Fort Providence. The fuel consisted of a 65-year old jack pine (*Pinus banksiana*) stand with the canopy averaging 12 m height, 4100 stems/ha, with a dense understory of black spruce (*Picea mariana*) of 4600 stems/ha. This fuel arrangement is well suited to crown fire development. The experimental fire plots were typically 150m by 150m. Fuel consumption for the July 4th fire that we report results from consisted of 1.83 kg/m^2 of organic duff layer, 1.06 kg/m^2 of aerial fuels, 1.38 kg/m^2 of surface fuels, producing a total fuel consumption of 4.27 kg/m^2. The fully developed crown fire had a spreading rate of ~30 m/min, flame heights averaging 6 m above the canopy, and an overall fire intensity of 38,400 kW/m. Even though the July 4th NWT fire was small (150m by 150m), the fire intensity it produced was consistent with

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intensities produced by very large boreal crown fires (Stocks and Kauffman, 1996). However, a fire of this size is not capable of generating its own local weather, like major boreal crown fires.

Smoke sampling

A helicopter was used to collect smoke samples. The primary advantage of a helicopter sampling platform stems from the ability to visually identify specific parcels of smoke and to subsequently chase, intercept, and collect samples from the identified smoke parcels. Thus, crown fire emissions could be specifically targeted and captured. A detailed description of the sampling system and analyses protocols are presented in Cofer et al. (1990), therefore only a brief synopsis of our sampling technique is presented here. The helicopter had forward mounted nose probes through which smoke samples were drawn through using particle-filtered high-volume pumps. A helicopter forward speed of $\geq$ 40 knots (65 km/hr) was maintained during sampling so that rotor downwash effects were behind the sampling probes. Smoke samples were fed directly into 10-L Tedlar bags, each bag constituting one sample. Within minutes, the gas samples were transferred into stainless steel grab bottles, and then later analyzed for CO_2, CO, CH_4, H_2, and total nonmethane hydrocarbons (TNMHC) measured as methane response. The NWT gases were analyzed within 10 days of collection and storage by gas chromatography with FID detection for CH_4 and TNMHC; TCD for CO_2 ; and by the hot mercury oxide technique for H_2 and CO. Precision for these techniques are all about 1 %, except for TNMHC, which is dependent upon NMHC concentration. For the NWT samples, the difference between CH_4 and TNMHC signal was sufficient to produce a precision of better than 5%.

Results

Mixing ratios (ppmv) of the gases sampled over the July 4th Northwest Territories fire are shown in Table 1, and are identified as representing upwind background (Bk) air samples, crown fire emission samples (CF), or smoldering emission samples (S). It is apparent in Table 1 that all the CF and S emissions collected were significantly above their background levels, which enhances our confidence in deriving emission ratios (or emission factors) from these data. Mean emission ratios (ERs) were determined based on normalization of selected species by carbon dioxide as shown by equation below, where

$$ER = dX(sample - background)/dCO_2(sample - background)$$

dX is the difference between a specific component in the smoke and its background. Mean emission ratios (ERs) for CO, H_2, CH_4, and TNMHC determined for the NWT fires are shown in Table 2, along with mean ER's determined for 7 prescribed boreal slash fires, and the Bor Island crown fire. Since both the Bor Island and NWT fires were high-intensity crown fires, these emissions will be contrasted with the more commonly reported boreal slash/tramp fire emissions.

Traditionally, CO/CO_2 or $CO/(CO2 + CO)$ ratios have been used to indicate combustion efficiency, and increased production of CH_4 , nonmethane hydrocarbons (NMHC's), and H_2 has typically correlated with the less efficient lower temperature combustion, thus, CO production (see Crutzen and Andreae, 1990; Lobert et al., 1991; Radke et al., 1991; Blake et al., 1996). Linear regressions of emission factors (EF's) for NMHC's, CH_4, and H_2 versus the ratio of CO/CO_2 generally have yielded high correlation coefficients (Laursen et al., 1992), and normalization with CO instead of CO_2 has often been done (Crutzen and Andreae, 1990; Andreae et al., 1988; Blake et al., 1996).

Since CO_2 typically accounts for ~ 90% of the carbon combustion product, we believe ERs based on CO_2-normalization inherently place all fire emissions in perspective, and consequently prefer to use CO_2 for normalization. However, background levels of CO_2 are ~ 360 ppmv in the troposphere, and even in relatively unaged fire plumes, CO_2 is rarely encountered at levels of more than a factor of 2-3 above its normal ambient background. CO levels measured under the same conditions, however, are often enriched by factors of several hundred above background. Therefore, as smoke plumes disperse, in-plume CO_2 concentrations converge with their ambient background levels more rapidly than CO. Thus, CO can become the only practical normalization agent for dispersed smoke plumes. These results should be of particular significance to those cases.

The data presented in Table 2 reveal significantly higher CO production during crowning, without accompanying increases in CH_4, TNMHC, and H_2 production. The same result can be seen in the EFs presented in Table 3 for boreal slash fires, the Bor Island fire, and the NWT crown fires. The EFs are expressed in grams of product produced per kg of fuel burned, and fuel carbon content in this case was assumed to be 45% by weight (wt. % of carbon in cellulose). Again, it can be seen that the crown fire

Table 1. Concentrations (ppmv) of trace gases determined for the Northwest Territories (NWT) crown fires.

Sample #	CO_2	CO	H_2	CH_4	TNMHC
1 (Bk)	360	0.10	0.51	1.76	0.10
2 (CF)	830	39	9.0	3.14	2.18
3 (CF)	660	28	5.2	2.67	2.00
4 (CF)	560	17	4.6	2.50	1.05
5 (CF)	545	20	4.7	2.52	1.20
6 (CF)	740	36	6.4	2.71	2.00
7 (CF)	815	44	10.4	3.20	1.77
8 (CF)	530	17	3.6	2.35	0.92
9 (CF)	660	28	6.6	2.95	1.27
10 (CF)	630	23	5.7	2.82	1.18
11 (CF)	575	21	6.8	3.11	1.45
12 (Bk)	357	0.09	0.49	1.77	0.09
13 (S)	505	30	7.0	3.82	2.55
14 (S)	535	31	8.2	4.23	2.22
15 (S)	480	23	6.0	3.56	1.78
16 (S)	570	37	9.7	4.92	2.89
17 (S)	540	31	8.0	4.28	2.44
18 (Bk)	365	0.10	0.50	1.77	0.12

Key: Bk = background, CF = crown fire emissions, S = smoldering

Table 2. Emission Ratios (%) of Boreal Slash/Tramp and Crown Fires.

Boreal slash/tramp	CO/CO2	CH4/CO2	TNMHC/CO2	H2/CO2
F(78)	6.7 ± 1.2	0.6 ± 0.2	0.6 ± 0.1	2.0 ± 0.5
S(22)	12.3 ± 1.9	1.2 ± 0.3	1.1 ± 0.2	3.1 ± 0.7
Bor Island				
CF(5)	11.3 ± 2.7	0.4 ± 0.1	0.5 ± 0.1	1.6 ± 0.1
S(4)	33.5 ± 4.5	1.3 ± 0.2	1.4 ± 0.4	2.2 ± 0.2
NWT Fires				
CF(10)	9.4 ± 1.0	0.4 ± 0.2	0.5 ± 0.1	2.0 ± 0.4
S(5)	18.5 ± 1.4	1.4 ± 0.2	1.4 ± 0.2	4.4 ± 0.2

( ) = Number of samples analyzed, F = flaming, S = smoldering, CF = crown fire.

Table 3. Emission factors (g/kg) for boreal slash/tramp and crown fires.

Boreal slash/tramp	CO_2	CO	CH_4	TNMHC	H_2
Flaming	1600 ± 45	70 ± 15	3.7 ± 1	3.8 ± 1	1.6 ± .6
Smoldering	1440 ± 60	135 ± 20	7.4 ± .8	7.3 ± 2	2.5 ± .7
Bor Island					
Crowning	1500 ± 50	120 ± 30	2.1 ± .5	3.1 ± 1	1.2 ± .2
Smoldering	1100 ± 80	350 ± 45	6.8 ± .8	7.9 ± 1	1.7 ± .4
NWT crownfires					
Crowning	1530 ± 80	100 ± 10	2.4 ± .6	3.0 ± 1	1.4 ± .5
Smoldering	1210 ± 100	184 ± 15	7.8 ± 2	8.4 ± 1	2.9 ± 1

EF for CO production is higher than for the flaming phase of the boreal slash fires, but that the crown fire EFs for CH_4, H_2, and TNMHC are lower. Since higher CO means lower CO_2, even identical ERs for CH_4, H_2, and NMHC from the crown fires would represent less production of these gases. This is the first clear indication that we know of where relative increases in CO production are not positively correlated with corresponding increases in CH_4, H_2, and TNMHC production, or that relative increases in CH_4, H_2, and TNMHC production are not associated with lower combustion efficiency.

The results from the samplings of smoldering combustion, shown in Tables 2 and 3, require some discussion. Real vegetation fires in systems with largely varying fuel types and sizes (e.g., boreal forests) seldom exhibit "purely flaming" or "purely smoldering" combustion phases. Slash/tramp fires are intentionally designed to consume as much fuel as possible. They are dried and arrayed to promote maximum fuel consumption. Thus, many large and small fuels are strategically placed at the surface together and burned under optimum conditions. Consequently, soon after ignition, many different size fuels are simultaneously burning, and combustion is probably better described as "predominantly flaming". Likewise, these slash/tramp fires, because of the way the fuels are arrayed, typically exhibit a significant "predominantly smoldering phase" over a long period of time (1-3 hr.).

Crown fire behavior is quite different. For crown fires, a fast-moving high-intensity fire rapidly sweeps through the standing fuels, largely consuming the small fuels, and leaving the bulk of the large fuels (e.g., tree trunks) unconsumed by combustion. Crown fires are fed by active surface fires on the forest floor. When the tree crowns (predominately needles and very small fuels) ignite, fire intensities are extreme, radiative vaporization of fuels (pyrolysis) is maximum, and part of the source of the air/oxygen/heat is the combusted hot gases/smoke from the forest floor emissions. Under these conditions it is easy to view a crown fire as a fuel-rich combustion system with an accompanying lower degree of combustion efficiency, i.e., more CO is produced. Explaining why methane, hydrogen, and TNMHC production do not proportionately increase (as CO) is difficult since a precise understanding of the mechanism(s) for their production (pyrolysis, combustion, or both) would have to be known. It is not.

The onset of the smoldering phase of combustion in a crown fire is rapid. There is much less of a significant smoldering phase, and it diminishes much faster (<1 hr), releasing relatively minor volumes of trace gases and smoke compared to slash/tramp fires of comparable area. In effect, early crown fire smoldering emissions probably correlate better to much later emissions from slash/tramp fires. Thus, samples reported by us previously as smoldering emissions for the boreal slash/tramp fires would probably be better referred to as predominantly smoldering emissions, while those reported for the Bor Island and NWT crown fires are closer to pure smoldering emissions. We believe that this explains some of the higher ERs determined for CO during the smolder phases of the Bor Island and NWT fires. Interestingly, the CH_4, H_2, and TNMHC ratios with respect to CO, are lower during the smoldering phase of the Bor Island and NWT fires, than for the slash/tramp fires, as well. The apparent disagreement in hydrogen production during smoldering between the Bor and NWT fires remains an enigma.

Conclusions

These new results are important since high-intensity crown fires account for the largest proportion of the area burned in boreal forests. First, the results indicate that a larger amount of CO is produced by boreal wildfires than previously believed. The portion of the CO budget attributed to boreal forest fires would increase by as much as 33%. Conversely, less CO_2 is produced, and based on our data, the change to the CO_2 budget would not be as significant ($\leq$ 5%). The budgets of CH_4, NMHC, and H_2 would also be impacted ($\leq$30% reduction on CH_4 and NMHC's; a $\leq$ 20% reduction in H_2). However, an overall assessment of the importance of these results is difficult since the amount of burning in the boreal forest system is highly variable from year to year. Cahoon et al. (1996), using satellite imagery, estimated that 14.5 million hectares of boreal forest burned in Russia in 1987, however, in 1992, only 2 million hectares burned (Goldammer and Furyaev, 1996). Thus, boreal fire impacts on atmospheric trace gas and particle budgets will vary significantly from year to year, dependent upon fire severity.

Second, these results represent the first clear indication that a significant increase in CO production (less efficient combustion) in a vegetation fire does not necessarily mean increased production of CH_4, H_2, and TNMHC's. These results also complicate the use of CO as a normalizing parameter for emissions from boreal forest fires. Although black carbon particles (soot) were not measured during these experimental fires, black carbon is a high-temperature flaming product (Kuhlbusch and Crutzen, 1996), and it was obvious (from the black color of the smoke) that significant amounts of black carbon particles are produced during crowning. Therefore, estimates of soot production by boreal and temperate forest fires should be reexamined. Most tropical burning does not involve fires of intensities comparable to boreal and temperate forest fires (a notable exception to this would be the high-intensity fires in eucalyptus forests of Australia) and thus, we suspect that these new results may have minor, if any, relevance to fires in most tropical systems.

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