Modeling Canadian wildland fire carbon emissions with the Boreal Fire Effects (BORFIRE) model

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Abstract: Wildland fires in Canada burn an average of 2.8 million hectares of forest annually. In years of extreme forest fire activity, total carbon emissions from wildland fires approach levels similar to industrial carbon emissions. Quantifying annual wildland fire carbon emissions is required for Canada to meet its international reporting obligations. Carbon emission rates within a fire vary considerably due to fire behaviour within the burn perimeter. Large fires typically burn a wide range of fuel types under weather conditions that change as the fire spreads across the landscape. This causes huge spatial and temporal variation in fuel consumption, which is directly related to carbon emissions. To capture spatial and temporal variability, the Boreal Fire Effects (BORFIRE) model estimates carbon emissions using detailed fuel and weather data. BORFIRE is initialized with forest inventory data to establish preburn fuel loads for forest stand components, including live tree material (coarse roots, 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). Carbon loss from each component is based on fuel consumption, which is calculated using fuel-specific fire behaviour models and burning conditions quantified by the Canadian Forest Fire Weather Index (FWI) System. Fire rate of spread is determined using the Initial Spread Index (ISI) of the FWI System and rate of spread algorithms of the Canadian Forest Fire Behavior Prediction System. This is combined with surface fuel consumption to calculate surface fire intensity using Byram's equation. If surface fire intensity exceeds the crown fire threshold, fuel consumption of aerial fuels is calculated. After determining carbon emissions, BORFIRE calculates the carbon transfers between stand components. BORFIRE has been incorporated as a submodel in the Canadian Wildland Fire Information System (CWFIS), and procedures have been developed to link CWFIS with the Carbon Budget Model of the Canadian Forest Sector to operationally calculate carbon emissions for Canadian wildland fires.

Keywords: fire behaviour, fire effects modeling, forest carbon, fuel consumption

1. Introduction

The amount of area burned by wildland fires in Canada has steadily increased during the last half century (Stocks *et al.*, 2002) to an average of 2.8 million hectares during the 1990s, more than double the average annual area burned during the 1970s (Amiro *et al.*, 2001; Stocks *et al.*, 2002). Recent estimates of direct carbon emissions from Canadian wildland fires indicate levels that approach industrial carbon emissions in years of extreme fire activity (Amiro *et al.*, 2001). Wildland fire activity is expected to increase across most of Canada, with the largest increase occurring in central and western Canada (Flannigan *et al.*, 2005), areas that are already characterized as having the highest national annual burn rates (Stocks *et al.*, 2002).

To meet international reporting commitments under agreements such as the United Nations Framework Convention on Climate Change (UNFCCC), Canada is required to provide annual carbon emission estimates from wildland fires. International reporting is conducted under Canada's National Forest Carbon Monitoring. Accounting and Reporting System (NFCMARS; Kurz and Apps. 2006). The core model of NFCMARS is the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3: Kurz *et al.*, 1992; Kurz and Apps, 1999). In 2004, Natural Resources Canada initiated a joint project between the Canadian Forest Service and the Canada Centre for Remote Sensing to develop a system to estimate annual national wildland fire carbon emissions[1]. To fully integrate the new system with CBM-CFS3. a new methodology to estimate carbon emissions based on fuel, weather, and fire behaviour was developed. By adapting the Boreal Fire Effects (BORFIRE) model with new fuel consumption algorithms. it was possible to match individual stand (fuel) components with carbon pools of the CBM-CFS3. This paper summarizes the fuel consumption modeling procedures used in BORFIRE to estimate wildland fire carbon emissions.

2. Wildland Fire Carbon Emissions in Canada

Amiro *et al.* (2001) provided the first detailed national estimates of direct carbon emissions from wildland fires, covering the period 1959–1999. Those results were based on the spatial large-fire database for Canada (Stocks *et al.*. 2002). weather data for days when fire was estimated to have spread. and basic fuel consumption models for standard fuel types in the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group. 1992). a subsystem of the Canadian Forest Fire Danger Rating System (CFFDRS: Stocks *et al.* 1989). Because few datasets are available, many fuel, weather, and fire behaviour assumptions were necessary to provide historical carbon emission estimates. Large (>200 ha) fires account for about 97% of the annual area burned in Canada (Stocks *et al.*, 2002) and they typically burn a wide range of fuel types and fuel loads under weather conditions that change as the fire spreads across the landscape. This causes large spatial and temporal variation in fuel consumption and carbon emissions (French *et al.*, 2004).

Variability in fuel consumption has been well documented by previous experimental burning projects in jack pine (*Pinus banksiana*) stands (Stocks. 1987. 1989; Stocks *et al.*, 2004). which are a frequently burned and prominent component of the Canadian forest. Detailed fuel data from those studies show total fuel consumption rates of 0.4–5.4 kg/m^2 in fires with intensities of 134–93,476 kW/m. The greatest range in fuel consumption rate occurred in the forest floor component. where 28–74% of the initial forest floor material was burned. representing fuel consumption of 0.2–2.8 kg/m^2. Overstory fuel consumption was 0.6–2.2 kg/m^2. less than 5% of the total aboveground tree biomass. Dead and downed woody fuel consumption generally represented a small amount of the total fuel consumption due to the limited initial fuel load. The wide range of total fuel consumption in this single fuel type was caused by variability in pre-fire fuel characteristics (fuel size. distribution. and total load). and burning conditions as influenced by weather. which affected fuel moisture content. In other fuel types characterized by deeper organic soils such as black spruce (*Picea marianna*). there is greater potential for a wider range of total

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[1] de Groot. W.J.. Landry. R.. Kurz, W.. Hall. R.J.. Anderson. K.R.. Fraser. R.H.. Raymond. D.. Decker. V.. Lynham, T.J., Englefield. P.. Banfield E. Estimating annual carbon emissions from Canadian wildland fires (manuscript in prep)

fuel consumption due to higher forest floor fuel loads. To account for the wide range of fuel consumption (and carbon emissions) that occurs within large fires, a new estimation procedure was developed by adapting the BORFIRE model.

3. BORFIRE Fuel Consumption Overview

The BORFIRE model is essentially a collection of Canadian fire behaviour models that are used to estimate first-order fire effects on physical stand characteristics (fuel load, condition, and distribution), and to estimate ecological effects (mortality and regeneration) based on the vital attributes of tree species. BORFIRE has previously been used to study the impacts of future fire regimes on forest composition and biomass storage (de Groot *et al.*, 2003) and fire management adaptation strategies to climate change (de Groot *et al.*, 2002). In this carbon emissions application, BORFIRE is being used to model the immediate impacts of fire on forest carbon pools.

BORFIRE is a stand-level model that simulates fire effects on six major boreal tree species in Canada (*Pinus banksiana, Picea glauca, Picea marianna, Populus tremuloides, Betula papyrifera,* and *Abies balsamea*). BORFIRE calculates fuel consumption in various stand components including live tree material (coarse roots, 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 is used to drive dynamic species-specific fuel consumption algorithms. Figure 1 presents an overview of the dataflow and procedures.

3.1 *Fuel load*

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 (Kasischke and Stocks, 2000; Amiro *et al.*, 2001; French *et al.*, 2004). 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. For this application, carbon pool data from CBM-CFS3 are used to provide the initial fuel condition. This ensures national consistency in carbon accounting and reporting. The CBM-CFS3 determines the carbon pool status for each burned stand at the time of fire using forest inventory data and growth and yield models. Carbon pool values are converted to fuel type and fuel load values for each stand component. BORFIRE calculates the amount of fuel consumed in each stand component during a fire and the 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.

3.2 *Surface fuel consumption*

As previously stated, 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

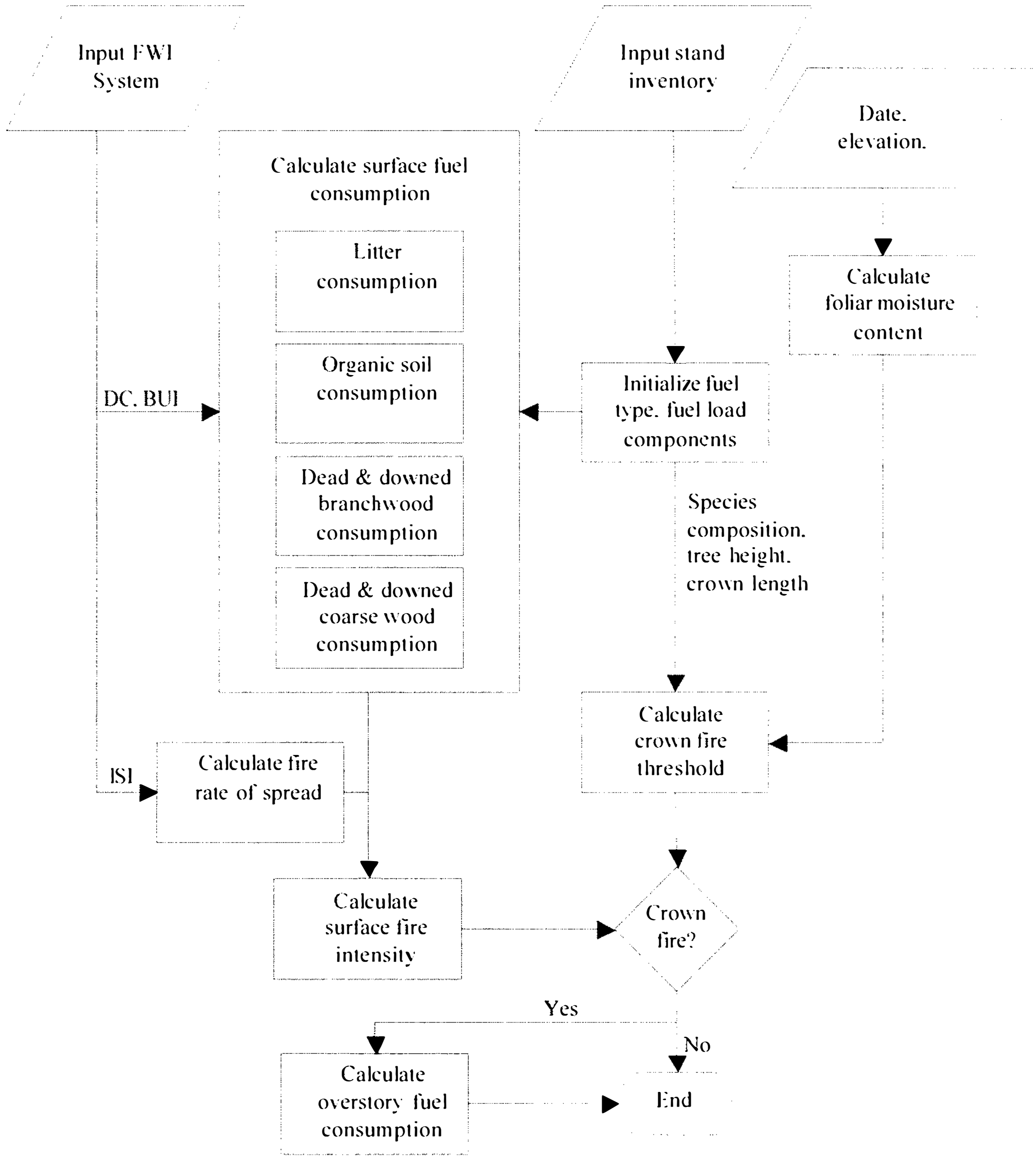

Figure 1. Dataflow of BORFIRE for modeling stand-level fuel consumption (DC=Drought Code, BUI=Buildup Index, ISI=Initial Spread Index).

Fire Weather Index (FWI) System (Van Wagner, 1987), another subsystem of the CFFDRS. 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 in BORFIRE as long as the fire is capable of spreading, which requires a minimum Initial Spread Index (ISI) value of one. The ISI is a component of the FWI System and is a general indicator of fire rate of spread. If the fire is not capable of spreading, it is assumed that the stand burned on another day and the model is initiated for the next day when the ISI criteria is met. Fuel consumption of both coarse and medium dead and downed woody debris follow McRae (1980) with a minor adjustment to the equations to ensure a gradual decrease in fuel consumption to zero as initial fuel load approached zero. These algorithms are 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[2]. 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 (>25 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.

3.3 *Overstory fuel consumption*

After calculating total surface fuel consumption, BORFIRE initiates procedures to determine if there is a crown fire (Figure 1). 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 height (Van Wagner, 1977). Seasonal foliar moisture content of conifers is calculated using Julian date and stand location data, following procedures in the FBP System (Forestry Canada Fire Danger Group, 1992). 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's (1959) intensity equation. Rate of fire spread is based on ISI 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. Although there is little data on overstory fuel consumption, this value is currently estimated as the sum of foliage and bark using tree biomass algorithms. Although they are preliminary estimates, these values are comparable to overstory fuel consumption data recorded on experimental burns in the FBP System database.

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[2] de Groot, W.J., Pritchard, J., Lynham, T.J., Wang, Y., Peters, V. Forest floor fuel consumption in Canadian wildland fires (manuscript in prep)

4. Discussion

When development of a new national system to estimate wildland fire carbon emissions began, one of the main hurdles was to link the CBM-CFS3 with fire behaviour models. The CBM-CFS3 and FBP System are capable of calculating carbon emissions and fuel consumption (respectively), but neither does so with dynamic algorithms based on the combined effects of fuel load and fire weather. CBM-CFS3 has variable carbon pools, which can be converted to fuel load and fuel type information, but it has no capacity to adjust fuel consumption due to different burning conditions. On the other hand, the FBP System was designed to model fire behaviour for 16 standard fuel types based on burning conditions, but cannot adjust fuel consumption for variable pre-fire fuel loads.

One of the main reasons for developing BORFIRE was to integrate the research being done in carbon and fire modeling communities. BORFIRE still follows many procedures used in the FBP System, such as crown fire determination and calculation of fire rate of spread, but a major difference is that BORFIRE is based on tree species and the FBP System is based on fuel type. The only exception to this is when fire rate of spread is calculated in BORFIRE because it relies on the FBP System rate of spread equations. Using a species-based approach provides BORFIRE with the flexibility to adjust fuel load values for different stand components by using biomass algorithms for individual tree species. This results in a better representation of the physical stand structure for any age and species composition of the stand. The effect this has on fuel consumption and carbon emissions is quite significant. Table 1 illustrates the range of fuel consumption that typically occurs under standard fire weather and forest stand conditions.

Table 1. Example of total fuel consumption range (kg/m^2) for several stand types in BORFIRE, based on stand age[1] and burning conditions[2].

Species	Ave. FWI System values Age (yrs)			Extreme FWI System values Age (yrs)		
	25	50	100	25	50	100
Pinus banksiana	2.4	2.8	2.8	2.7	4.8	5.1
Picea marianna	2.7	3.9	5.8	3.2	4.4	6.7
Picea glauca	2.1	3.8	5.0	2.4	4.3	5.7
Populus tremuloides	1.5	2.1	1.9	1.9	2.5	2.3

[1] Stand age used to provide initial fuel load for stand components using growth and yield algorithms of Alberta Forest Service (1985) for pure, fully stocked stands on medium productivity sites. Pre-fire forest floor fuel load was 4 kg/m^2 for all stand types except *Picea marianna*, which was 8 kg/m^2.

[2] Burning conditions quantified by mean and extreme FWI System parameters during 1953–1980 for a west-central Canada location (Prince Albert, SK) using Harrington *et al.* (1983) data. FWI System values represent mid-June (summer) conditions for the conifer species (*Pinus*, *Picea*) and early May (spring) conditions for the hardwood species (*Populus*).

In general, BORFIRE fuel consumption estimates are higher than FBP System estimates. This is primarily due to greater forest floor fuel consumption in BORFIRE. The new algorithm used in BORFIRE was developed with the FBP System database plus additional post-fire field survey data. Large wildland fires that burned under high burning conditions were targeted in that study to supplement the FBP System database, which was restricted to experimental burns with generally lower burning conditions. The FBP System was developed during a time when fire behaviour research was focused on products in support of fire suppression, such as fire rate of spread and head fire intensity predictors. Experimental burning projects were not specifically designed to cover a wide range of fuel consumption conditions. This was the reason for collecting additional wildfire fuel consumption data to develop a new algorithm.

BORFIRE has been incorporated as a submodel within the Canadian Wildland Fire Information System (CWFIS) to spatially estimate national wildland fire carbon emissions. CWFIS is a system used to apply the CFFDRS and the Fire Monitoring, Mapping, and Modeling (FireM3) system at the national level (Lee *et al.*, 2002; Englefield *et al.*, 2004). CWFIS provides daily spatial FWI System data to drive BORFIRE algorithms, and it links with CBM-CFS3 to convert carbon pool data into fuel data for BORFIRE. If spatial inventory and fire spread data (using remotely sensed hot spots) are available, it is possible for CWFIS to spatially model wildland fire carbon emissions on the landscape, and temporally adjust the carbon emissions for the fire weather conditions on the day each stand burned. It is known that a wide variation in fuel consumption and carbon emissions occurs on an individual fire, and the CWFIS product in Figure 2 provides a good example of this.

5. Future BORFIRE Modifications

Although most of the area burned in Canada occurs in the boreal forest, national application of BORFIRE has demonstrated the need for many more tree species to be included in the model. This will be a major focus of research over the next year. There is also a recognized limitation of fuel consumption algorithms for some stand components, including slash, stand overstory, and forest floors with deep organic soils. A new model to estimate overstory fuel consumption is currently being developed using experimental burn data from the FBP System database, with completion anticipated by the end of 2006. Sufficient slash consumption data can likely be obtained from existing publications and reports, but further field study and experiments will probably be required to develop reliable algorithms for fuel consumption of deep organic soils.

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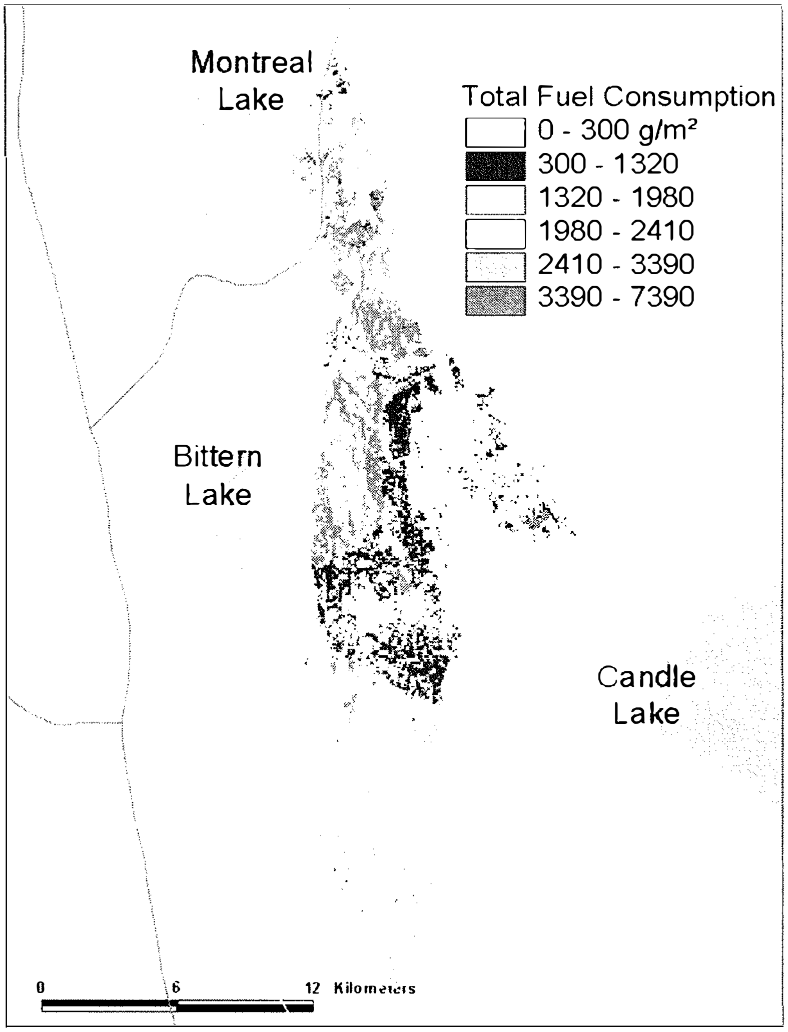

Figure 2. Example of the spatial variability in fuel consumption in an individual fire (2003 Montreal Lake fire. central Saskatchewan. Canada) calculated using the Canadian Forest Fire Behaviour Prediction System. If spatial forest inventory data were available for this example. BORFIRE would produce a similar spatial pattern in fuel consumption.

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