

Carbon, Trace Gas, and Particulate Emissions from Wildfires in the Boreal Regions of North America

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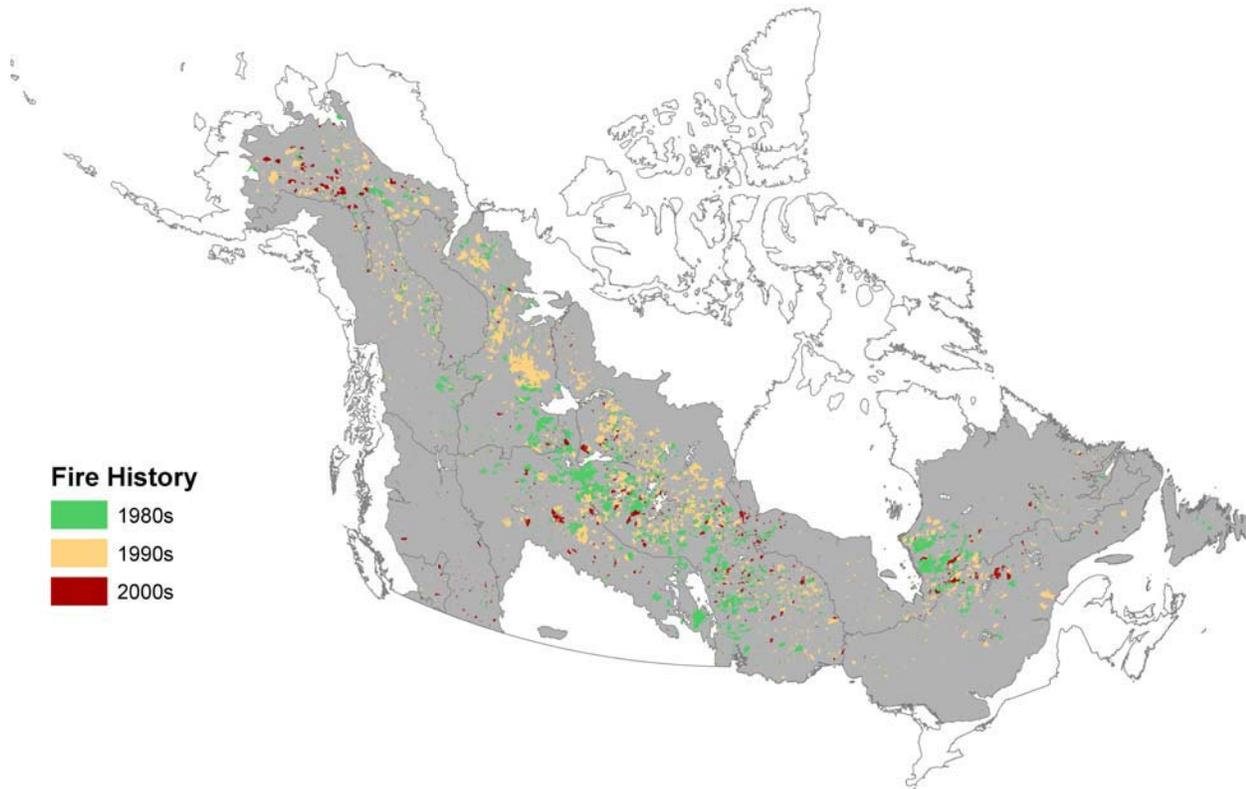
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ABSTRACT

Large wildfires have a considerable impact on the atmospheric concentrations of CO₂, CO, O₃, NO_x, and CH₄ across North America. Carbon releases can be as high as 4 to 8 kg C-m⁻² per fire event. These emissions significantly affect concentrations far downwind. With funding from NASA, the Joint Fire Science Program, NSF, and the Canadian Government, US and Canadian researchers have been developing a uniform approach to estimate carbon, trace gas, and particulate emissions from wildfire. Models to estimate the consumption of the forest floor and peatlands in boreal North America are being developed to study terrestrial carbon cycling and estimate trace gas emissions. Measurements of atmospheric CO, O₃, nitrogen oxides, and equivalent black carbon show boreal fires to be of great importance to levels of these gas and aerosol species on the continental to hemispheric scale. The work presented in this paper examines how fuel consumption varies in the deep surface organic layers found in many boreal forests and peatlands, and how factors controlling the variations in fuel consumption influence inter-annual to decadal variations in the North American terrestrial carbon budget and the emissions of CO, and ozone precursors.

Figure 1. Map of wildfires in the boreal regions of North America for 1980 to 2003.



INTRODUCTION

Boreal fires are very large and often severe in many ecosystems of the region¹. Average annual area burned in Alaska and Canada based on a record of more than 40 years is approximately 2 million hectares (ha), although fire in boreal North America is episodic with many years with very little fire and several extreme fire years representing a large proportion of the total area burned over the fire record^{1,2} (Figure 1). In 2004, more than 5.8 million ha burned in Canada and Alaska, one of the largest fire year on record for the North American boreal region, and the largest fire year known for Alaska. In 2004 and 2005 combined, more than 4.5 million ha burned in Alaska alone, which represents 10% of boreal interior Alaska. Over the past 4 decades, there has been a doubling of the annual area burned across the North American boreal region^{3,4}, which has resulted in an increase in the atmospheric emissions from fires⁵.

Severe stand replacement burns, where forest trees are killed and a large proportion of the aboveground biomass is consumed, are typical in black spruce (*Picea mariana*) and white spruce (*P. glauca*) dominated forests and common in forests dominated by jack pine (*Pinus banksiana*), lodgepole pine (*P. contorta*), and fir species (*Abies spp.*). Together, these forests represent most of the forested landscape of the North American boreal regions. Low evapotranspiration and cool conditions of the boreal region promote the build up of organic carbon in deep duff layers in forests and peat in forested and open peatlands. These organic deposits hold the majority of organic-based carbon in many boreal ecosystems where forest productivity is low resulting in low aboveground biomass.

With climate change, an increase in area burned in boreal North America is predicted⁶, and the deep organic layers found in boreal ecosystems may be more vulnerable to burning because of warming of permafrost and drying of peatlands⁷. Fuel consumption in ecosystems with large organic deposits (peatlands and forests with deep duff layers) is highly variable, depending primarily on fuel moisture and layer thickness. Fire can result in little to no consumption of the surface fuels to consumption of 10

to 20 cm or more of organic material, in many cases exposing the mineral soil. These organic deposits are very old, having survived many previous burns, with higher carbon density compared with more recently deposited organic litter at the surface⁸. Fire in these surface organic layers will subject more carbon to combustion and often burn in residual smoldering combustion which results in less efficient burning and higher levels of non-CO₂ trace gasses than flaming fires⁹. In addition, new evidence indicates wildfires in the boreal forest regions generate substantial amounts of mercury emissions (2 to 7 mg Hg-m⁻² per fire event) due to the build-up in surface material over long time periods¹⁰.

Large regional fire events over short time periods produce very high rates of emissions. Analysis of atmospheric measurements of CO, O₃, and nitrogen oxides at the Pico Mountain station in the Azores (38.48 N, 28.40 W) provide evidence of the significance of these large events. Other atmospheric measurements have pointed to boreal wildfires as a significant source of CO to the atmosphere. For example, during summer 2004 there were times when CO from the Alaska/Canada fires exceeded anthropogenic CO in the New England region¹¹ and exacerbated ozone levels as far south as Houston¹². By combining our understanding of the mechanisms that drive variability in fire emissions, we can improve interpretations of atmospheric measurements at locations around the globe.

The research projects reviewed in this paper illustrate the importance of boreal wildfire to regional and global carbon and trace gas emissions. The approaches to understanding boreal wildfire emissions, both through bottom-up accounting methods and through direct measurements of atmospheric constituents, are designed to fill knowledge gaps in emissions inventories related to natural and anthropogenic processes. The work presented in this paper examines how fuel consumption varies in the deep surface organic layers found in many boreal forest and peatland ecosystems, and how factors controlling the variations in fuel consumption influence inter-annual to decadal variations in the North American terrestrial carbon budget and the emissions of CO and ozone precursors.

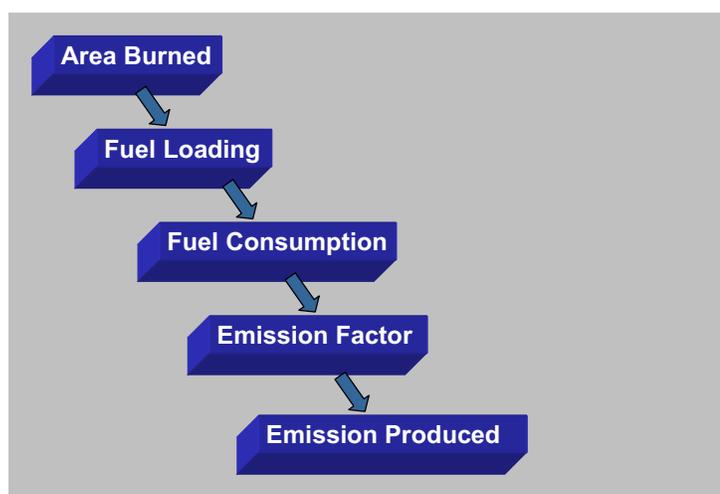
BODY

Approaches to estimating wildfire emissions from boreal regions

To acquire a better understanding of the emissions generated by the fire, the source strength must be characterized¹³. This requires explicit knowledge of the source including: (1) area burned; (2) fuel characteristics, (3) fuel consumption; and (4) pollutant-specific emission factors¹⁴⁻¹⁸. Although errors and uncertainties arise during each step of the process of estimating emissions, the largest errors are related to the characteristics of the fuels and fuel consumption (Figure 2)¹⁵⁻¹⁷.

Three approaches to estimating wildfire emissions from boreal regions will be reviewed in this paper, the Boreal Wildfire Emissions Model (BWEM) developed in Alaska, CONSUME 3.0 used in the United States for fires throughout the US and its territories, and the Boreal Fire Effects Model (BORFIRE) the Canadian model for boreal forest fire emissions. These approaches have similarities that will be apparent, although they are the result of different research groups' efforts.

Figure 2. Information needs for determining wildland fire emissions.



BWEM

The Boreal Wildfire Emissions Model (BWEM) is the result of many years of research sponsored, primarily, through grants from the National Aeronautics and Space Administration (NASA)¹⁹⁻²¹. As reviewed in French *et al.*¹⁹, calculating total carbon released during biomass burning (C_t) is generally done by estimating the area affected by fire along with the amount of fuel (carbon) consumed during the fire²². The emission of a particular gas species (E_g) is calculated from C_t using experimentally derived emission factors (E_{fg}), the ratio of gas released to total carbon released²³. For the boreal region, the analysis is separated into two fuel components, the aboveground or aerial component, and the surface organic material component, because of the large differences in these two pools in fuel composition and consumption characteristics. In estimating the contributions of each gas species, the proportion of flaming and smoldering burning is defined for each component to account for differences in emission factors for the two combustion types.

Typically the amount of carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH_4) released from fires is estimated. By separating carbon pools and combustion type, these fundamental variables are accounted for within the model parameter set. The following equations are used in the BWEM:

$$C_t = A(C_a\beta_a + C_g\beta_g) \quad (1)$$

$$E_g = A[C_a\beta_a(0.8 E_{fg-f} + 0.2 E_{fg-s}) + C_g\beta_g(0.2 E_{fg-f} + 0.8 E_{fg-s})] \quad (2)$$

where:

A = area burned (hectares, ha)

C_a = carbon density of the aboveground component (assumed to be 0.5 of biomass; t ha^{-1}),

C_g = carbon density of the organic material found in the ground-layer, which is composed of the litter and duff layers (t ha^{-1}),

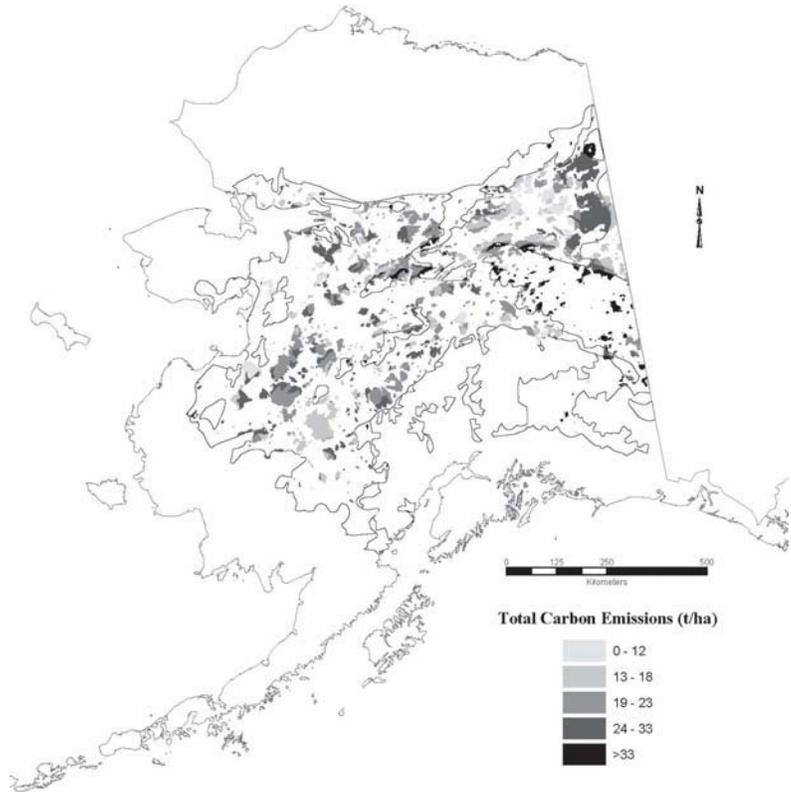
β_a and β_g = proportions of the aboveground vegetation and ground-layer organic carbon, respectively, consumed in the burn,

E_{fg} = emission factor for each of three gas species, CO_2 , CO , and CH_4 (in units of gas released per unit of carbon consumed)

The analysis using (2) is carried out for each gas independently. The f and s subscripts on the emission factor terms in (2) refer to flaming and smoldering combustion, respectively.

This approach has been used in a geospatially explicit application to estimate carbon emissions for Alaska over the 50 years for which fire records exist^{19,21} (Figure 3).

Figure 3. Map of carbon emissions ($\text{t}\cdot\text{ha}^{-1}$) for 50 years of fire in boreal Alaska. Estimates are the result of combining maps of fire occurrence with aboveground and surface organic carbon pools and expected fraction of carbon consumed in the fires as described French *et al.* (2002).



CONSUME 3.0

Research and application of emissions estimation by the USDA Forest Service, Pacific Northwest Research Station has used the same basic approach as the BWEM, in that fuel components are considered separately, and flaming and smoldering combustion are measured and accounted for as distinct phases. The Fire and Environmental Research Applications Team (FERA) have developed the CONSUME 3.0 fire consumption and emissions model. CONSUME 3.0 is a decision-making tool, designed to assist resource managers in planning for prescribed fire, wildland fire for use, and wildfire. Consume predicts fuel consumption, pollutant emissions, and heat release based on a number of factors including fuel loadings, fuel moisture, and other environmental factors. Using these predictions, resource managers can determine when and where to conduct a prescribed burn or plan for a wildland fire to achieve desired objectives, while reducing the impact on other resources²⁴.

Consume uses information collected on fuel consumption and emissions through field collections. Fuel consumption was measured at 106 sites during a project concentrating on the Conterminous US²⁴. Forest floor consumption was measured at 24 black spruce and white spruce forested sites in Alaska during 8 wildfires in Alaska in 2003 and 2004²⁵. In addition, 32 units burned prior to this project (1994-1997) were reanalyzed and incorporated into development of fuel consumption models in Consume 3.0. For the Alaska study, forest floor reduction was measured as the dependent variable using fire pins placed before the active fire front. Possible independent variables were also measured, including pre-fire live moss, dead moss, upper duff, and lower duff, litter and duff moisture content, and weather variables (relative humidity, temperature, days since rain, and wind speed). Linear regression models were developed to predict fuel consumption for all fuelbed types. For forested types, woody fuel consumption was predicted by timelag category (i.e., 1-, 10-, 100-, 1000- and 10,000-hr), and litter and duff consumption. The data analysis was used to generate coefficients for theoretical and empirical fuel consumption model design for implementation into Consume 3.0²⁶.

Emissions factors for CO₂, CO, CH₄, and NMHC were refined for emissions from boreal wildfires during the 2003 and 2004 field collection campaigns²⁵. The fire atmosphere sampling system (FASS)²⁷ was used to collect canister and filter samples and to record temperature, wind speed, CO and CO₂ during the flaming stage as the flaming front passed. A portable sample chamber was placed over the fuels to capture trace gas emitted during smoldering stage following the passage of the flaming front. At each fire site, four to six plots were selected and staked out at the start of sampling. The objective was to begin taking residual smoldering consumption samples as soon as possible to characterize the initial smoldering rates. Each plot was then revisited, at intervals of one to four hours. Background samples of ambient air were collected periodically as well.

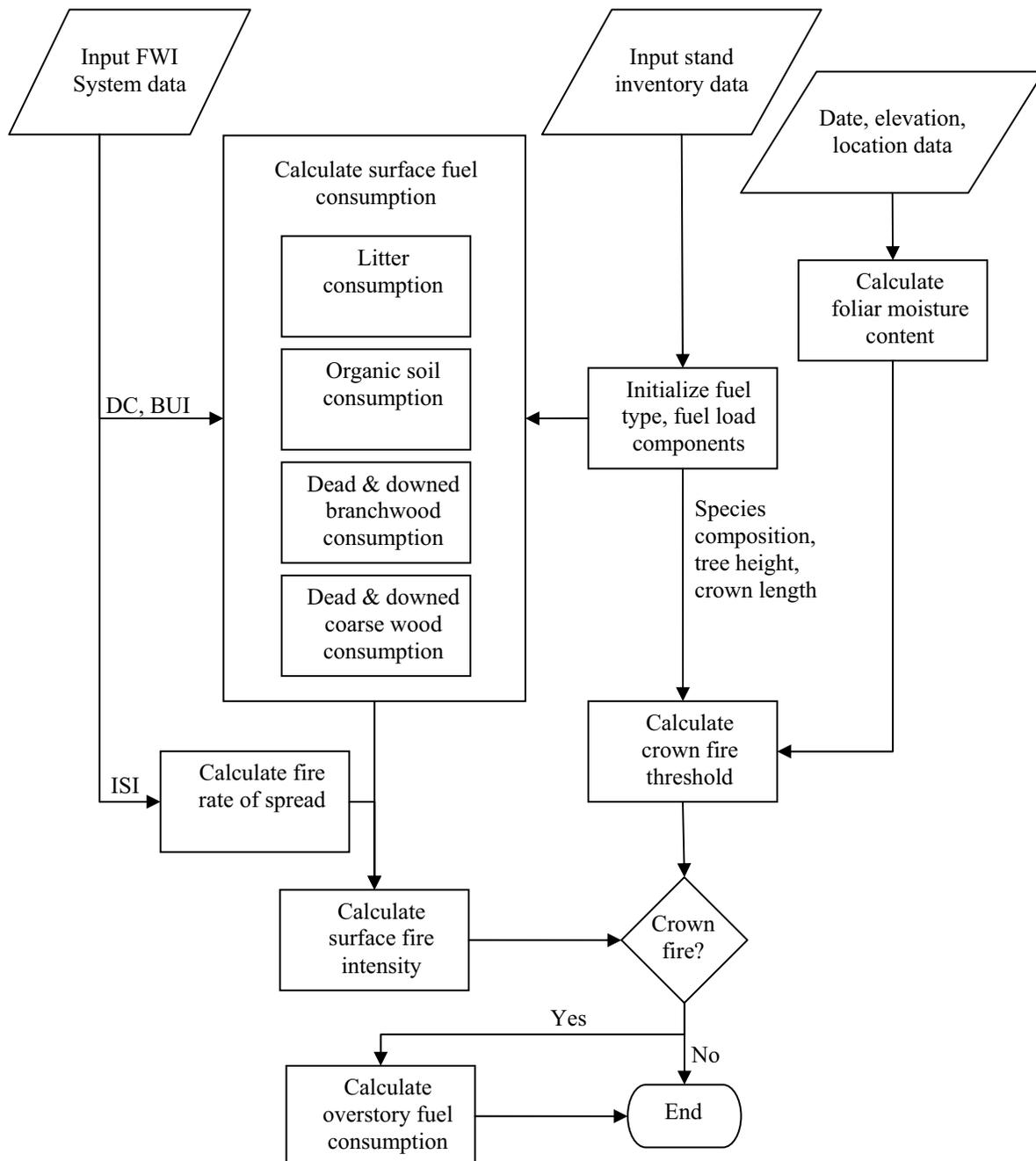
BORFIRE

In Canada, the Boreal Fire Effects Model (BORFIRE) is used to estimate wildland fire carbon emissions^{28,29}. BORFIRE is a collection of Canadian forest fire behavior algorithms that are used to calculate first-order fire effects on physical stand characteristics (fuel load, condition, and distribution), and to determine ecological effects (mortality and regeneration) based on the vital attributes of tree species. The model operates at the stand-level and includes 'fuel types' for six major boreal tree species (*Pinus banksiana*, *Picea glauca*, *Picea mariana*, *Populus tremuloides*, *Betula papyrifera*, and *Abies balsamea*). In this particular application of the model, it is used to estimate carbon emissions based on fuel consumption. BORFIRE calculates fuel consumption of various stand components including live tree material (fine roots, stemwood, branchwood, foliage), standing dead trees (stemwood, branchwood), dead and downed wood (coarse woody debris, medium woody debris), and forest floor organic matter (surface litter, duff). Fire weather and fuel load are used to drive dynamic species-specific fuel consumption algorithms. Figure 4 presents an overview of the dataflow and procedures. BORFIRE is used to provide spatial estimates of carbon emission by running as a submodel within the Canadian

Wildland Fire Information System^{30,31}, and is closely linked to the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3^{32,33}), which is the primary model for reporting national forest carbon stock changes, including carbon emissions.

Fuel consumption is primarily dependent on the pre-fire fuel characteristics and burning conditions (or fire weather) at the time of fire, which subsequently has an effect on direct carbon emissions^{5,21,34}. Pre-fire fuels in BORFIRE can be initialized to any single or multiple species combination, in any proportion. The preburn fuel load can also be adjusted in each stand component by species. Forest inventory and growth and yield models are generally used to provide the initial fuel condition. BORFIRE calculates the amount of fuel consumed in each stand component during a fire and the

Figure 4. Dataflow of BORFIRE for modeling stand-level fuel consumption (DC=Drought Code, BUI=Buildup Index, ISI=Initial Spread Index). Source: de Groot 2006.



amount of fuel transferred between components as a result of fire. Examples of the latter include transferring live tree material to standing dead snag components, and transferring standing dead snag material to dead and downed woody debris components.

Fuel consumption is greatly influenced by burning conditions, or fire weather (current and historical) at the time of fire. This is reflected in BORFIRE by fuel consumption algorithms that are driven by codes and indices of the Canadian Forest Fire Weather Index (FWI) System³⁵. The first step in calculating total stand fuel consumption is to determine surface fuel consumption, represented by the sum of fuel consumed in organic soil (or duff), surface litter, dead and downed coarse woody debris (logs), and dead and downed medium woody debris (branches). Each of these stand components has a separate fuel consumption algorithm. All surface litter material is assumed to be consumed by fire. Fuel consumption of both coarse and medium dead and downed woody debris follow a model based on results from experimental burning projects conducted in standing timber by the Canadian Forest Service, and incorporated in the Canadian Forest Fire Behavior Prediction (FBP) System³⁶ database. This algorithm is driven by Buildup Index (BUI) values of the FWI System, a general indicator of the total amount of fuel available for combustion.

Due to the large amount of fuel stored in the organic soils of many boreal stand types, forest floor fuel consumption can be very high. Unfortunately, there is limited data to model fuel consumption in this stand component. A new forest floor fuel consumption algorithm was recently developed for BORFIRE using the FBP System experimental burn database and post-fire data collected on large wildfires in 2004 and 2005. The forest floor algorithm is currently applied to all boreal stand types, but it is recognized that further research is required to model fuel consumption on deep (>30 cm) organic sites. The forest floor fuel consumption algorithm is driven by the Drought Code (DC) component of the FWI System, which is an indicator of the moisture content of deep organic layers.

After calculating total surface fuel consumption, BORFIRE initiates procedures to determine if there is a crown fire (Figure 4). This step is necessary to determine if there is any fuel consumption of the stand overstory. The crown fire threshold is measured in terms of the surface fire intensity required to initiate a crown fire and is dependent on foliar moisture content and the live crown base height³⁷. Seasonal foliar moisture content of conifers is calculated using Julian date and stand location data, following procedures in the FBP System³⁶. This step accounts for the spring dip in needle moisture content, which reduces the crown fire threshold (or critical surface fire intensity). Tree height and crown length are used to calculate the live crown base height, which is combined with foliar moisture content to calculate the crown fire threshold of coniferous species. Broadleaf species are not capable of supporting a crown fire in BORFIRE. A crown fire is only possible if at least 50% of the trees in the stand are capable of crowning.

Surface fire intensity is calculated by applying the total surface fuel consumption and fire rate of spread to Byram's³⁸ intensity equation. Rate of fire spread is based on the Initial Spread index (ISI) of the FWI System, following the FBP System algorithms for 16 broad fuel types. If surface fire intensity is greater than the crown fire threshold, then overstory fuel consumption is calculated. Overstory fuel consumption is estimated with an algorithm developed from the FBP System experimental burn database²⁸. Fuel consumption estimates from BORFIRE are combined with estimated pre-fire fuel load and the proportion (area) of each fuel burned to estimate total carbon emissions.

Using average FWI conditions for central Saskatchewan in BORFIRE, standard fuel consumption estimates from boreal fires range from 1.7–2.3 kg/m² in aspen stands to 3.2–6.3 kg/m² in black spruce stands²⁹. Using average monthly extreme FWI values, fuel consumption ranged from 2.2–2.8 kg/m² in aspen stands to 3.8–7.3 kg/m² in black spruce stands. In a spatial application of BORFIRE for a large 2003 fire in central Saskatchewan²⁹, fuel consumption estimates ranged 3.0–3.6 kg/m² across all

standing timber fuel types, except black spruce which was 4.6 kg/m^2 (however, all values are believed to be about $0.4\text{--}0.5 \text{ kg/m}^2$ too high due to higher than normal prefire fuel loads modeled for dead woody debris; see paper for details²⁹) (Figure 5). Overall, $\frac{1}{2}$ to $\frac{3}{4}$ of total fuel consumption occurred in the forest floor of all stand types.

Building a uniform approach

Based on these three established approaches, the authors are working towards a consistent methodology across the North American boreal region to estimate carbon, trace gas, and particulate emissions from wildfire. Emissions factors, used to partition total carbon emissions into specific trace gas emissions, are based on field and laboratory measurements that are fairly consistent for boreal fires, making this step relatively straightforward. The two most difficult factors to account for are variations in fuel loading and fuel consumption. The groups plan to share data on fuels and consumption, and are working towards a common approach to modeling fuel moisture using environmental variables and the established modeling frameworks.

The importance of surface fuel combustion to emissions from boreal fires

The three approaches described here for estimating boreal wildfire emissions put much of the effort into a better understanding of fuels and fuel consumption because of the high level of variability in these factors. Fuel consumption is one of the key variables in the modeling of fire effects¹⁵. In an analysis of the uncertainty of fire emissions in Alaska, it was found that the variability in biomass consumption during burning is the main driver of uncertainty in the emission of carbon-based greenhouse gases from wildland fires²¹. Fuel consumption varies based on ecosystem type, fuel load, fuel moisture condition, weather, and fire behavior. The variability is both spatial and temporal in nature; a particular site could experience a range of impacts due to temporally varying phenomenon. The problem of characterizing consumption, therefore, can be very complex.

Black spruce forests represent $>50\%$ of the forest cover of the N. American boreal region, and are found across the landscape in range of topographic positions. Because of the highly flammable nature of the understory vegetation as well as the canopy fuels, this forest type represents a major portion of the area burned in this region. The surface organic layers of this forest type range between 8 and $> 40 \text{ cm}$,

Figure 5. Example of the spatial variability in fuel consumption in an individual fire (2003 Montreal Lake fire, central Saskatchewan, Canada) calculated using BORFIRE and the Canadian Forest Fire Behaviour Prediction System (from de Groot 2007).

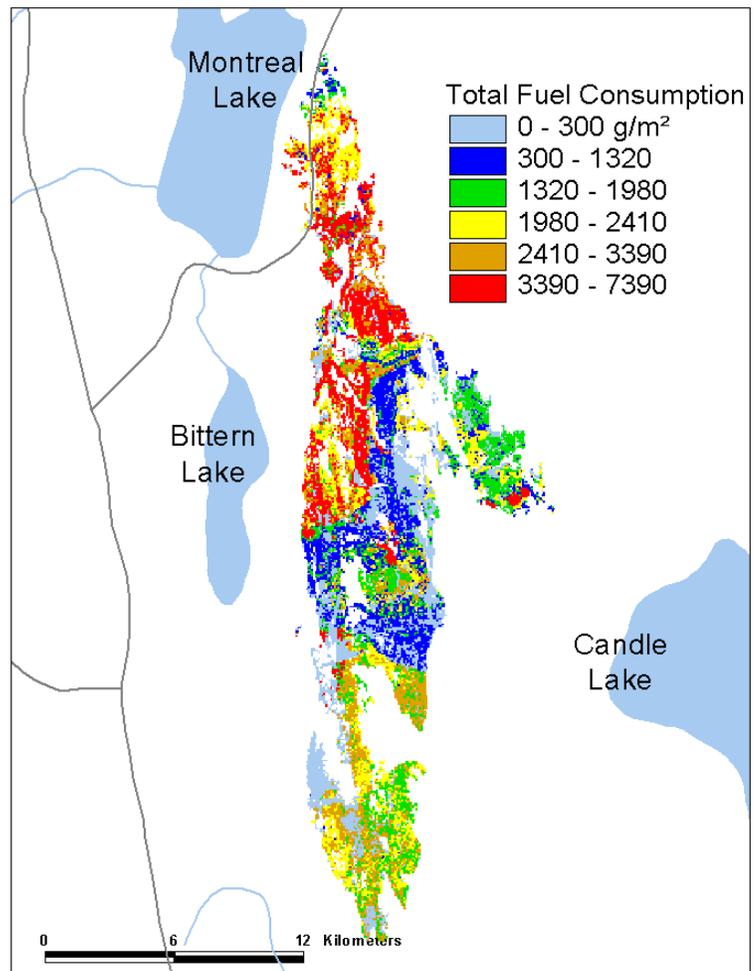
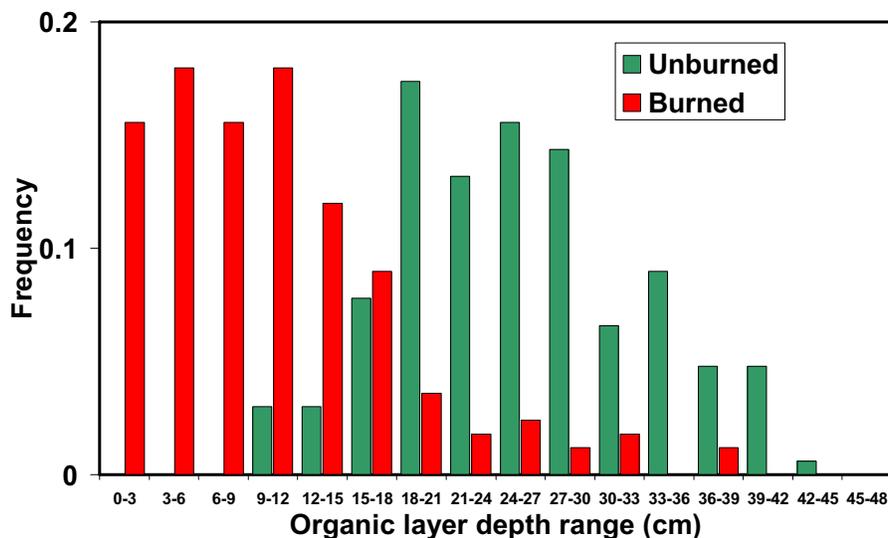


Figure 6. Histogram of the depths of the surface organic layer depths in burned and unburned black spruce forests from sites located in Interior Alaska. (Data used in this figure were collected by the authors of this paper - Kasischke, Turetsky, Ottmar, and French - as well as from other collaborators, including J. Harden and K. Manies of the U.S. Geological Survey and E. Kane of Mich. State Univ.).



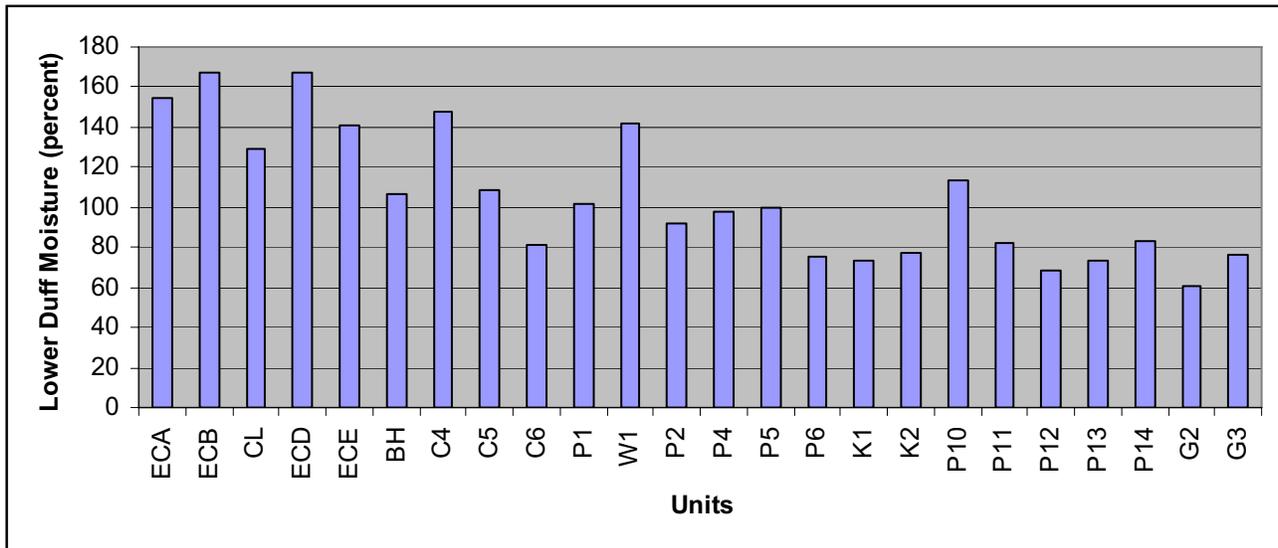
2005, as well as in sites that burned between 1983 and 2003 (Figure 6). Initial analyses of these data show that on average, unburned black spruce stands have a surface organic layer depth of 27 cm, which contain some 7.7 kg C/m². The average depth of the surface organic layers in the burned black spruce stands was 10 cm, with > 4.0 kg C/m² being released during fires. This level of fuel consumption is at least 50% greater than the values used in our current emission models for boreal forests. Additional measurements of duff depth and consumption are planned for Canadian forests because this fuel component is not well quantified for Canada, but recognized as an important component for carbon emissions estimation.

Peatlands cover between 15 and 20% of the land surface in the N. American boreal region boreal regions, with many peatland being forested bogs and fens. Until recently, the common perception was that these peatlands burned much less frequently than adjacent upland forests, with fire frequencies between 200 and 1000 years³⁹. Also, because of wet conditions, when peatlands did burn, it was estimated that fuel consumption levels were low. Recent studies show that peatlands may in fact be burning more frequently and with higher levels of fuel consumption. Research indicates that peatlands in western Canada may in fact be burning just as frequently as upland forests⁴⁰, and that levels of fuel consumption may average 3.0 to 4.0 kg/m²^{41,42}.

It should be noted that the burning of duff and peatland fuels affects the proportion of trace gas species emitted during fires, and in turn, the emission factors used in equation (2). While flaming combustion is common during the burning of aboveground vegetation in boreal systems, surface organic layer fuels (particularly organic peat and organic soils) are primarily consumed during smoldering combustion²⁰. Both laboratory⁴³ and field measurements^{25,44,45} show that smoldering combustion releases a higher proportion of a number of important reduced trace gas (e.g., CO, CH₄) species than does flaming combustion because of lower combustion efficiencies. However, very few measurements of boreal wildfires exist, so accurate partitioning of flaming and smoldering combustion for estimation of emissions is not typically possible. By varying assumptions on flaming/smoldering proportions, French *et al.*¹⁹ found a wide variation in CO and CH₄ emissions.

and variations in depth of burning in this layer represents a major source of uncertainty in estimating emissions²¹. Because of this uncertainty, over the past several years, field research has focused on measuring depth of burning in the recent Alaskan fires. When combined with previous field observations, the Alaskan data set consists of surface organic layer measurements from well over 350 sites in burned and unburned black spruce forests. While the majority of the data were collected in sites that burned during the 2004 fires, data were also collected from several sites that burned in

Figure 7. Lower duff fuel moisture content for each area measured for forest floor reduction during 2003 and 2004 (Duff moisture can exceed 100% in situations where the material is saturated).



Field data collected for the forest floor consumption and smoke characterization study in Alaska by FERA²⁵ includes measured live and dead moss, upper and lower duff moisture content, forest floor reduction, and smoke measurements (Figures 7 & 8). Although the lower duff moisture content did not vary much during the 2003 wildfire season, there was a wide range of lower duff moisture contents during the 2004 fire season. This was an extremely rare event and provided the opportunity to develop a very robust forest floor reduction data set. In late spring and early summer, the ice layer which formed during winter months in the duff begins to melt and the upper layers become ice free. In late June, the upper layers of the mineral soil become ice free and moisture from the forest floor begins to drain. Rapid drying occurs unless there is rainfall. The 2004 fire season was very dry late in July and August, providing an opportunity to measure forest floor consumption under low fuel moisture conditions not often available. Analysis of these data showed forest floor consumption for Alaskan boreal forest

Figure 8. Forest floor reduction measured during 2003 and 2004 wildfire season.

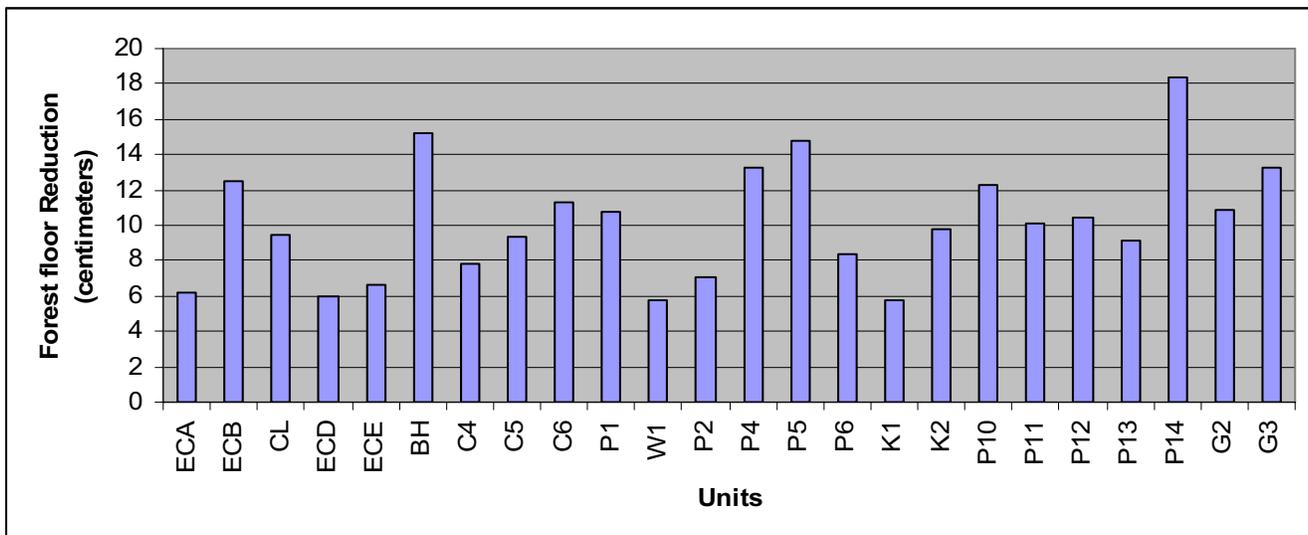


Table 1. Emission factors for crown fires during flaming (F), intermediate (I) and smoldering (S) phases from the FAAS tower measurements (Table 5 in Ottmar and Baker, 2007).

Fire	Date	Phase	EF _{CO₂}	EF _{CO}	EF _{CH₄}	EF _{NMHC}	EF _{PM_{2.5}}	MCE
			-----g/kg-----					
Chicken	6/24/2004	F	1692	68.4	2.08	2.66	5.59	0.940
		I	1612	108.1	4.38	3.94	7.65	0.905
		S	1515	155.5	7.92	6.39	9.02	0.861
Porcupine 1-1	6/26/2004	F	1734	50.3	1.20	1.83	3.19	0.956
		I	1642	92.6	2.84	3.07	7.82	0.919
		S	1509	165.7	5.62	5.18	9.08	0.853
Porcupine 1-2	6/26/2004	F	1681	82.2	2.66	3.14	1.83	0.929
		I	1553	156.3	6.23	5.84	NS	0.863
		S	1535	168.1	5.94	5.15	0.57	0.853

fuelbeds were predicted by pre-burn forest floor depth and upper duff moisture content. Forest floor depth is important for determining total consumption, while moisture content is the major heat sink, determining total amount of forest floor that will consume. The equation developed from this analysis is used in CONSUME 3.0 to determined forest floor consumption as follows:

$$\text{Proportion Forest Floor Reduced} = \text{EXP}(y) / (1 + \text{EXP}(y)) \quad (3)$$

where $y = 1.2383 - (0.0114 \times \text{Duff FM})$
Duff FM = fuel moisture of upper duff layer

Comparisons of CO to CH₄, NMHC, and PM_{2.5} from the FASS tower smoke sampling in the 2004 Alaska field campaign conducted by the Rocky Mountain Research Stations Fire Chemistry project in conjunction with FERA²⁵, show that CO is a good predictor of other fire emissions products (regression r² values were: 0.84, 0.98, 0.87 for CH₄, NMHC, and PM_{2.5} respectively)²⁵. The CH₄ regression analysis shows the characteristically high r² value for these gases that has been observed for most prescribed and wildland fires measured in the contiguous United States. A similar relationship with CO is also produced for non-methane hydrocarbons (NMHC) in this study. The r² value of 0.98 indicates that variation in CO concentration highly predicts NMHC concentration. Emission factors during the passage of the fire front for flaming, intermediate, and smoldering combustion phase, are shown in Table 1. Flaming phase emission factors can be considered representative of crown fire emission factors for Alaska boreal forest for model inputs. The emission factors and modified combustion efficiency (MCE) ratios were quite consistent among the three sites sampled.

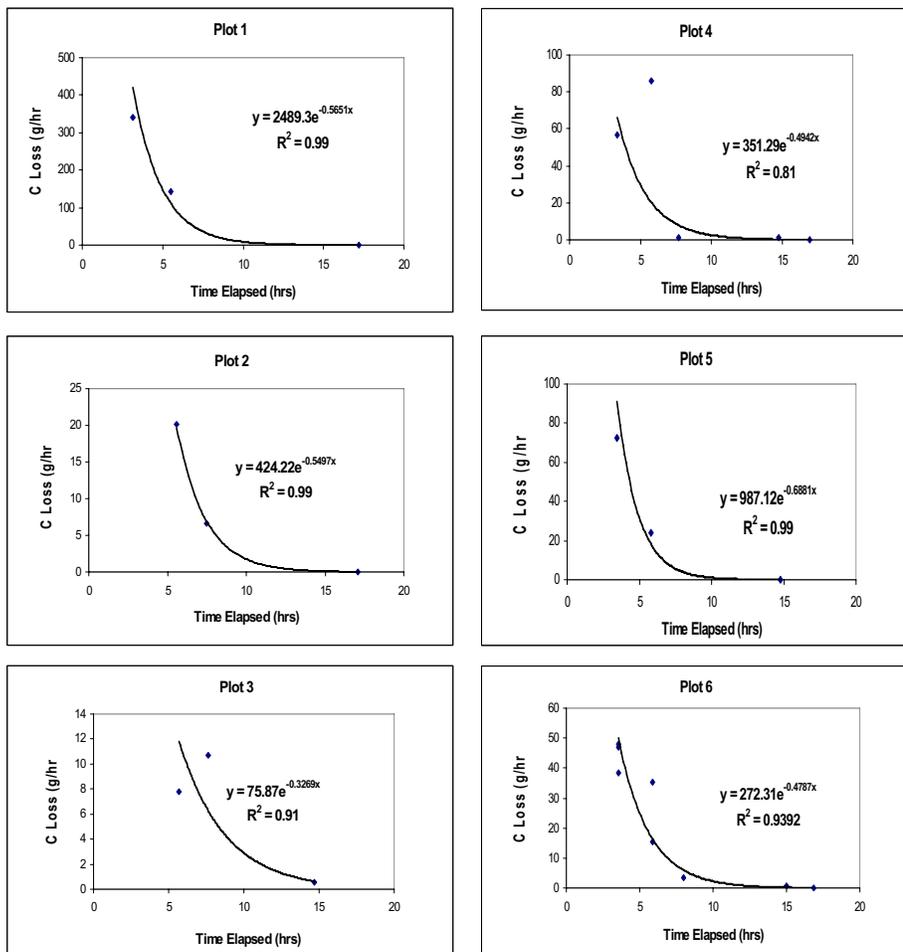
Table 2. Residual smoldering combustion emissions factors for the 2003 Alaskan fires (Table 6 in Ottmar and Baker, 2007).

Fire	Date	EF _{CO₂}	EF _{CO}	EF _{CH₄}	EF _{C₂H₄}	EF _{C₃H₆}	EF _{NMCH}	MCE
		-----g/kg-----						Ratio
Erickson Wildfire	6/22/03	1425	244	6.3	1.35	1.04	1.35	0.79
Erickson 2 Wildfire	6/22/03	1463	247	8.5	0.88	0.69	0.88	0.81
Chena Lake	6/25/03	1419	240	10.1	1.49	1.24	1.86	0.79
Average		1436	244	8.4	1.23	0.99	1.37	0.80
Standard deviation		33	43	3.4	0.94	0.72	1.03	0.02

Smoldering emission factors reported in Table 2 are for short term smoldering in crown fires – shortly after cessation of flaming phase. The residual smoldering combustion (RSC) emission factors for the 2003 for longer term smoldering phase emissions and MCE ratios are shown in Table 2. In comparison with emission factors from previous RSC studies in the western and southeast United States, the Alaska boreal forest had lower MCE values. This may be an indication of different fuel moistures or a difference in the smoldering characteristics of the boreal forest fuels, mainly the duff layer. These data also show a strong positive linear relationship between CH₄ and CO (*r*² of 0.70) and NMHC and CO (*r*² of 0.67) for RSC. This indicates that CO can be used as a good predictor of these other compounds for RSC in Alaska.

Figure 9 displays the set of carbon release curves for the six plots measured on the Chicken wildfire of 2004. All six display a characteristic exponential decay curve. This exponentially declining consumption rate is used by modelers to determine fuel consumption and total emissions at any point from the onset of RSC. In Plot 1 of Figure 10, the RSC consumption rate at time *t* is $2489.3e^{-0.5651t}$, where the initial rate is 2489.3 and the *k* value is -0.5651. In general, the initial rate is proportional to the total fuel available, while the value of *k* is usually indicative of the type of fuel and environmental factors affecting consumption. For all plots, the rate of carbon release declined rapidly between 10 and 15 hours after initiation of the residual smoldering phase.

Figure 9. Carbon loss rate graphs for six sample plots measured in a Alaskan wildfire (Fig 19 in Ottmar and Baker, 2007).



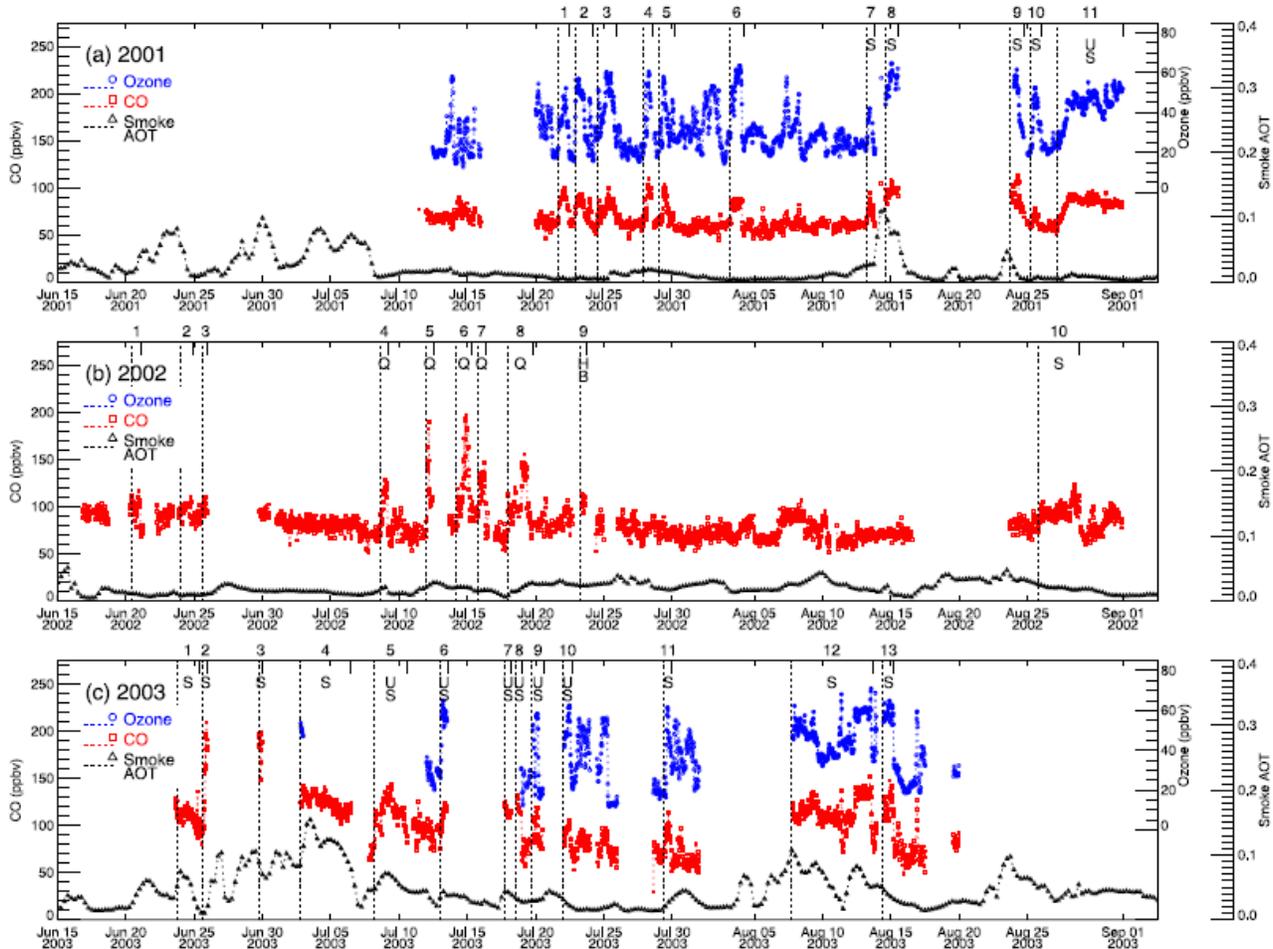
Atmospheric sampling of boreal wildfire emissions

Estimation of wildfire emissions, as detailed here, allows a comparison to direct measurements of the atmosphere and can help in interpretation of atmospheric measurements of pollutants. Observations in urban regions indicate that upwind boreal fires have significantly increased CO, ozone, and particulate levels during specific events^{11,12,46}. However, with the exception of major fire events it is difficult to quantify the contribution of fire emissions to pollutant levels in otherwise polluted regions, as a result of local and regional anthropogenic emissions. This is especially the case for reactive gases such as ozone and nitrogen oxides. Measurements in remote regions avoid this problem and, if the location is chosen carefully, provide information on large-scale impacts of boreal fires that are relevant to assessments of

Figure 10. Photo of the Pico Mountain station showing haze layer originating from a 2002 fire in Quebec.



Figure 11. Time series of measured CO, measured O₃, and NAAPS/FLAMBE smoke aerosol optical thickness (AOT) for measurements at the Pico Mountain station during the summers of 2001–2003. CO is plotted with red squares, ozone is plotted with blue circles, and smoke AOT is plotted with black triangles. (Ozone measurements are not available for summer 2002, and are missing during some periods in 2003.) Source-fire regions for biomass burning-impacted periods are identified near the top of each plot: S, Siberia; Q, Quebec; HB, Hudson Bay; US, the western United States (from Honrath et al. 2004).



effects on populated regions such as the United States and western Europe.

Honrath and others⁴⁷⁻⁴⁹ have conducted multi-year measurements at the free tropospheric at Pico Mountain station in the Azores Islands for this purpose. This station is frequently exposed to flow from northern North America that does not pass over the high-emission regions of the U.S. and southeastern Canada. A visual example of one such event is shown in Figure 10, which shows a haze layer originating in a 2002 fire in Quebec visible behind the Pico Mountain station. Fire impacts can be unambiguously identified using a combination of CO measurements and simulations of the transport of fire-emitted CO. In addition, because of its location in the lower free troposphere, upwind deposition of ozone and nitrogen oxides is minimized. However, the station is far downwind from the boreal regions – for example, 6 to 15 days downwind from the 2004 fires in Alaska and eastern Canada. As a result, measurements there are indicative of conditions over a very large region. Here, we briefly review the findings from these measurements to date.

Figure 11 shows time series of all Pico Mountain measurements of CO and ozone during the summers of 2001, 2002 and 2003⁴⁷. Frequent correlated enhancements in both compounds are identified as events in the graph. Those events that are attributed to upwind wildfire emissions are labeled with “S,” “Q,” “HB,” or “US” indicating source fires in Siberia, Quebec, the Hudson Bay region or the northwestern U.S. (Events not labeled with a fire source were the result of upwind anthropogenic emissions.) It is clear that a significant fraction of the variability in ambient CO and ozone at this location is the result of transport of wildfire emissions. As a result, interannual variability in boreal fire magnitude results in interannual variability in CO and ozone levels. Figure 12a shows the distribution of CO observed during 2001 (a year of relatively low boreal fire activity), 2003 (a year of elevated fire activity in Siberia) and 2004 (a year of elevated fire activity in Alaska and western Canada)⁴⁸. The CO distribution is shifted significantly toward higher mixing ratios. Figure 12b shows the corresponding distributions of ozone, which also exhibited higher levels during the high-fire years. To determine whether this shift in ozone levels was the result of increased ozone in air from the fire regions, we analyzed the distribution of ozone observations during only those periods when backward trajectories indicated air flow from northern North America. These northern North American-outflow measurements were divided into two subsets: one that was apparently impacted by upwind fire emissions (based on the presence of elevated CO), and one that was not impacted by significant upwind fire emissions (based on relatively low CO levels). As shown in Figure 13, the distributions of ozone levels in these “fire” and “non-fire” data subsets differed significantly, indicating a significant impact of boreal fire emissions on free tropospheric ozone far downwind of the fires.

Figure 12. Distributions of (a) CO and (b) O₃, including all measurements for each summer. (from Lapina et al. 2006).

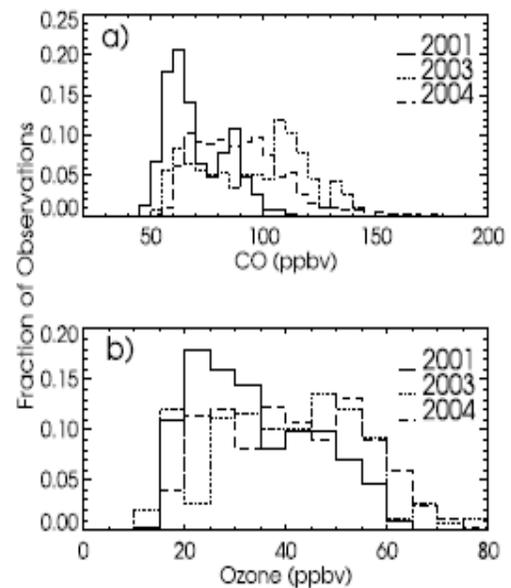
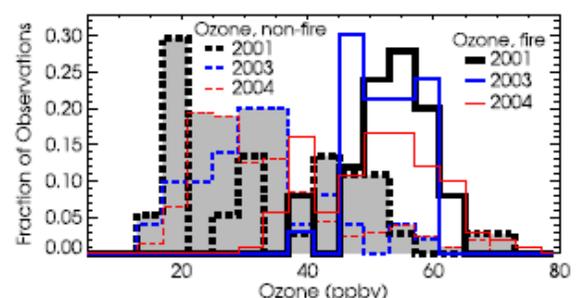


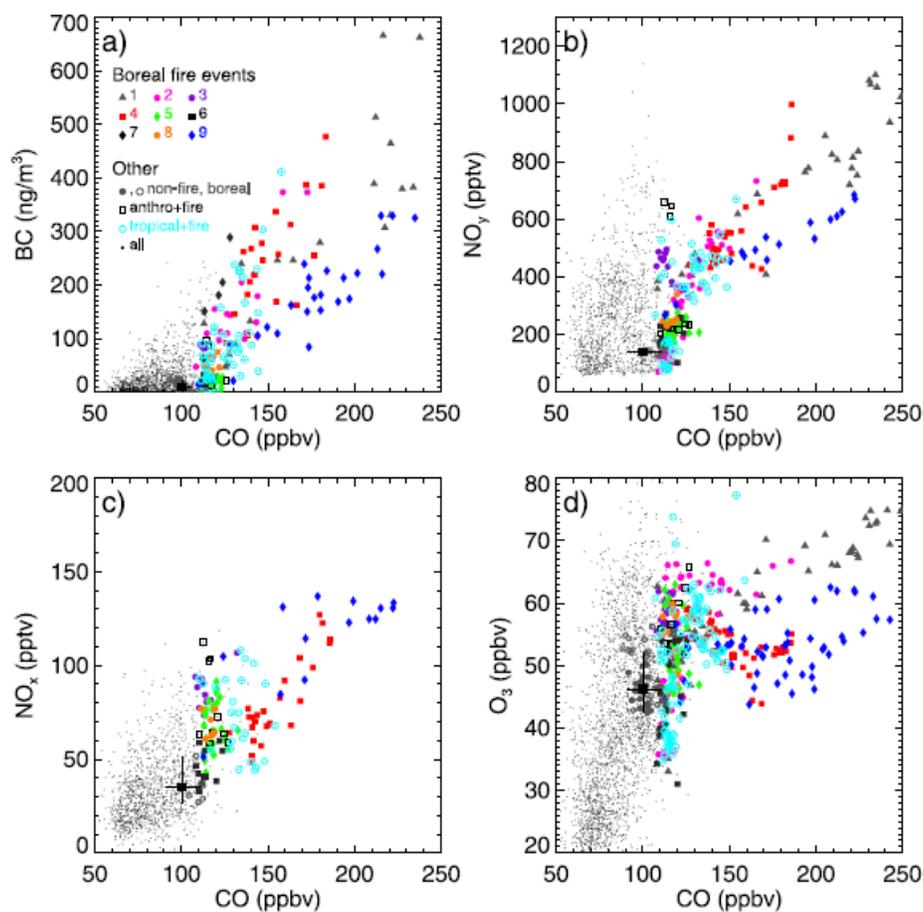
Figure 13. O₃ frequency distribution in Northern N. American (NNA) flow, fire and non-fire subsets. The area under the non-fire O₃ distributions is shaded (from Lapina et al. 2006).



Additional analyses of observations during 2004 were used to further probe the magnitude of ozone, ozone precursor, and particulate enhancements due to boreal fires. Since the lifetime of CO is long even relative to the duration of transport from the fires to the Azores region, we treat CO as a semi-conserved tracer. Figure 14⁴⁹ presents plots of equivalent black carbon (absorbing aerosol), total reactive nitrogen oxides (NO_y), NO_x ($\text{NO}+\text{NO}_2$) and ozone against CO. Observations during periods significantly impacted by fire emissions and not significantly impacted by recent anthropogenic emissions are highlighted using colored symbols. A non-reactive compound that is emitted at a constant emission ratio relative to CO would exhibit a linear relationship in a plot of this type, with the slope indicating the emission ratio. Despite the potential for wet removal of black carbon and NO_y , these plots are well correlated for equivalent black carbon, NO_y and NO_x . Indeed, the magnitude of the observed enhancement ratios of black carbon and NO_y are consistent with loss of less than one-half of the emitted black carbon and nitrogen oxides (i.e., very efficient long-distance transport of the fire emissions). For black carbon, this implies a potential for significant large-scale impacts on direct radiative forcing^{50,51}. For nitrogen oxides, it implies a potential for large-scale impacts on tropospheric ozone, since most of the NO_y is believed to be peroxyacetyl nitrate, PAN^{52,53}, which thermally decomposes to release NO_x . This process is believed to be the mechanism responsible for the enhanced NO_x levels shown in Figure 14c. The size of the fire NO_x source is significant. If the mean NO_y :CO enhancement ratio observed during the 2004 fire events reflected the mean emission ratio in boreal fires, then the total NO_x emissions during a typical fire season in which total boreal fire emissions total $\sim 61 \text{ Tg CO}^{20}$ would be 0.24 TgN, more than 2/3 of the eastern North American anthropogenic NO_x emissions during a period of similar duration⁴⁹. Actual fire emissions are expected to exceed this value, since the observed NO_y :CO enhancement ratios are affected by loss during transport to the Azores.

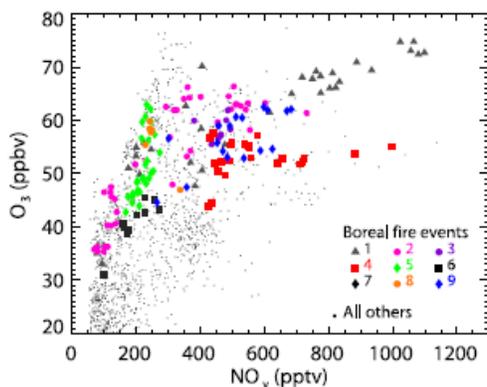
Ozone levels were also enhanced during most of the fire events, but were not highly correlated with CO. This may be a result of varying photochemistry during transport and varying ratios of NO_x and CO in the upwind fires. Figure 15 shows that ozone varies with NO_y in a more consistent manner than it does with CO (Figure 14d). This supports the hypothesis that ozone enhancements are affected by varying levels of NO_x , released by NO_y compounds (i.e., PAN). Despite the variability, ozone was significantly enhanced during all major fire events, relative to non-fire conditions. Using the mean observed ozone:CO enhancement ratio, we

Figure 14. Relationship between CO and the indicated species during summer 2004: (a) BC versus CO, (b) NO_y versus CO, (c) NO_x versus CO and (d) O_3 versus CO (from Val Martin et al. 2006).



estimate that the 2004 North American boreal wildfires resulted in net production of 10-21 Tg ozone⁴⁹. This is a significant perturbation to the background ozone budget. The Pico Mountain measurements have also been used in a photochemical modeling study of the impact of the 2004 North American boreal fires upon tropospheric ozone, which produced results consistent with these measurement-based findings⁵⁴.

Figure 15. Relationship between O₃ and NO_y during summer 2004 (from Val Martin et al., 2006)



hypothesis. The Pico Mountain measurements can be used to provide important constraints on this process. As shown in Figure 16, NO_y and equivalent black carbon are better correlated than are NO_y and CO (compare Figure 14a). Since emissions of both NO_x and black carbon⁵⁶ are higher in flaming than in smoldering combustion, while CO emissions are higher in smoldering combustion, this is consistent with impacts from variations in fire type. We are currently using the Pico Mountain NO_y:CO enhancement ratios to constrain the magnitude of the seasonal variation in NO_x:CO emission ratios.

Summary

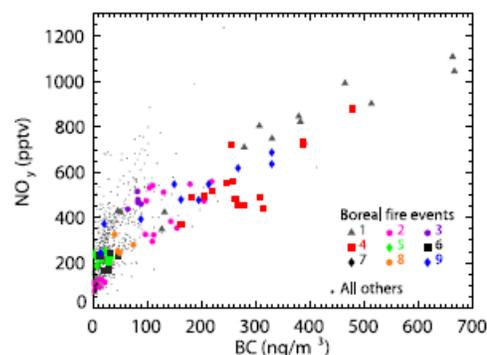
Three approaches for quantifying emissions from boreal ecosystems have been presented. The efforts have strong similarities, that will allow them to be used together to further improve our estimates of wildfire emissions. Carbon emissions can be as high as 4 to 8 kg C·m⁻² for a single fire, but with high variability in space and from year-to-year. Variability in trace gas emissions is highly variable due to variability in depth of duff or peat burning and proportion of flaming versus smoldering burning. This annual variability is detected in atmospheric measurements of CO and ozone at the Pico Mountain station, indicating the broad-scale implications of these fire events. by combining our understanding of the mechanisms that drive variability in fire emissions, we can improve interpretations of atmospheric measurements at locations around the globe. Potential release of mercury stored in the organic material stored in boreal ecosystems provides another motivation for improving estimates of duff and peat consumption during biomass burning.

CONCLUSIONS

The research presented in this paper represents a broad set of activities that, taken together, provide an understanding of how fire in boreal North America, and the unique ecological structure of boreal ecosystems influence the spatial and interannual variability in emissions from wildfire. The importance

This work to date demonstrates that boreal fires have a significant impact on tropospheric ozone. However, model-based estimates of those impacts remain highly uncertain, as a result of the extreme paucity of direct measurements the magnitude and variability of boreal fire NO_x emissions. The existing near-fire observations indicate significantly larger emissions from flaming combustion than from smoldering combustion⁵⁵, and the understanding of fire emissions incorporated into the models discussed above indicates that there is a shift toward increased prevalence of smoldering combustion later in the fire season. Thus, we expect a shift toward reduced NO_x:CO emission ratios as the fire season progresses each year, but there are currently no measurements to support or refute this

Figure 16. Relationship between BC and NO_y during summer 2004 (from Val Martin et al., 2006)



of developing a more complete understanding of the role of fire in the carbon cycle and its influence on the atmosphere as well as the unique situation in boreal ecosystems of deep organic deposits that are subjected to fire is now being realized. The research reviewed in this paper represents part of this new understanding and provides a set of questions to be explored that will contribute to a better quantification of fire emissions and the uncertainties that remain.

Some areas of active research and where new research is needed include:

1. A better understanding of the level of fire that occurs in N. American boreal peatlands: We are currently carrying out a detailed correlation between burned area maps derived from analysis of satellite imagery with maps of peatlands derived from interpretation of aerial photography in central Alberta. Such comparisons will eventually be carried out in a number of regions where peatlands are common to determine the actual area burned during peatland fires. In addition, we are collecting field data necessary to estimate the levels of surface fuel consumption that occur in peatlands.
2. Improved surface fuel maps: Fuelbeds vary widely in their physical attributes and are one of the key input variables required to adequately estimate carbon stores and fuel consumption and smoke resulting from wildland fires. FERA has developed a national system called the Fuel Characteristic Classification System (FCCS)⁵⁷ that enables a user to build fuelbeds and capture the structural complexity and geographical diversity of all fuelbed components that have a potential to burn during a wildland fire. Although the FCCS fuelbeds, standard to the system, represent the boreal forest region of Alaska, they have been mapped at 1 kilometer only for the contiguous 48 states. An effort to extend the FCCS fuelbed map to include the boreal forest regions of North America is urgently needed.
3. Fuel consumption: Although great strides have been made toward quantifying fuel consumption in the boreal regions, the data used for these models has been limited to total forest floor consumption collected in upland forests. Little research has been completed on quantifying consumption of tree crowns, peatland fires, or separating total consumption into the flaming and smoldering combustion periods. These will be critical needs in the future to improve our prediction of carbon, trace gas, and particulate matter generated from wildfire in the boreal regions of North America.
4. Partitioning of flaming and smoldering combustion: A better quantification of the partitioning between flaming and smoldering combustion is very important for rectifying the measurements of smoke and other atmospheric constituents that are the result of boreal fires, such as the measurements collected at the Pico Mountain station. Some field measures have been done, but more are needed in burning of a variety of forest and peatland types.

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KEY WORDS

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