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Emissions from Boreal Forest Fires: Are the Atmospheric Impacts Underestimated?

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Atmospheric emissions from boreal forest fires have been estimated to constitute no more than 1 to 3% of the average annual global mass of biomass burning emissions (Andreae 1991; Stocks 1991) and occur at Northern Hemisphere latitudes, where their impacts may be masked by high levels of industrial emissions. Nevertheless, the impacts on atmospheric chemistry and climate from biomass burning in the boreal forests of North America, Europe, and Asia may currently be seriously underestimated. Recent measurements during a high-intensity stand-replacement fire in Siberian taiga suggest that much higher levels of incompletely oxidized reactive combustion products (e.g., carbon monoxide, CO) are produced during intense flaming combustion in the tree crowns than previously thought. If true, several indigenous properties of boreal forests and characteristics of boreal wildfires may combine synergistically with the higher levels of reactive combustion products to produce environmental impacts of greater significance than the 1 to 3% estimates suggest.

Because more than 80% by mass of the world's biomass burning occurs in the tropics (Crutzen and Andreae 1990; Delmas et al. 1991), the focus of most biomass burning research is directed toward the rain forests and savannas in South America, Africa, and to a lesser extent, Southeast Asia and Australia. It has been estimated that 820 million hectares (ha) of tropical savanna burn annually (Andreae this volume). Biomass burning is considered to be the most dominant perturbation on atmospheric chemistry in the tropics (Delmas et al. 1991; Lacaux et al. 1993; Fishman et al. 1990; Delany et al. 1985). In contrast, only about 5 to 10 million ha of boreal forest, or taiga, have been estimated to burn on average each fire season (Stocks 1991), representing little more than 1% of the annual global carbon budget from fossil-fuel combustion and biomass burning. However, we believe that the environmental impacts resulting from boreal forest fires may be substantially more important than these numbers suggest, for the following reasons.

First, there are tremendous fluctuations in annual burning in the boreal zone, tied mostly to extremes in

fire weather. Consequently, atmospheric impacts can vary dramatically from season to season. For example, boreal wildfires in eastern Siberia and northern China alone burned about 14.4 million ha from May to July 1987 (Cahoon et al. 1994). During this period the carbon dioxide (CO₂), carbon monoxide (CO), and methane (CH₄) released by these fires was estimated to be about 20, 36, and 69%, respectively, of the total yearly release for savanna-fire emissions in Africa (Cahoon et al. 1994). A total of 22 million ha of boreal forest was estimated from AVHRR imagery to have burned during 1987, and the estimate for total area burned in 1992 was only 2 to 3 million ha (Cahoon personal communication).

Second, boreal forest fires are located at climatically sensitive northern latitudes, where small changes in surface temperatures can significantly influence the critical ice (snow)/albedo feedback. Thus, infrared absorption/emission processes by greenhouse gases (H₂O, CO₂, CH₄, N₂O, etc.), as well as fire-induced changes in surface albedo, are more environmentally significant than in the tropics.

Third, vegetation fires in the boreal system may be coupled to global warming in a manner that is self-amplifying. That is, global warming may cause more frequent and extended drought, thereby increasing fire frequency, which in turn would generate additional emissions and further surface albedo changes with accompanying warming, forming an escalating spiral (Dixon and Turner 1991; Kurz et al. 1994). Exacerbating this effect, boreal forests are one of the world's largest terrestrial organic carbon pools (Kauppi et al. 1992), which, once burned, cannot quickly reincorporate equivalent amounts of carbon into new growth or into a new, rich organic forest floor. In addition, postburn effects on soil and vegetation may release significant amounts of carbon to the atmosphere (Smith and Shugart 1993).

Fourth, vegetation fires in the boreal (and temperate) ecosystems are potentially the most energetic. Though fires in the tropics usually burn in seasonal forests and mainly involve the grass-leaf litter layer, typically not exceeding 2000 to 5000 kg/ha of fuels

(Goldammer 1993), or involve small, inefficient, low-intensity fires in deforested areas (Andreae 1991), the average fuel consumption per unit area for boreal forest fires is about an order of magnitude more (25 000 kg/ha, Stocks 1991) than for most tropical ecosystems. Large boreal fires typically spread very quickly, most often as crown fires. The energy-release rate, or intensity, of such fires should be considered when estimating atmospheric chemistry and climate effects. Large boreal wildfires release enough energy to generate smoke/convection columns that routinely reach well into the troposphere, and on occasion penetrate the tropopause. As an example, a 1986 forest fire in northwestern Ontario (Red Lake) at times generated a convection column 12 to 13 km high, penetrating the tropopause (Stocks and Flannigan 1987). Vegetation fires of such intensity may directly influence stratospheric chemistry. Typically, only molecules with long atmospheric lifetimes, such as methyl chloride, methyl bromide, and nitrous oxide (Mano and Andreae 1994; Cicerone 1994) produced by vegetation fires are considered to have any significant effect on stratospheric chemistry. Identifying a viable mechanism for direct stratospheric injection of biomass burning emissions could necessitate new considerations on the influence of fire emissions, particularly the fraction of short-lived, highly reactive emissions (e.g., NO_x , olefinic hydrocarbons) produced during high-intensity taiga wildfires. It is additionally significant to this discussion that the tropopause is at lower altitudes at boreal-zone latitudes.

Fifth, the quantities of chemically or photochemically active combustion products (e.g., CO, hydrocarbons) produced per unit of fuel burned in boreal fires are consistently higher than those resulting from fires in other major global ecosystems. This excess is largely due to combustion in the compacted surface organic layer and the large mixture of fuel sizes. Often, during smoldering combustion, as much as 25% of the carbon emissions released into the atmosphere have been found to be in a chemical form other than CO_2 (Crutzen and Andreae 1990).

Of some concern, however, is that most data obtained for boreal forest-fire emissions have come from prescribed fires. Such fires, though they may represent a significant amount of burning in their own right, in general may not serve as good models for emissions or smoke-plume behavior from large wildfires. Prescribed fires in the boreal system typically consist of slashed or tramped (whole trees bulldozed down) fuel that has been allotted sufficient time to air dry and burned only under optimally controlled combustion conditions. Wildfires, of course, involve standing, live forest

burning out of control, and though large wildfires are only about 10% of the boreal fires, they account for about 90% of the area burned. It is very difficult to obtain smoke-emission data from large, high-intensity boreal wildfires or to find prescribed fires involving live stands of boreal forest, though this information is exactly what is needed to draw proper conclusions about boreal wildfire emissions.

Bor Forest Island Fire

An experimental high-intensity stand-replacement fire was conducted in the Siberian taiga on July 6, 1993. Science experiments designed around this fire were the first joint East-West fire-research activities organized under the Fire Research Campaign Asia-North (FIRESCAN) and sponsored by the Siberian Branch of the Russian Academy of Sciences, the Russian Aerial Forest Fire Protection Service, the International Boreal Forest Research Association (IBFRA), the International Global Atmospheric Chemistry Program (IGAC), and the Max Planck Institute for Chemistry. The Bor Forest Island site ($60^\circ 45' \text{N}$, $89^\circ 25' \text{E}$) is about 600 km north of Krasnoyarsk, Siberia, and consisted of about 50 ha of 130-year-old, 20-m high, live, standing Scots Pine (*Pinus silvestris*), with a forest floor covering composed essentially of lichen (*Cladonia* sp) residing on 5 to 7 cm of partially decomposed organic matter. Fuel loading was determined to be 3.4 kg/m^2 . A high-intensity experimental fire was possible because the burn site was a small island of live trees surrounded by relatively wet marshlands—preventing fire-control problems. The fire burned from about 1430 to 1700 local time, during which there were no significant natural winds. Due to the low wind conditions, the fire was ignited by hand torch along the perimeter, creating a convection fire. Once ignited, the fire generated its own wind field and produced a smoke column rising to about 5 km. The Bor fire can be divided into three distinct phases. First, a flaming surface fire consisted primarily of the combustion of litter, lichen, and duff. This phase transitioned into an intense flaming fire involving explosive migrations of fire into the needled tree crowns. Last was a relatively brief smoldering stage.

Smoke Samples

Grab samples were collected using a Russian MI-8 helicopter fitted with NASA-Langley Research Center smoke-sampling equipment. Particle-filtered samples were drawn (via high-volume pump) through a nose-mounted probe, coupled to the high-volume pump

with flexible hose. Smoke samples were fed into 10-l Tedlar gas sampling bags. Each bag constituted one sample, which was composed of one helicopter pass through the smoke column. After sample collection, the gas was transferred into stainless-steel grab sampling bottles, which were returned to our laboratory and analyzed for CO₂, CO, H₂, and CH₄ within two weeks of collection. Smoke sampling was conducted at altitudes as low as safety would permit, determined most often by fire intensity and smoke turbulence. Flight paths chosen during smoke plume/column sampling were based on visual keys such as smoke color, flame characteristics, apparent turbulence, and combustion stage. It is this ability to select and sample smoke from specific parts of a fire that is the real strength of helicopter sampling. For example, when the crowns of a section of trees were observed to explode into flames, we were able to chase and sample the resulting smoke. The helicopter was always moving forward during sampling at no less than 40 knots. At 40 knots, rotor downwash is well behind the sampling probe, thereby eliminating collection of smoke other than that targeted.

Chemical analyses of the samples were performed for CO₂, CO, H₂, and CH₄. CO₂ analysis was performed using isothermal (45°) gas chromatography with thermal conductivity detection. A Porapak N column was used for separation. CO and H₂ were analyzed by the hot mercury oxide technique. CO and H₂ are separated chromatographically, then reacted on a hot mercury oxide bed, liberating mercury vapor, which is then detected by UV absorption. Linearity (response) problems were eliminated by using several sample injection loop volumes, ensuring that roughly the same amounts of CO (or H₂) were injected on to the column regardless of actual sample concentration. Analysis for N₂O was performed by Ni⁶³ electron-capture gas chromatography with a 5% CH₄/Ar carrier. A Porapak Q packed column was operated isothermally at 65° for separation, and detector temperature was maintained at 345°. Flame-ionization gas chromatography was used for CH₄ analysis. Separation was accomplished with molecular sieve 13X at a constant 75°. Calibration standards were master gravimetric certified and supplied by Scott Specialty Gases at the ±1% level. The precision of the analytical techniques as used in the field had been previously determined to be better than ±2%.

Results

Mean emission ratios (ERs) for CO, H₂, and CH₄ determined for the Bor Forest Island Fire are presented

Table 79.1 CO₂-normalized emission ratios (in percentages) for biomass fires in the boreal ecosystems

	CO/CO ₂	CH ₄ /CO ₂	H ₂ /CO ₂
Boreal			
F(78) ^a	6.7 ± 1.2	0.6 ± 0.2	2.0 ± 0.5
S(22)	12.3 ± 1.9	1.2 ± 0.3	3.1 ± 0.7
Bor Island			
F1(4)	8.8 ± 2.7	0.5 ± 0.1	1.2 ± 0.2
F2(5)	11.3 ± 2.7	0.4 ± 0.1	1.6 ± 0.1
S(4)	33.5 ± 4.5	1.3 ± 0.2	2.2 ± 0.2

a. Combustion phase and number of samples:

F = flaming phase

S = smoldering phase.

in table 79.1. ERs are determined as shown in equation form:

$$ER_X = 100 \frac{\text{plume } X - \text{background } X}{\text{plume CO}_2 - \text{background CO}_2}$$

and are normalized with CO₂. The ratios are based on a mole/mole (v/v) and are expressed in percentages. Upwind measurements made several times during the lifetime of the Bor fire served as background. CO₂-normalized ERs provide a convenient method for intercomparing the behavior of combustion emissions relative to CO₂ and each other. The data presented for the Bor Forest Island fire include two sets for flaming emissions. The first set (designated F1) is for flaming combustion before the ground fire erupted into the tree crowns. Thus, it consisted of emissions produced by burning lichen, surface litter, and duff. The second set of flaming ERs, designated F2, were made during flaming combustion on both the ground and in the tree crowns. The focus for the F2 samples was to collect smoke rich in crown-fire emissions; that is, we directed helicopter sampling to capture as much smoke from the combustion in the treetops as possible. The designation S is for samples collected during smoldering combustion under conditions with essentially no discernible flames. ERs shown in table 79.1 under the category of boreal are a compilation of our results from five prescribed boreal slash fires in Canada.

The mean CO/CO₂ ratio derived from the Bor Island fire during the F1 stage, although suggestively higher, is not statistically different from the mean CO/CO₂ ratio determined for flaming combustion for the five Canadian boreal prescribed slash fires (Cofer et al. 1990). The CH₄/CO₂ ratio is also equivalent to the results from the prescribed fires. The mean ER for H₂ is actually lower.

The mean CO/CO₂ ratios determined for the F2 series of samples appears numerically closer to the previously measured smoldering emissions ratios in

Table 79.2 Average emission factors (g/kg) for major combustion products determined from fires in North American boreal and temperate forests

CO ₂	CO	CH ₄	TNMHCs	Particles	N ₂ O	NO _x	H ₂	Source
1650 ± 35	93 ± 16	3.8 ± 1.0	1.8 ± 0.4	20 ± 15	0.23 ± 0.05	4 ± 6	1.8 ± 0.7	(1, 2)
1595 ± 45	105 ± 20	3.5 ± 1.1	3.7 ± 1.1	15 ± 10	0.15 ± 0.05	NM	1.4 ± 0.6	(3)
1625 ± 85	107 ± 45	4.1 ± 1.7	3.2 ± 2.1	20 ± 15	NM	2 ± 2 ^a	1.9 ± 0.7	(4, 5)
1475 ± 40	180 ± 40	4.2 ± 0.8					0.8 ± 0.3	(Bor)

NM = not measured

a. NO, not NO_x(1) Radke et al., in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, MIT Press, Cambridge, Mass. 209–224, 1991.(2) Laursen et al., *J. Geophys. Res.*, 97, 20 687–20 701, 1993. (3) Cofer et al., *Atmos. Environ.* 24A, Mass, 1653–1659, 1990. (4) Susott et al., in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, MIT Press, Cambridge, Mass, 245–257, 1991. (5) Ward et al., *J. Geophys. Res.* 97, 14 601–14 619, 1992.

(Source 1, 2 = fixed-wing aircraft; 3 = helicopter; 4, 5 = tower measurements)

boreal slash fires. The higher CO/CO₂ ratios suggest movement toward inefficient combustion during intense flaming in the crowns. It is somewhat disturbing that the corresponding mean ERs determined for CH₄ and H₂ for the Bor Island fire during crowning do not seem to support this assertion. The relative production of methane and hydrogen in fires usually is positively correlated with decreasing combustion efficiency (Laursen et al. 1992; Ward 1990).

The mean CO/CO₂ ratio obtained for smoldering combustion in the Bor fire is the highest we have ever determined. Notice that the mean CH₄/CO₂ and H₂/CO₂ ratios determined for the Bor fire during smoldering is statistically the same as the ratios determined for smoldering in prescribed boreal slash fires.

Emission factors (EFs) for the Bor fire are contrasted with EFs determined by several groups (and methods) in table 79.2. The EFs in table 79.2 were all calculated using the same methods and do not distinguish between combustion phases. EFs are used to relate the mass of a particular species released into the atmosphere during burning to the mass of fuel combusted (Ward et al. 1979). EFs usually are expressed as the ratio of grams of product to kg of dry fuel burned. The development of EFs requires precise correlation of fuel consumption, vegetation type, and fire conditions, with the resulting emissions. Once developed, EFs can have broad application in estimating emissions for generic types of vegetation fires.

Ward et al. (1979) and Nelson (1982) developed a technique referred to as the carbon mass balance (CMB) technique for calculating EFs, which can be used to develop EFs for wildfires and fires where no prefire or postfire fuel characterizations have been done. The following synthesizes the CMB approach. Because more than 97% of the carbon released during biomass combustion is in the form of CO₂, CO, CH₄,

and particulates, the amount of carbon (g of C above background levels) can be measured in a smoke plume. Since the C content in woody fuels is about 50% of the dry mass, the amount of carbon can be related to the original mass of fuel by multiplying by 2. By convention, it is expressed in g/kg. EFs determined by the CMB technique would be expected to be within a few percent of EFs developed in the conventional manner. This technique has been applied to aircraft-obtained smoke-plume measurements by Radke et al. (1988). The establishment of the CMB method for determining EFs has greatly assisted in developing global biomass burning emission budgets.

It can be seen in table 79.2 that the EFs for the Bor fire for CO₂ and CO conflict with previously published results from several research groups (including our own). The Bor data suggest a significant increase in the proportion of CO emissions, no statistical difference in H₂ or CH₄, and a reduction in the proportion of CO₂ emissions. The proportion of CO₂ emissions would be expected to be less, based on the CO emissions, but H₂ and CH₄ would not be expected to remain equivalent.

Conclusions

We have previously suggested that very-high-intensity flaming combustion may significantly change the emissions chemistry typically associated with the flaming phase, leading to more incomplete combustion and correspondingly higher proportions of incompletely oxidized combustion products (Cofer et al. 1989), though a strong case could not be made. The Bor Island fire is the first boreal fire in which we have captured samples of predominantly crown-fire emissions. The enhanced proportion of CO emissions would support our thesis that extremely vigorous flaming biomass combustion, such as crowning, can become

inefficient, emitting a higher proportion of incompletely oxidized products. However, because the Bor fire is the first boreal fire we have studied that involved combustion of live, green needles, this might serve as an alternate interpretation of the CO results. The apparent conflict between the CO emissions and those for CH₄ and H₂ are very disturbing. Lower-efficiency combustion would also be expected to show up in the CH₄ and H₂ results. It did not. Because this is the only crown fire we have studied, we cannot be sure if these results are typical, anomalous, or even possibly spurious.

Traditionally, the study of boreal forest-fire emissions has focused on determining combustion-product vs. combustion-phase relationships and attempting to quantify the amounts of emissions generated and released during these phases; that is, how much product is released during flaming, how much during smoldering? This has been the focus because of the large difference between the amounts of incompletely oxidized combustion products emitted in the different phases. Our results lead us to speculate that boreal wildfire emissions during intense crowning may release combustion-product proportions more like smoldering combustion, at least with regard to CO. If this reasoning should be correct, then simple differentiation between smoldering and flaming combustion may not be adequate for quantitatively characterizing emissions.

Since large boreal wildfires typically cycle through phases of high-intensity and low-intensity combustion as environmental conditions (e.g., winds, temperatures, time of day) change, the problem of quantifying the amounts of combustion occurring during very intensely burning stages compared with less intense flaming stages may be very difficult, indeed. Nevertheless, the potential importance of direct injection of highly reactive wildfire emissions into the upper troposphere and lower stratosphere at very sensitive northern latitudes clearly dictates the need for additional study of high-intensity boreal wildfires. Wofsy et al. have asserted, "Assessments of global environmental change should recognize the pervasive influences of biomass burning in the boreal zone" (Wofsy et al. 1994).

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