Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires

W.J. de Groot, J.M. Pritchard, and T.J. Lynham

Abstract: In many forest types, over half of the total stand biomass is located in the forest floor. Carbon emissions during wildland fire are directly related to biomass (fuel) consumption. Consumption of forest floor fuel varies widely and is the greatest source of uncertainty in estimating total carbon emissions during fire. We used experimental burn data (59 burns, four fuel types) and wildfire data (69 plots, four fuel types) to develop a model of forest floor fuel consumption and carbon emissions in nonpeatland standing-timber fuel types. The experimental burn and wildfire data sets were analyzed separately and combined by regression to provide fuel consumption models. Model variables differed among fuel types, but preburn fuel load, duff depth, bulk density, and Canadian Forest Fire Weather Index System components at the time of burning were common significant variables. The regression R^2 values ranged from 0.206 to 0.980 ($P < 0.001$). The log–log model for all data combined explained 79.5% of the regression variation and is now being used to estimate annual carbon emissions from wildland fire. Forest floor carbon content at the wildfires ranged from 40.9% to 53.9%, and the carbon emission rate ranged from 0.29 to 2.43 kg·m^{-2}.

Résumé : Dans plusieurs types de forêts, plus de la moitié de la biomasse totale du peuplement se retrouve dans la couverture morte. Les émissions de carbone durant un incendie de forêt sont directement reliées à la consommation de la biomasse (combustible). La consommation des combustibles de la couverture morte varie grandement et constitue la source la plus importante d'incertitude dans l'estimation des émissions totales de carbone durant un incendie. Nous avons utilisé les données de brûlages expérimentaux (59 brûlages et quatre types de combustibles) et d'incendies de forêt (69 placettes et quatre types de combustibles) pour élaborer un modèle de consommation des combustibles de la couverture morte et des émissions de carbone pour des types de combustibles avec du bois sur pied mais excluant les tourbières. Les données des brûlages expérimentaux et des incendies de forêt ont été analysées séparément et ensemble au moyen d'équations de régression pour constituer des modèles de consommation. Les variables des modèles différaient selon le type de combustibles mais la charge de combustibles antérieure au feu, l'épaisseur d'humus, la densité apparente et les composantes de la méthode canadienne de l'indice forêt-météo au moment du brûlage étaient des variables communes significatives. Les valeurs de R^2 des régressions variaient de 0,206 à 0,980 ($P < 0,001$). Le modèle log-log pour toutes les données combinées expliquait 79,5% de la variation et est maintenant utilisé pour estimer les émissions annuelles de carbone provenant des incendies de forêt. Le contenu en carbone de la couverture morte lors des incendies de forêt variait de 40,9 à 53,9% et le taux d'émission de carbone variait de 0,29 à 2,43 kg·m^{-2}.

[Traduit par la Rédaction]

Introduction

Wildland fires burn about 2.8×10^6 ha annually in Canada (Amiro et al. 2001; Stocks et al. 2002), releasing large amounts of carbon into the atmosphere. Estimates obtained from 1959–1999 data indicate that annual direct carbon emissions from Canadian wildland fires have ranged from 3 to 115 Tg; for major fire years, levels were near 75% of carbon dioxide emissions from the Canadian energy sector (Amiro et al. 2001). The average annual area burned in Canada has more than doubled during the past two decades (Amiro et al. 2001; Stocks et al. 2002) and is expected to continue increasing across most of Canada as climate change progresses (Flannigan et al. 2005). Increasing fire severity, or increasing forest floor fuel consumption, will also contribute to greater total carbon emissions in the future (de Groot et al. 2003).

The amount of direct carbon loss in a wildfire depends on the amount of forest biomass consumed (French et al. 2004; Kasischke et al. 2005), including crown fuels (foliage, branch wood, bark), surface fuels (shrubs, dead and downed woody material), and forest floor fuels (litter, organic soils). The organic soils of the forest floor represent large carbon stores. Much of the Canadian boreal forest consists of stand types that can store over half of the total fuel load in the forest floor (Nalder and Wein 1999; Kasischke et al. 2000). A fire typically consumes 0%–25% of the preburn fuel load for aboveground fuels (de Groot et al. 2007), but consumption of forest floor fuel can range from near 0% to 100% (Dyrness and Norum 1983; Wein 1983; Kasischke et al. 2000).

The greatest uncertainty in modeling wildfire carbon emissions at the forest-stand level is estimating the forest floor component of those emissions (French et al. 2004). A

Received 1 February 2008. Accepted 6 October 2008. Published on the NRC Research Press Web site at cjfr.nrc.ca on 6 February 2009.

W.J. de Groot[1] and T.J. Lynham. Canadian Forest Service, 1219 Queen Street East, Sault Ste. Marie, ON P6A 2E5, Canada.
J.M. Pritchard.[2] Canadian Forest Service, 5320-122 Street, Edmonton, AB T6H 3S5, Canada.

[1]Corresponding author (e-mail: bill.degroot@nrcan.gc.ca).
[2]Present address: Department of Plant Sciences, 51 Campus Drive, University of Saskatchewan, Saskatoon, SK S7N 5E8, Canada.

number of factors contribute to variation in consumption of forest floor fuel. Moisture content, bulk density, mineral soil content, and depth of the forest floor all influence forest floor combustion, consumption, and depth of burn (Hartford 1989; Frandsen 1997; Miyanishi and Johnson 2002). The forest floor is composed of several distinct fuel layers with differing characteristics that affect flammability. Dead needles, leaves, small (<1 cm) twigs, herbaceous plant material, lichen, and live mosses form the uppermost surface litter (L) layer. Depending on the forest fuel type and moisture regime, all components may or may not be present. The key characteristic of the L layer is that the moisture content of these fine fuels adjusts very quickly (hourly) to changing environmental conditions. Underlying this material is a layer of partially decomposed organic soil, often characterized as duff by the fire science community (others cited in Kasischke and Johnstone 2005) or the fibric or fermentation (F) layer of soil science. This layer corresponds to the dead moss and upper duff layers of Harden et al. (2004). The deepest organic soil, or lower duff, layer is characterized by well-decomposed plant material, represented by mesic (M) and humic (H) layers. Bulk density generally increases from the top to the bottom of the duff layer, so drying rate decreases with organic soil depth. Alternately, the uppermost duff layer is affected first (and most) by precipitation, and the lowest duff layer is affected only if there is sufficient rainfall to percolate downwards. Moisture content of the lowest duff layer is also strongly influenced by site drainage characteristics. Forest stands on north-facing and toe slopes have cooler, wetter, and deeper organic soils (Kane et al. 2007). Kasischke and Johnstone (2005) suggest that greater drainage on coarse-textured soils can result in drier soils and deeper burning. In the northern boreal region permafrost impedes drainage from deep duff layers.

Many predictive models of forest floor fuel consumption have been based on moisture content relationships. The Duff Moisture Code (DMC) of the Canadian Forest Fire Weather Index (FWI) System is an indicator of the moisture content of loosely compacted forest floor organic matter, roughly corresponding to the F layer (Van Wagner 1987). It represents forest duff layers about 7 cm deep with 5 $kg \cdot m^{-2}$ dry mass. The DMC has correlated well with forest floor moisture in many stand types (e.g., Wotton et al. 2005; Abbott et al. 2007; Otway et al. 2007) and cut-over areas (Chrosciewicz 1989). The Drought Code (DC) component of the FWI System was originally developed as an index of water stored in the soil, but it can also be used to represent the moisture content of slow-drying heavy fuels because it simulates exponential moisture loss (Van Wagner 1987). The DC fuel layer is described as compact organic soil corresponding to the F and H layers, about 18 cm deep with 25 $kg \cdot m^{-2}$ dry mass, a water-holding capacity of 100 mm, and theoretical maximum moisture content of 400% (Van Wagner 1987; Lawson and Dalrymple 1996). The DC is also a good model of the moisture content of deep organic soils (Lawson and Dalrymple 1996). Predictive equations for forest floor fuel consumption and depth of burn have been developed using the DMC or the Buildup Index (BUI; an indicator of the total amount of fuel available to the spreading fire, calculated from DMC and DC) as an independent variable (e.g., Van Wagner 1972; Stocks 1987*a*, 1989). The Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) has generated predictive equations for consumption of surface fuel (forest floor, understory vegetation, dead woody debris) for 16 fuel types, all based on the Fine Fuel Moisture Code (FFMC; an indicator of the moisture content of surface litter and other cured fine fuels) and (or) BUI components of the FWI System. Although the FBP System accounts for variability in fuel consumption because of forest floor moisture content, it does not incorporate preburn fuel load, depth, or bulk density of the forest floor as independent variables.

The purpose of this study was to develop more robust models of the consumption of forest floor fuel for use in estimating carbon emissions from Canadian wildland fire (de Groot et al. 2007). The study was initiated in support of the National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) (Kurz and Apps 2006), which is being used to meet international reporting commitments under the United Nations Framework Convention on Climate Change.

Methods

Two sources of data were used to develop new models of forest floor fuel consumption: data from experimental fires, taken from the FBP System database, and field data collected from recent wildfires. These data were compiled by data source into a single data set representing a broad range of fuel types, preburn fuel loads, and burning conditions (which, in turn, represented the influence of both past and present fire weather). Data were restricted to those from fires on upland or well-drained sites; peatlands will be examined in subsequent studies. The data used in this study were tree species composition, preburn depth of the forest floor, fuel load by depth within the forest floor, bulk density by depth within the forest floor, inorganic content at the point where mixing between organic and mineral soil layers occurred, and values of FWI System components for the day of burning. Data on the carbon content of the forest floor were collected during the wildfire field study and were used with the fuel consumption model to estimate carbon emissions.

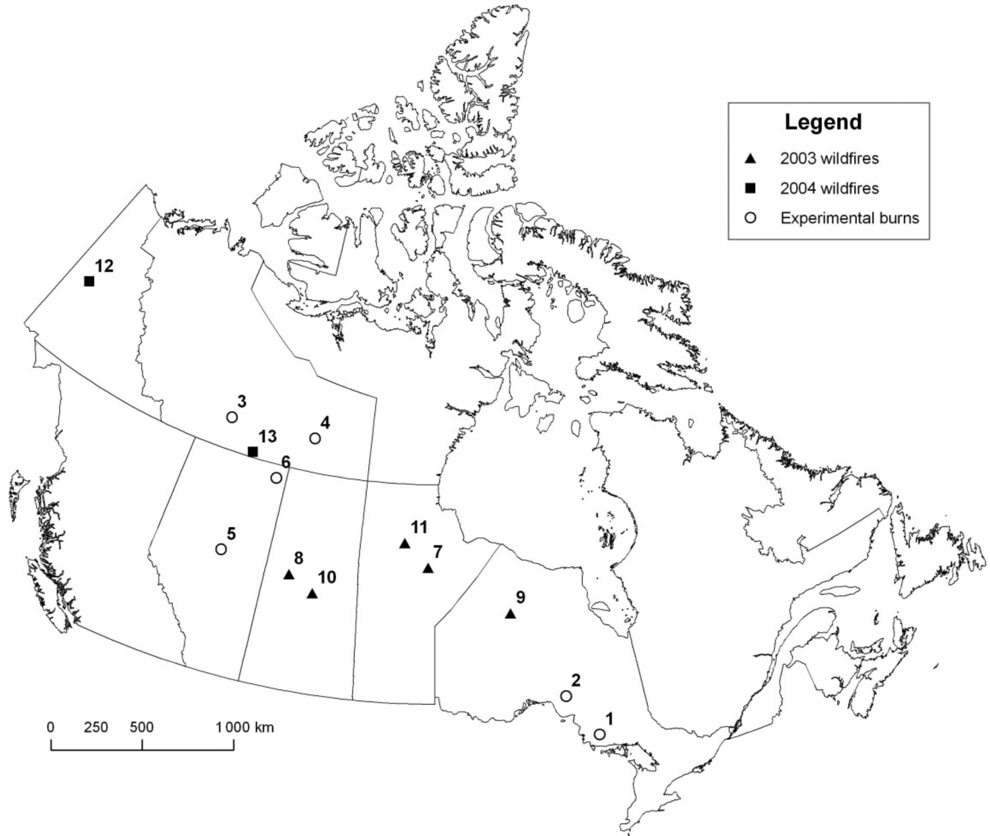
Experimental fires

The Canadian Forest Service has conducted numerous experimental burning projects across Canada over the past 30 to 40 years. Data from those projects account for a large component of the current FBP System database, which, until the current study, was the only compiled database of fuel consumption in Canadian standing-timber fuel types. Data from six experimental burning projects in the database were used in this current study. A brief description of each project follows.

The Hondo experimental burning project in central Alberta (Fig. 1) was conducted in a semimature trembling aspen (*Populus tremuloides* Michx.) stand with scattered white spruce (*Picea glauca* (Moench) Voss) and jack pine (*Pinus banksiana* Lamb.) and infrequent white birch (*Betula papyrifera* Marsh.) (Quintilio et al. 1991). The well-drained site was characterized by a moderate L layer, shallow duff (F and H) layer, and very low total forest floor fuel loading.

Four experimental burning projects were conducted in jack pine dominated stands. The Darwin Lake project (Quintilio

Fig. 1. Locations of experimental fires and wildfires used in this study. Numbers refer to specific fire sites (see Table 1).



et al. 1977) was located in upland jack pine stands on the Canadian Shield of northeastern Alberta (Fig. 1). Seven plots, each 1 to 3 ha in area, were located on very dry sites within the study area. The plots were characterized by a shallow forest floor layer of low fuel load, although bulk density was very high (Table 1). Data from five of the seven Darwin Lake burns were used for this study (two plots were missing the necessary preburn data). The Sharpsand Creek experimental burning project in northeastern Ontario (Fig. 1) was conducted on 0.4 ha plots in a very dense stand of young jack pine (Stocks 1987*a*). The stand had experienced significant self-thinning, and dead trees represented over half of the total standing stems. Relative to the Darwin Lake site, forest floor depths were greater but the fuel load was lighter because of lower bulk density. The Kenshoe Lake project in north-central Ontario (Fig. 1) used 0.4 ha plots in a mature jack pine stand with a well-established black spruce (*Picea mariana* (Mill.) BSP) understory (Stocks 1989). The forest floor was characterized by low fuel load because of low bulk density. The International Crown Fire Modeling Experiment (ICFME) was conducted in a semimature jack pine stand near Fort Providence, Northwest Territories (Fig. 1). The 65-year-old pine stand had a black spruce understory (Stocks et al. 2004). The forest floor had moderate depth and very high bulk density, which resulted in high preburn fuel loads. Data on forest floor fuel consumption from 10 plots ranging in size from 0.56 to 2.25 ha were used in the current study.

A black spruce and lichen woodland stand was burned in the Porter Lake experimental burning project in the southeastern Northwest Territories (Alexander et al. 1991). Ten plots of various sizes (0.021–0.650 ha), characterized by sparsely stocked and open black spruce with scattered jack pine trees and clumps of white birch, were established in the stand. The shallow forest floor had low fuel loading and consisted almost entirely of *Stereocaulon paschale* (L.) Hoffm. lichen. Data for forest floor fuel consumption obtained from 6 of the 10 plots were used for this study.

Wildfires

Forest floor fuel consumption was measured 1 year after large wildfires that burned in 2003 and 2004. Fires that were associated with high DC values were targeted for sampling to extend the range of fire weather (representing fuel moisture) conditions represented in the data set. The choice of fires was also based on accessibility and availability of mapping data for fire weather and fuels. Many sites were reached by all-terrain vehicle, helicopter, or boat. Similar to a recent study by Kasischke and Johnstone (2005), forest floor fuel consumption was determined by comparing pairs of burned and unburned sites. In this study, fuel consumption was determined by comparing forest floor depths within each pair of sites and calculating the fuel load of the upper forest floor layer that had been burned on the burned site. Pairs of sites were chosen to represent a range of fuel types that had been burned. As much as possible, each pair was located within the same stand, and the distance between the two sample sites of each pair was kept to a minimum (preferably <200 m) while maintaining a minimum distance of 25 m to the fire edge. Within each pair, physical and eco-

Table 1. Mean (and standard deviation) of preburn forest floor characteristics and mean (min.–max.) values for selected components of the Canadian Forest Fire Weather Index System, by type of fire source.

Fire No.	Location	FBP System fuel type(s)(*n*)	Preburn FF depth (cm)	Preburn FF fuel load ($kg \cdot m^{-2}$)	FF fuel consumption ($kg \cdot m^{-2}$)	Preburn FF bulk density ($kg \cdot m^{-3}$)	Fine Fuel Moisture Code	Duff Moisture Code	Drought Code	Buildup Index
Experimental fires										
1	Sharpsand Creek, Ont.	C-4 (12)	4.6 (0.5)	1.3 (0.2)	0.9 (0.4)	27.9 (1.6)	90.5 (89.4–93.3)	43 (25–57)	161 (73–272)	50 (27–70)
2	Kenshoe Lake, Ont.	C-3 (12)	6.5 (0.5)	1.7 (0.3)	0.6 (0.2)	25.8 (2.7)	89.6 (87.2–91.4)	32 (19–42)	111 (65–178)	37 (25–50)
3	Fort Providence, N.T.	C-3 (10)	5.8 (0.9)	4.7 (0.9)	1.7 (0.3)	81.6 (2.1)	91.7 (89.3–94.1)	55 (35–84)	364 (332–410)	78 (51–108)
4	Porter Lake, N.T.	C-1 (6)	3.4 (0)	1.5 (0)	0.9 (0.3)	44.7 (0)	89.7 (82.0–92.8)	57 (49–66)	232 (204–256)	70 (64–75)
5	Hondo, Alta.	D-1 (14)	4.2 (0.5)	0.3 (0.1)	0.1 (0.1)	7.6 (1.0)	91.5 (84.7–93.1)	22 (14–33)	42 (25–62)	22 (14–33)
6	Darwin Lake, Alta.	C-3 (5)	2.0 (0.5)	1.8 (0.3)	1.3 (0.3)	96.2 (14.7)	91.6 (90.0–93.0)	39 (30–47)	230 (214–246)	53 (43–61)
Wildfires										
7	Burntwood River, Man.	C-2 (4)	17.3 (2.9)	7.2 (1.2)	1.9 (0.5)	42.1 (6.5)	91.3 (90.0–92.5)	28 (25–31)	312 (306–321)	45 (42–50)
8	Green Lake, Sask.	C-3 (3), D-2 (3), M-2 (1)	8.5 (3.4)	3.6 (1.3)	3.1 (1.6)	42.4 (6.8)	90.0 (86.0–91.3)	41 (29–45)	375 (346–385)	60 (36–69)
9	Kasabonika, Ont.	C-2 (6), M-2 (3)	15.7 (2.6)	6.9 (1.9)	3.8 (3.0)	44.0 (8.9)	85.9 (83.0–90.4)	61 (54–63)	214 (197–220)	71 (64–73)
10	Montreal Lake, Sask.	C-3 (1), M-2 (1)	6.7 (0.3)	2.3 (1.4)	2.0 (0.8)	33.4 (19.4)	81.8 (71.7–92.0)	32 (14–50)	245 (223–267)	46 (24–67)
11	Thompson, Man.	C-2 (7), C-3 (11), M-2 (2)	12.8 (5.1)	6.1 (4.1)	3.5 (1.7)	47.6 (19.0)	88.0 (84.9–91.3)	27 (21–36)	293 (234–354)	44 (36–57)
12	Dawson City, Y.T.	C-2 (12), D-2 (1), M-2 (2)	15.1 (8.6)	8.4 (3.0)	3.9 (2.2)	63.3 (19.5)	82.5 (77.5–90.0)	72 (68–82)	344 (318–389)	91 (88–98)
13	Wood Buffalo National Park, N.T.	C-2 (1), C-3 (10), M-2 (1)	7.9 (2.1)	3.7 (0.9)	2.2 (1.2)	48.8 (11.8)	86.6 (84.2–88.3)	76 (44–82)	367 (340–461)	97 (70–105)
	All plots combined	128	9.0 (6.1)	4.1 (3.4)	2.2 (2.1)	44.7 (24.5)	88.5 (71.7–94.1)	46 (14–84)	248 (25–461)	59 (14–108)

Note: FF, forest floor; C-1, upland, open spruce–lichen woodland; C-2, moderately well-stocked boreal black or white spruce; C-3, fully stocked mature jack or lodgepole pine; C-4, pure, dense immature jack or lodgepole pine; D-1, leafless deciduous; D-2, summer deciduous; M-2, summer boreal mixedwood (neither conifer nor deciduous constituting more than 75% of stand basal area).

logical site variables (species composition, tree density, age, slope, aspect, moisture and nutrient regimes) were matched as closely as possible.

A 100 m transect was established on each burned and unburned site. Digital photographs of general stand conditions and location (according to geographic positioning system) were recorded at the 50 m point along the transect. Basal area by species was measured using a 5 or 10 basal area factor prism at points located 10, 30, 50, 70, and 90 m along the transect. Stand density by species was measured using a point-centred quarter plot (Cottam and Curtis 1956; Mueller-Dombois and Ellenberg 1974) at the same five locations.

Forest floor depth (including mosses, lichens, surface litter, and the organic soil layer) was measured every 5 m (n = 20 measurements) along the transect, and a soil core sample was collected at 10, 30, 50, 70, and 90 m along the transect line. Samples were collected to the depth of the mineral soil using a 5 cm diameter corer attached to a battery-operated drill (as described by Nalder and Wein 1998). Soil cores were separated into three 2 cm layers from 0 to 6 cm and a single 4 cm layer from 6 to 10 cm; for deeper soils, 5 cm layers were obtained beyond 10 cm until mineral soil was reached. On unburned sites, the surface litter and the leaf layer were measured together for depth and were collected separately from the organic soil layers. Each soil sample was placed in a separately labeled bag for storage and transport to the laboratory for analysis. All samples were oven-dried to constant mass at 70 °C for a minimum of 48 h. Ovendry mass was used to calculate fuel load and was combined with sample volume to calculate bulk density by soil layer. Loss-on-ignition testing was conducted on samples collected near the boundary between the mineral layer and the organic horizon to determine inorganic content. Following the procedures of Kalra and Maynard (1991), samples were ground and screened through a 2 mm Endecotts sieve and were weighed before and after heating in a muffle furnace at 375 °C for 16 h. The mass of the remaining unburned material was used to adjust bulk density values for inorganic content. A subsample of organic soil layers was randomly selected for determination of total carbon content using the LECO CR12 carbon system (LECO Corp., St. Joseph, Michigan). Samples of 0.05–0.10 g were burned in an oxygen environment at a furnace temperature of 1371 °C (2500°F). Moisture and dust were removed, and CO_2 was measured using an infrared detector, as a way to determine total carbon.

The depth of burn for each pair of sites was calculated by subtracting the average remaining organic soil depth at the burned site from the average organic soil depth at the unburned site. Fuel consumption was calculated using the average depth of burn and the average forest floor fuel load for the same depth at the unburned site. Bulk density values were calculated by dividing fuel load by depth of the organic layer.

Burning conditions for the day when each site was burned were quantified using the six standard components of the FWI System. Given that large fires spread over a number of days, the daily fire spread was determined using hot-spot data recorded by the Moderate Resolution Imaging Spectroradiometer (available on the Aqua and Terra satellites) and the Advanced Very High Resolution Radiometer (available on National Oceanic and Atmospheric Administration 15, 16, and 17 satellites). Fire progression was mapped by the Spatial Fire Management System (Englefield et al. 2000) using hot-spot data and the nearest-neighbor interpolation method described by de Groot et al. (2007). Noon weather conditions for each site on the day the site was burned were interpolated in the Spatial Fire Management System by inverse distance weighting from surrounding weather stations and were used to calculate corresponding values for the FWI System components.

Data analysis

Each experimental burn plot and wildfire site was classified by FBP System fuel type. Classifications were determined by the percent basal area of tree species. Conifer-dominated (>75%) stands were classified by the dominant tree species. Stands were classified as mixedwood if conifer content was 25%–75% and as deciduous if hardwood content was >75%.

Experimental fire and wildfire data were analyzed separately, and together as a combined data set. Correlation (Pearson's) between forest floor fuel consumption and the following variables was determined: preburn forest floor fuel load (Load), preburn forest floor depth (Depth), average bulk density (BD) of the burned forest floor, DMC, DC, and BUI. Data were transformed by natural logarithm, and regressions to predict forest floor fuel consumption were performed using variables with the highest correlations. All analyses were conducted using SYSTAT version 11 (SYSTAT Software Inc. 2004). Carbon emission rates (kilograms per square metre) for fuel types sampled during the wildfire study were calculated using depth of burn, fuel consumption, and total carbon values for forest floor layers.

Results

Experimental fires

Forest floor fuel consumption data were available for 59 plots from the experimental fires. During the Hondo experimental burning project, thirteen 0.15 ha aspen plots were burned by low-intensity fires (15–390 $kW \cdot m^{-1}$) (Quintilio et al. 1991). Total forest floor fuel consumption was very low (Table 1), consisting mainly of cured surface vegetation and the previous year's leaf litter. There was no fuel consumption of the F and H layers, primarily because of the high moisture content of the forest floor layers, as indicated by low DMC and very low DC values. Six years after the original burns, two of the plots were reburned together (i.e., as a single unit) by a high-intensity surface fire (4392 $kW \cdot m^{-1}$), which resulted in a greater depth of burn and greater consumption of forest floor fuel.

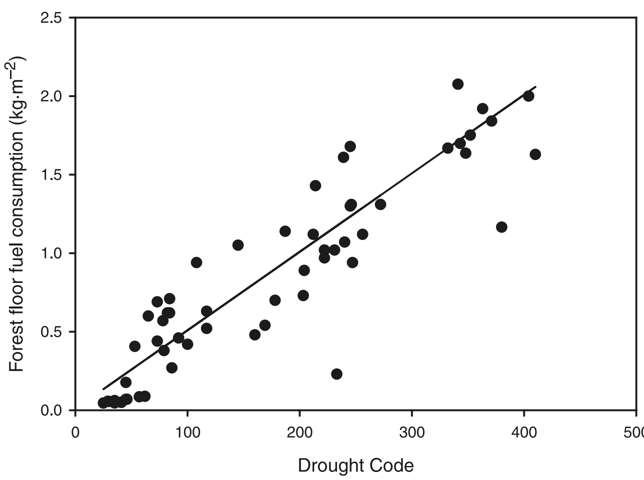
The consumption of forest floor fuel varied among the four jack pine experimental burning projects. The Darwin Lake plots were burned in summer 1974 under diverse burning conditions. The fires ranged from a slowly spreading surface fire of 670 $kW \cdot m^{-1}$ to a high-intensity crown fire of 7460 $kW \cdot m^{-1}$. DC values during the burns were moderate, and forest floor fuel consumption was low, largely because of the low preburn fuel loads (Table 1). Twelve plots were burned between 1975 and 1981 as part of the Sharpsand Creek project, with fires ranging from a slowly spreading surface fire with intensity of 291 $kW \cdot m^{-1}$ to a fully devel-

Table 2. Summary of significant ($P < 0.001$) regression models for forest floor fuel consumption on the experimental fires (all fuel types combined, $n = 59$).

Model	R^2	SEE
FFFC = –0.001 + 0.004BD + 0.004DC	0.840	0.247
FFFC = 0.009 + 0.005DC	0.827	0.254
FFFC = –0.216 + 0.009BD + 0.014BUI	0.822	0.260
FFFC = –0.280 + 0.012BD + 0.017DMC	0.795	0.280
FFFC = –0.176 + 0.156Load + 0.015BUI	0.787	0.285
FFFC = –0.195 + 0.219Load + 0.016DMC	0.742	0.313
FFFC = –0.250 + 0.022BUI	0.718	0.325
FFFC = 0.175 + 0.016BD	0.666	0.354
FFFC = 0.236 + 0.325Load	0.637	0.369
FFFC = –0.305 + 0.029DMC	0.567	0.403

Note: SEE, standard error of the estimate; FFFC, forest floor fuel consumption ($kg{\cdot}m^{-2}$); BD, bulk density of forest floor ($kg{\cdot}m^{-3}$); DC, Drought Code; BUI, Buildup Index; DMC, Duff Moisture Code; Load, preburn forest floor fuel load ($kg{\cdot}m^{-2}$).

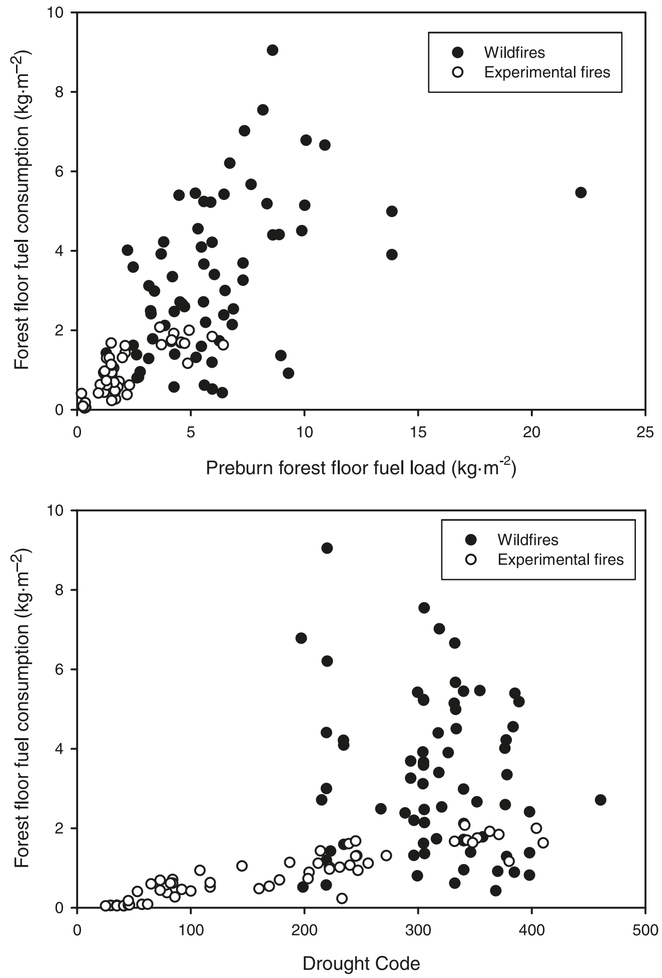
Fig. 2. Comparison of Drought Code and fuel consumption for experimental fires. The regression line represents $y = 0.009 + 0.005DC$ (where DC is the Drought Code) ($R^2 = 0.827$, $P < 0.001$, $n = 59$, standard error of the estimate = 0.254).



oped continuous crown fire with extremely high intensity (40 903 $kW{\cdot}m^{-1}$). The DC values were low to moderate, and forest floor fuel consumption was limited by the low preburn forest floor fuel loads. Another 12 plots were burned in the Kenshoe Lake project. The fires ranged from a low-intensity surface fire (134 $kW{\cdot}m^{-1}$) to active crown fires (maximum fire intensity 4826 $kW{\cdot}m^{-1}$). The DC values were low for all burns and were reflected in low forest floor fuel consumption. At the ICFME project, all 10 plots were burned by fast-spreading (24.3–69.8 $m{\cdot}min^{-1}$) crown fires of extremely high intensity (36 902 – 93 476 $kW{\cdot}m^{-1}$). The DC values were moderate to high, and all plots had a moderate depth of burn. Fuel consumption was much higher for the ICFME project than for all other experimental burning projects, largely because of the available ground and surface fuels.

For the Porter Lake project, which took place in upland black spruce plots, the fires on the burned plots ranged from a very slowly spreading surface fire (47 $kW{\cdot}m^{-1}$) to a very quickly spreading, high-intensity crown fire (32 367 $kW{\cdot}m^{-1}$).

Fig. 3. Comparison of fuel consumption with preburn fuel load (top) and Drought Code (bottom) for all data.



The DC values were moderate, and DMC values were moderate to high. In all but one of the fires, most of the lichen layer was consumed, the exception being the single slow-spreading, low-intensity fire. Forest floor fuel consumption was low on all burn plots (Table 1) because of the limited amount of fuel in the lichen layer.

Wildfires

Sixty-nine pairs of burned and unburned sites were sampled from seven wildfires across Canada, from northern Ontario to the Yukon Territory (Fig. 1). The sample sites represented stands of black spruce, jack pine, mixedwood (FBP System M-2 fuel type), and aspen (D-2 fuel type, summer condition). (Note that although the FBP System defines only one deciduous fuel type for the leafless preflush period, the D-1 fuel type, numerous fire management agencies have adopted the D-2 fuel type descriptor for postflush deciduous forests, a designation that closely parallels the distinction between the M-1 and M-2 fuel types.) For all of the wildfires, preburn forest floor depths were greater than those measured for the experimental fires (Table 1). Preburn forest floor fuel loads were considerably higher (>6 $kg{\cdot}m^{-2}$) for the four wildfires with the deepest preburn depths.

Table 3. Mean (and standard deviation) of preburn forest floor characteristics and mean (min.–max.) values for selected components of the Canadian Forest Fire Weather Index System, by type of fire source.

FBP System fuel type	Sample size: Experimental burns	Sample size: Wildfires	Preburn FF depth (cm)	Depth of burn (cm)	Preburn FF fuel load (kg·m^{-2})	FF fuel consumption (kg·m^{-2})	Fine Fuel Moisture Code	Duff Moisture Code	Drought Code	Buildup Index
C-1	6	0	3.4 (0)	2.0 (0.8)	1.5 (0)	0.9 (0.3)	89.7 (82.0–92.8)	57 (49–66)	232 (204–256)	70 (64–75)
C-2	0	30	17.1 (5.6)	9.5 (4.6)	8.3 (3.5)	3.9 (2.1)	86.2 (77.5–92.6)	54 (22–82)	302 (199–389)	70 (36–101)
C-3	27	25	6.8 (3.0)	3.9 (2.1)	3.3 (1.6)	1.8 (1.3)	88.7 (71.7–94.1)	44 (14–84)	276 (65–461)	60 (24–108)
C-4	12	0	4.6 (0.5)	3.5 (1.1)	1.3 (0.2)	0.9 (0.4)	90.5 (89.4–93.3)	43 (25–57)	161 (73–272)	50 (27–70)
D-1	14	0	4.2 (0.5)	1.7 (0.7)	0.3 (0.1)	0.1 (0.1)	91.5 (84.7–93.1)	22 (14–33)	42 (25–62)	22 (14–33)
D-2	0	4	7.6 (1.6)	5.2 (1.2)	3.9 (0.6)	3.6 (1.7)	88.7 (82.8–91.3)	50 (42–69)	380 (377–385)	73 (66–91)
M-2	0	10	10.5 (3.3)	5.8 (2.9)	5.7 (1.8)	2.9 (2.2)	86.5 (77.5–92.0)	55 (27–78)	292 (197–377)	71 (43–96)

Note: FF, forest floor; C-1, upland, open spruce–lichen woodland; C-2, moderately well-stocked boreal black or white spruce; C-3, fully stocked mature jack or lodgepole pine; C-4, pure, dense immature jack or lodgepole pine; D-1, leafless deciduous; D-2, summer deciduous; M-2, summer boreal mixedwood (neither conifer nor deciduous constituting more than 75% of stand basal area).

Data analysis

Analysis of individual data sets

Forest floor fuel consumption (FFFC) in the experimental fire data set showed high correlation with DC (R = 0.910), BUI (R = 0.847), BD (R = 0.816), Load (R = 0.798), and DMC (R = 0.753) (P < 0.05 for all correlations within the individual data sets). There was also moderate to high correlation between some of the FWI System components and fuel variables: DC and Load (R = 0.847), DC and BD (R = 0.827), BUI and Load (R = 0.730), and BUI and BD (R = 0.685). DMC correlations were lower with Load (R = 0.626) and BD (R = 0.557). The higher than expected correlations of DC, BUI, and DMC with Load and BD are primarily due to the ICFME experimental fires in the data set, which coincidentally had the highest preburn fuel loads and highest FWI System values. Regression analyses of different combinations of FWI System components and fuel factors in the experimental fire data set resulted in numerous significant models to predict forest floor fuel consumption (Table 2). DC was the single most influential factor affecting FFFC (Fig. 2). Although Load was highly correlated with FFFC, it was not a significant (P < 0.05) factor when combined with DC because of high correlation between Load and DC. Even though BD was a significant factor when combined with DC, it only marginally increased the variance explained in FFFC because of correlation between DC and BD.

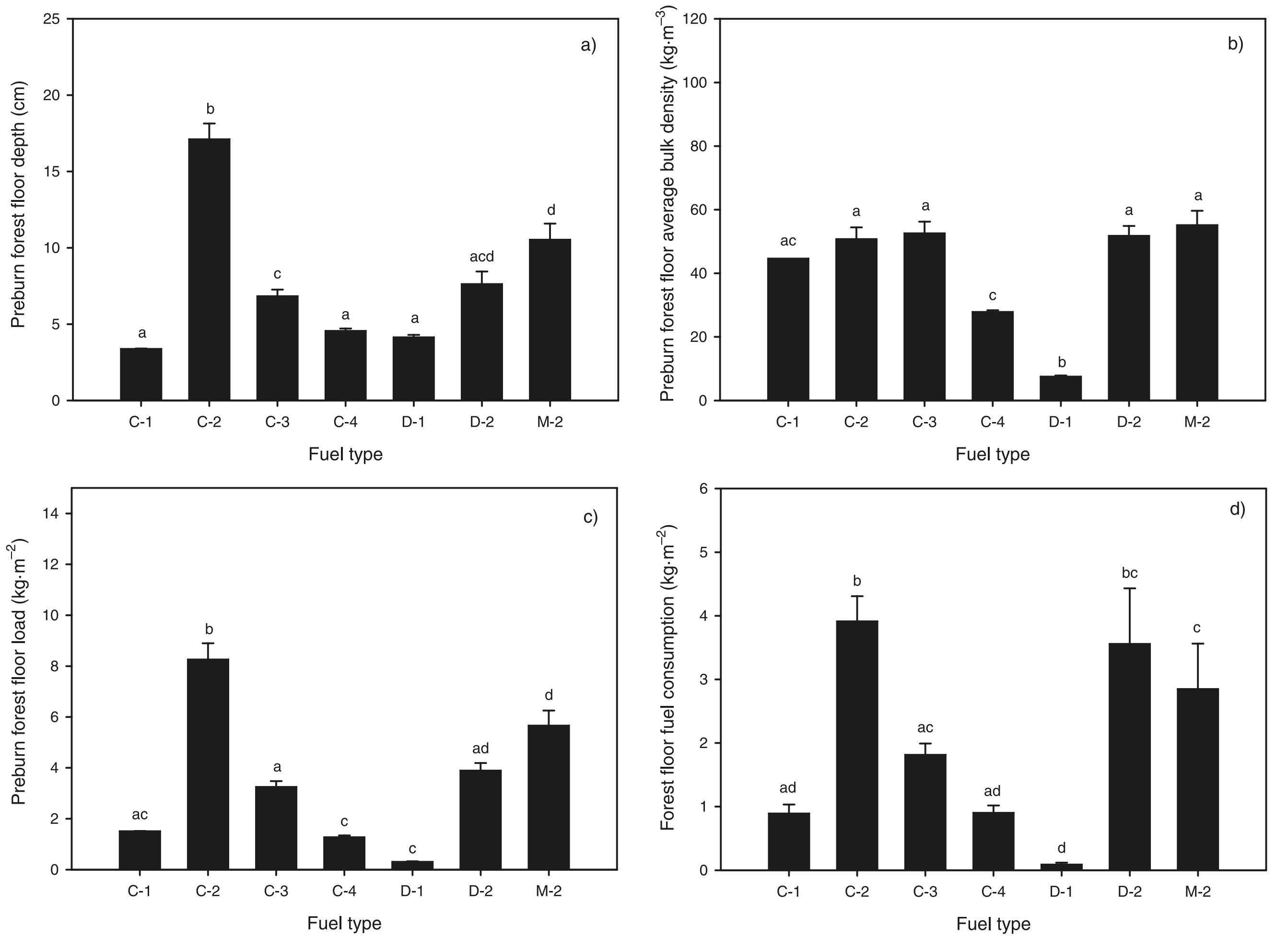
The wildfire data set generally showed low correlation between FFFC and the tested independent variables. FFFC correlations with fuel variables were low (Load, R = 0.476; Depth, R = 0.367; BD, R = 0.202), and correlations with FWI System components were extremely low (DC, R = –0.119; BUI, R = 0.039; DMC, R = 0.043). Correlations changed very little when the wildfire data were transformed by logarithm before analysis. As a result, there were no regression models of the wildfire data that explained more than 25% of the variation in FFFC.

Briefly comparing the wildfire and experimental fire data sets, the wildfire data had a much higher range of Load values. Both data sets showed a general increasing trend in FFFC with increasing Load (Fig. 3), which is reflected in the correlation statistics. The experimental fire data set contained a broad range of DC values, whereas all of the DC values in the wildfire data set were located at the higher end of the DC range. The high correlation between FFFC and DC in the experimental data set was clearly not evident in the wildfire data set (Fig. 3). Although the experimental fire data set produced very strong regression models of FFFC for the experimental fires (Table 2), none of those models were capable of predicting the high FFFC values for the wildfires.

Analysis of combined data sets

Data from experimental fires and wildfires were combined to generate summary statistics by fuel type (Table 3). Preburn depth of the forest floor was lowest in the black spruce and lichen woodland (C-1) fuel type (3.4 cm) and highest in the boreal spruce (C-2) fuel type (17.1 cm). In general, preburn forest floor fuel load values increased with preburn forest floor depths. DC values for the D-1 (leafless aspen) fuel type were much lower than those for all other fuel types, although the data sets for the mature jack and

Fig. 4. Comparison of means for preburn forest floor depth, average bulk density, fuel load, and fuel consumption by Canadian Forest Fire Behavior Prediction System fuel type (standard error indicated). Fuel types with the same lowercase letter are not statistically different (least significant difference α = 0.05).



lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) (C-3) and immature jack and lodgepole pine (C-4) fuel types also contained a few low DC values. Overall, FFFC was wide-ranging, the lowest value (0.1 kg·m^{-2}) occurring with the lowest preburn fuel load and DC combination (D-1 fuel type) and the highest values (>3 kg·m^{-2}) occurring with the highest average preburn fuel load (C-2 fuel type) and highest average DC value (D-2 fuel type).

A comparison of means indicated significant differences among fuel types in terms of Depth, BD, Load, and FFFC (Fig. 4). Regressions were conducted separately for each fuel type using all variables and transformed variables. Calculated values of R^2 for these regression models varied from 0.206 for the C-2 fuel type to 0.980 for the C-1 fuel type (P < 0.001) (Table 4). Regression was also applied to the pooled data set for all fuel types combined (n = 128), which resulted in the following model of FFFC (kilograms per square metre) based on Load (kilograms per square metre) and DC:

$$[1] \qquad \ln(\text{FFFC}) = -4.252 + 0.710 \ln(\text{DC}) + 0.671 \ln(\text{Load})$$

Equation 1 (for which the standard error of the estimate (SEE) was 0.583) explained 79.5% (P < 0.001) of the variation in the transformed data (Fig. 5). Regression models using transformed data for Load and DC, separately, explained similar levels of variance in the transformed data set (regression R^2 = 0.741 and 0.699, respectively; P < 0.001) (Table 4). The R^2 for those models is only slightly lower than that for eq. 1 because of correlation between Load and DC. Regression analyses of the combined data set also resulted in a model based on BD (kilograms per cubic metre), Depth (centimetres), and DC (regression R^2 = 0.796, P < 0.001, SEE = 0.585, correction factor = 1.1866):

$$[2] \qquad \ln(\text{FFFC}) = -7.388 + 0.754 \ln(\text{DC}) + 0.691 \ln(\text{Depth}) + 0.608 \ln(\text{BD})$$

To back-transform the data from eqs. 1 and 2 to arithmetic FFFC values, the transformed data are multiplied by a correction factor (CF). The correction factor (CF = exp(SEE^2/2)) (Sprugel 1983) is applied to account for bias due to logarithmic transformation, a common source of error that occurs when back-transforming with the antilogarithm, yielding the median value, which always underestimates the mean value (Baskerville 1972). A correction factor of 1.1852 was used to test the predictive capacity

Table 4. Summary of significant ($P < 0.001$) regression models for forest floor fuel consumption by fuel type, based on experimental fire and wildfire data sets (combined).

Fuel type	Model	R^2	SEE
All upland fuel types combined (n = 128)	ln(FFFC) = –4.252 + 0.710 ln(DC) + 0.671 ln(Load) [FFFC = 1.1852 exp(–4.252 + 0.710 ln(DC) + 0.671 ln(Load))]	0.795	0.583
	ln(FFFC) = –7.388 + 0.754 ln(DC) + 0.691 ln(Depth) + 0.608 ln(BD) [FFFC = 1.1866 exp(–7.388 + 0.754 ln(DC) + 0.691 ln(Depth) + 0.608 ln(BD))]	0.796	0.585
	ln(FFFC) = –0.882 + 1.082 ln(Load) [FFFC = 1.2384 exp(–0.882 + 1.082 ln(Load))]	0.741	0.654
	ln(FFFC) = –7.672 + 1.478 ln(DC) [FFFC = 1.2821 exp(–7.672 + 1.478 ln(DC))]	0.699	0.705
	FFFC = 0.006 + 0.351Load + 0.003DC	0.514	1.350
	FFFC = –0.943 + 0.178Depth + 0.017BD + 0.003DC	0.504	1.369
	FFFC = 0.495 + 0.403Load	0.494	1.372
	FFFC = 0.053 + 0.008DC	0.250	1.670
C-1 (n = 6)	FFFC = –6.142 + 0.083FFMC	0.856	0.144
	ln(FFFC) = –71.682 – 2.732 ln(DMC) + 18.347 ln(FFMC) [FFFC = 1.0064 exp (–71.682 – 2.732 ln(DMC) + 18.347 ln(FFMC))]	0.980	0.113
C-2 (n = 30)	FFFC = 0.721 + 0.187Load + 0.030DMC	0.206	1.975
C-3 (n = 52)	FFFC = –0.505 + 0.134Depth + 0.005DC	0.320	1.051
	ln(FFFC) = –3.184 + 0.746 ln(DC) – 0.318 ln(DMC) + 0.577 ln(Load) [FFFC = 1.1031 exp (–3.184 + 0.746 ln(DC) – 0.318 ln(DMC) + 0.577 ln(Load))]	0.636	0.443
	ln(FFFC) = –4.872 + 0.950 ln(DC) [FFFC = 1.1389 exp (–4.872 + 0.950 ln(DC))]	0.497	0.510
C-4 (n = 12)	FFFC = 0.220 + 0.004DC	0.687	0.228
	ln(FFFC) = –5.902 + 1.773 ln(Depth) + 0.610 ln(DC) [FFFC = 1.0208 exp (–5.902 + 1.773 ln(Depth) + 0.610 ln(DC))]	0.825	0.203
	ln(FFFC) = –3.477 + 0.609 ln(DC) + 1.116 ln(Load) [FFFC = 1.0214 exp (–3.477 + 0.609 ln(DC) + 1.116 ln(Load))]	0.820	0.206
D-1 (n = 14)	FFFC = 0.629 – 0.083BD + 0.002DC	0.911	0.031
	ln(FFFC) = –0.230 – 2.471 ln(BD) + 1.108 ln(DC) [FFFC = 1.0186 exp (–0.230 – 2.471 ln(BD) + 1.108 ln(DC))]	0.923	0.192
D-2 (n = 4)	ln(FFFC) = –3.873 + 2.493 ln(Depth) [FFC = 1.0266 exp (–3.873 + 2.493 ln(Depth))]	0.911	0.229
M-2 (n = 10)	FFFC = 4.855 + 0.666 Load – 0.082 BUI	0.810	1.111
	ln(FFFC) = 11.658 – 2.598 ln(BUI) [FFFC = 1.3328 exp (11.658 – 2.598 ln(BUI))]	0.489	0.758
C-3 and C-4 (n = 64)	FFFC = –0.965 + 0.181Depth + 0.012BD + 0.003DC	0.429	0.922
	ln(FFFC) = –3.486 + 0.612 ln(DC) + 0.484 ln(Load) [FFFC = 1.0959 exp (–3.486 + 0.612 ln(DC) + 0.484 ln(Load))]	0.639	0.428
D-1 and D-2 (n = 18)	FFFC = 0.924 + 0.023DC – 0.082BUI	0.906	0.541
	ln(FFFC) = –10.713 – 0.948 ln(BD) + 1.949 ln(DC) + 1.982 ln(Depth) [FFFC = 1.0732 exp (–10.713 – 0.948 ln(BD) + 1.949 ln(DC) + 1.982 ln(Depth))]	0.960	0.376

Note: SEE, standard error of the estimate; FFFC, forest floor fuel consumption (kg·m^{-2}); Depth, preburn forest floor depth (cm); BD, bulk density of forest floor (kg·m^{-3}); DC, Drought Code; Load, preburn forest floor fuel load (kg·m^{-2}); FFMC, Fine Fuel Moisture Code; DMC, Duff Moisture Code; BUI, Buildup Index. Back-transformed equations (including correction factors) are indicated in square brackets.

of eq. 1 by comparing actual FFFC values with the back-transformed FFFC values predicted using:

$$[3] \quad \mathrm{FFFC} = 1.1852 \exp(-4.252 + 0.710 \ln(\mathrm{DC}) + 0.671 \ln(\mathrm{Load}))$$

Analysis of this data showed that eq. 3 explained 48.7% ($P < 0.001$) of the variation in actual FFFC. The data plot (Fig. 6) shows eq. 3 provided good representation (R^2 = 0.715) of the experimental fire data, but not the wildfire data (R^2 = 0.182).

Fig. 5. Comparison of the natural logarithms of actual and predicted fuel consumption using eq. 1 (regression $R^2 = 0.795$, $P < 0.001$, $n = 128$, standard error of the estimate = 0.583). Data for experimental fires and wildfires are presented separately to better distinguish plot data by study site (see Fig. 7 for combined data set).

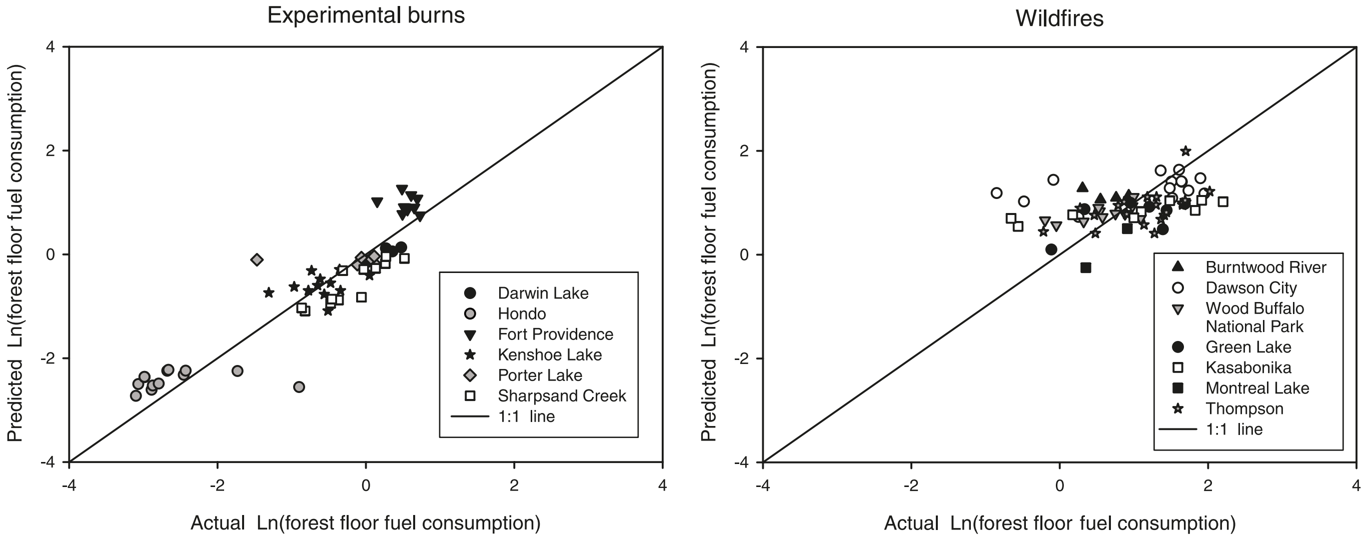
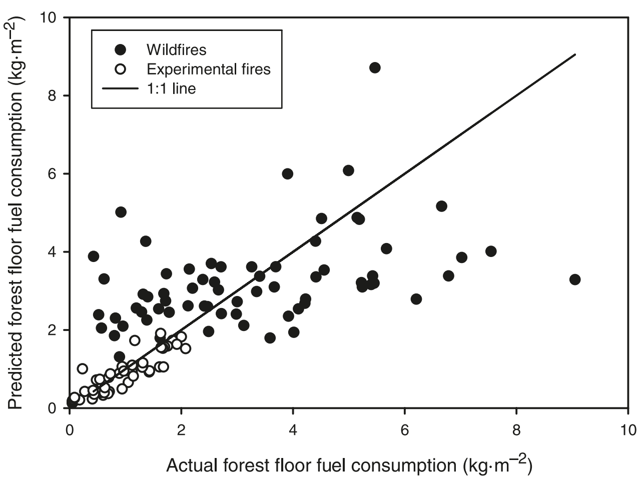


Fig. 6. Comparison of actual and predicted fuel consumption for all data using eq. 3 ($R^2 = 0.487$, $P < 0.001$, $n = 128$, standard error of the estimate = 1.381).



Average total carbon values for forest floor organic layers were 40.9%–53.9% (Table 5). These data were combined with the bulk density data (Table 6) to calculate carbon emission rates for fuel types sampled during the wildfire study, which ranged from 0.29 to 2.43 kg·m^{-2} (Table 7).

Discussion

The experimental fire data set produced strong regression models (Table 2) that can be confidently applied as predictors of forest floor fuel consumption across a significant range of forest stand and fire weather conditions. This includes jack pine (pure stands or mixed stands with spruce understory), aspen, and spruce–lichen woodland stands with low to moderate forest floor fuel loads (<5 kg·m^{-2}) and low to moderate DC values (<400). However, these models become less reliable when they are applied to conditions beyond those represented in the original data set. In particular, they consistently underestimate forest floor fuel consumption when they are applied to forest stands with high preburn forest floor fuel load (>6 kg·m^{-2}), including most, if not all, boreal spruce (C-2) fuel types. The performance of these models under high DC values (>400) is unknown.

The wildfire data set did not produce any reliable models of forest floor fuel consumption when analyzed separately. However, when wildfire and experimental fire data were analyzed together, the combined data set provided models with substantial predictive capacity over a greater range of preburn forest floor fuel loads than the experimental fire models were capable of representing. For this reason, the models resulting from the combined analysis (Table 4) are recommended for forest stands with high preburn forest floor fuel loads. The "all fuel types combined" models in Table 4 represent a wide range of stand composition, preburn forest floor fuel loads, bulk densities, forest floor depths, and DC values such that those models can be used to estimate past (or predict future) fuel consumption and carbon emissions across diverse Canadian forest stand and fire weather conditions. The broad applicability of the "all fuel types combined" models makes them very useful in landscape-level applications in the boreal forest region. In particular, these models can be applied to the mixed forest stands with multiple-species composition that are common in landscape data sets; in contrast, models that are specific to individual fuel types are difficult to apply in those situations.

The fuel consumption models in Table 4 represent a summary of regression analyses for currently available Canadian data sets for standing-timber fuel types (excluding forested peatlands) that contain data on preburn forest floor fuel load, preburn duff depth, duff bulk density, forest floor fuel consumption, and all corresponding values for FWI System components. The models for the C-1 (Porter Lake project in spruce–lichen woodland), C-4 (Sharpsand Creek project in immature jack pine), and D-1 (Hondo project in leafless aspen) fuel types shown in Table 4 were developed entirely from existing experimental fire data. The models for the C-2 (boreal spruce), D-2 (aspen, summer condition), and

Table 5. Data for total carbon of forest floor layers by fuel type for wildfires.

		Forest floor layer					
Fuel type[a]	Statistic	Litter	0–2 cm	2–4 cm	4–6 cm	6–10 cm	10–15 cm
C-2	Mean %	47.2	47.7	48.5	47.7	45.3	46.1
	SD	4.1	4.5	5.5	8.1	5.9	1.7
	n	25	26	28	24	16	3
C-3	Mean %	48.6	49.6	40.9	50.6	53.9	—
	SD	2.5	1.3	14.1	4.3	—	—
	n	5	5	4	4	1	—
D-2	Mean %	49.7	45.4	51.8	46.8	—	—
	SD	3.6	7.7	5.6	4.6	—	—
	n	7	6	5	4	—	—
M-2	Mean %	48.0	47.4	48.4	47.9	50.7	50.1
	SD	5.0	7.1	9.0	2.4	1.6	—
	n	12	12	7	5	3	1

Note: SD, standard deviation.

[a]Fuel types from the Canadian Forest Fire Behavior Prediction System.

Table 6. Data for bulk density of forest floor layers (g·cm^{-3}) by fuel type for wildfires.

		Forest floor layer								
Fuel type[a]	Statistic	Litter	0–2 cm	2–4 cm	4–6 cm	6–10 cm	10–15 cm	15–20 cm	20–25 cm	25–30 cm
C-2	Mean	0.023	0.037	0.047	0.059	0.068	0.071	0.078	0.086	0.077
	SD	0.021	0.027	0.036	0.040	0.046	0.034	0.045	0.057	0.041
	n	148	153	155	148	131	90	36	22	12
C-3	Mean	0.038	0.055	0.067	0.065	0.066	0.065	—	—	—
	SD	0.024	0.035	0.046	0.033	0.028	0.041	—	—	—
	n	108	101	80	54	25	6	—	—	—
D-2	Mean	0.043	0.084	0.099	0.095	—	—	—	—	—
	SD	0.024	0.027	0.033	0.047	—	—	—	—	—
	n	20	20	15	2	—	—	—	—	—
M-2	Mean	0.027	0.063	0.080	0.082	0.085	0.102	—	—	—
	SD	0.022	0.024	0.037	0.028	0.027	0.036	—	—	—
	n	48	50	44	39	22	5	—	—	—

Note: SD, standard deviation.

[a]Fuel types from the Canadian Forest Fire Behavior Prediction System.

M-2 (mixedwood, summer condition) fuel types are new and are based entirely on the wildfire data. The C-3 (mature jack and lodgepole pine) model was obtained from analysis of the combined data sets from the Kenshoe Lake project, the Darwin Lake project, the ICFME project, and wildfires. Given the large spatial variation that typically occurs in preburn forest floor depths, fuel load, and subsequent fuel consumption, the individual models appear reasonably reliable for all fuel types except C-2. The C-2 fuel type is defined broadly and includes all boreal spruce stands from upland white spruce to lowland black spruce. Forest floor fuel consumption may be more difficult to model within this fuel type because of variability in soil moisture regimes. The lack of any FWI System component serving as a significant variable in the C-2 fuel consumption model suggests that other factors are affecting soil moisture dynamics. Further study on field drying rates and ignitability of forest floor material under different moisture regimes and on the relation of these variables with FWI System components is needed to better model fuel consumption in the C-2 fuel type. Considerable study is continuing in black spruce forests of Alaska where forest floor fuel consumption can be very high (about 8.0–11.3 kg·m^{-2}) and highly variable (Kasischke and Johnstone 2005; Kane et al. 2007).

Most of the fuel consumption models for individual fuel types include one (sometimes two) FWI System component(s), such as FFMC, DMC, DC, or BUI, as an independent variable (Table 4). The particular variable or variables differed among fuel types, but in general the FWI System component in each model reflected duff depth or forest floor fuel load. For example, FFMC was most representative of the lichen-dominated forest floor fuels of the C-1 fuel type, whereas DC was most significant for fuel types with higher forest floor fuel loads or greater duff depths. DMC and BUI were representative of fuel types with moderate forest floor fuel loads and duff depths. DC was a strong indicator of forest floor fuel consumption for all fuel types combined because it is a significant indicator for many of the individual fuel types and is by definition the best indicator for deeper forest floor sites and drier burning conditions. Although DMC was a significant factor in only two of the models

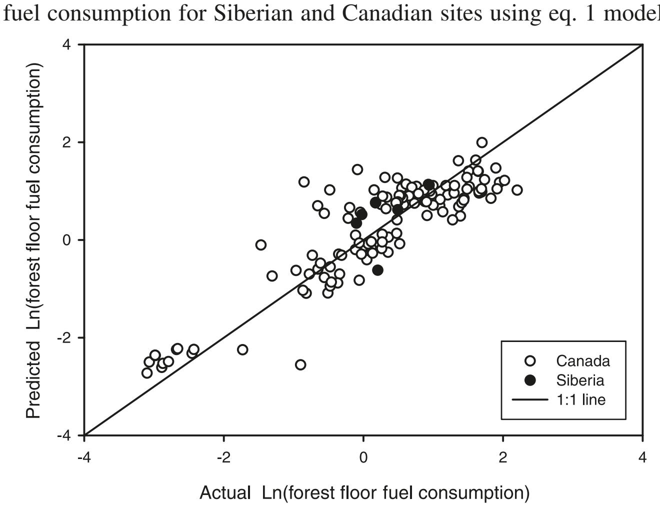
Table 7. Summary of depth of burn, fuel consumption, and carbon emission rates by fuel types sampled in the wildfire study.

Wildfire	Fuel type[a]	*n*	Depth of burn (cm)	FF fuel consumption (kg·m^{-2})	Carbon emissions (kg·m^{-2})
Burntwood River, Man. (2004)	C-2	4	6.2	2.04	0.98
Green Lake, Sask. (2004)	C-3	3	5.4	2.45	1.19
	D-2	3	5.7	4.17	2.03
	M-2	1	9.2	3.36	1.61
Kasabonika, Ont. (2004)	C-2	6	8.8	3.43	1.64
	M-2	3	7.8	3.89	1.86
Montreal Lake, Sask. (2004)	C-3	1	5.0	1.90	0.92
	M-2	1	3.4	1.53	0.73
Thompson, Man. (2004)	C-2	7	10.9	4.59	2.17
	C-3	11	5.4	2.97	1.35
	M-2	2	7.4	5.05	2.43
Dawson City, Y.T. (2005)	C-2	12	10.9	4.62	2.17
	D-2	1	3.8	2.17	1.03
	M-2	2	2.2	0.59	0.29
Wood Buffalo National Park, N.T. (2005)	C-2	1	7.1	2.83	1.35
	C-3	10	5.1	2.83	1.29
	M-2	1	3.3	1.88	0.89

Note: FF, forest floor.

[a]Fuel types from the Canadian Forest Fire Behavior Prediction System.

Fig. 7. Comparison of the natural logarithms of actual and predicted fuel consumption for Siberian and Canadian sites using eq. 1 model.



listed in Table 4, it is still an important indicator when determining forest floor fuel consumption. For example, a DC value of 500 may indicate the potential for a deep-burning fire, but a fire with DMC less than 20 is unlikely to spread and burn downward into deeper organic soil because the upper organic soil horizon will be too wet to burn. This situation could arise if a rain event occurs after an extended period of drying, creating a wet upper organic layer over the deeper dry organic layers.

The current FBP System (Forestry Canada Fire Danger Group 1992) includes models specific to fuel type for predicting ground and surface fuel consumption (duff, litter, dead and downed woody material, understory vegetation) during flaming combustion. These models were generally based on the experimental fire data, but they exclude data from the ICFME (which took place after publication of the first edition of the FBP System in 1992) and include data from the Big Fish Lake experimental burning project in north-central Alberta (the primary source of data for the C-2 fuel consumption model in the FBP System but excluded from the current upland study because it took place on permafrost peatland); the Aubinadong River project (FBP System M-3 and M-4 fuel types; dead balsam fir (*Abies balsamea* (L.) Mill) mixedwood; Stocks 1987*b*); experimental fires in red pine (*Pinus resinosa* Ait.) and white pine (*Pinus strobus* L.) stands (Van Wagner 1963) and jack pine stands (Van Wagner 1972; Weber et al. 1987) near the Petawawa National Forestry Institute, Chalk River, Ontario; and lodgepole pine experimental fires near Prince George, British Columbia (Lawson 1973). The data sets from the Aubinadong River project, the experimental fires at the Petawawa site, and the experimental fires near Prince George were not included in the current study because complete plot-level data for all preburn forest floor fuel parameters and corresponding FWI System data were not available. Fuel consumption data are missing for some of the 16 FBP System fuel types, so models for consumption of ground and surface fuels for some FBP System fuel types were developed from models of closely related fuel types.

The FBP System models can be readily applied across Canada, since most provincial and territorial forestry agencies have interpreted their forest inventories in terms of the FBP System fuel types for the purposes of fire management. Fire managers use primarily the fire rate of spread and fire intensity components of the FBP System for suppression planning. Fuel consumption has limited application in fire suppression beyond its use in calculating fire intensities, but it is the foundation of carbon emissions accounting related to wildland fires. One difficulty in using the current fuel consumption models of the FBP System for carbon emissions modeling is that, strictly speaking, they are valid only for stands with the same composition (species, age, height, density, fuel load, FWI System components, etc.) as that expressed by the original experimental fire data sets. To model carbon emissions with the greatest accuracy, the models must be dynamic with respect to preburn fuel load and burning conditions (specifically, fire weather and fuel moisture). For that reason, eq. 3 is now being used for the purposes of national carbon reporting under NFCMARS. In operational practice, eq. 3 was incorporated into the Boreal Fire Effects (BORFIRE) model, which serves as the core model for calculating stand-level fuel consumption and carbon loss (de Groot 2006).

The experimental burning projects of the Canadian Forest Service have yielded the most accurate and detailed database of fire behavior in Canadian forests through extensive pre- and postburn fuel sampling and on-site monitoring during the fires. The postburn fuel consumption data for wildfires in this study were calculated from data for paired (burned and unburned) sites, which are not direct measures of fuel consumption. The forest floor fuel consumption data of the experimental fires are therefore considered more accurate than the surrogate wildfire data. Another factor affecting the wildfire data set is the source of weather data itself. The experimental fires had on-site weather stations, so the FWI System component values are very accurate at the plot level. Weather data for the wildfires were obtained by interpolating from the nearest weather stations, but these can be tens of kilometres distant from the fire. Isolated showers or thunderstorms that are localized near a weather station or near a fire will cause inconsistencies between forest floor fuel consumption and fire weather data, but there is no way of knowing the extent of this effect on the wildfire data set.

In Fig. 5, the experimental fire data tend to be clumped by project, whereas the wildfire data tend to show more lateral spread. This finding is partly explained by the greater accuracy of the experimental fire data but it is also a reflection of the fact that each wildfire is represented by numerous fuel types, whereas each experimental burning project represents not only a single fuel type, but a single stand. The experimental fire data are generally limited in terms of the range of fuel load and the number of plots burned under higher fire danger conditions, the latter because of the risk of escaped fire. Experimental burning projects represent expensive, long-term research commitments. Conversely, wildfires provide a great opportunity to collect data under diverse and more severe burning conditions than would typically be possible with experimental fires. In wildfire studies, forest stands would ideally have been sampled for fuel and moisture conditions before burning, and equipment for monitoring fire behavior would be set up before the site is overrun by a wildfire. After the wildfire has passed, fire behavior data would be downloaded and the stands resampled for fuel load. Use of this data collection technique for wildfires has been increasing during the past decade (Lentile et al. 2007), but safety concerns and logistic requirements make it a difficult undertaking. As a result, determining preburn fuel properties and fuel consumption for wildfires is often restricted to postburn sampling. The advantages of postburn wildfire sampling are the range of data (representing different fuel types and days with different burning conditions) that can be collected relatively quickly for each wildfire and the ability to tailor sampling design to address known data gaps. The combined data set used in this study was almost equally split between experimental fires and wildfires, so the models benefited equally from the accuracy of the experimental fire data and the range of wildfire data. Future development of fuel consumption models will likely occur through a combination of detailed experimental burning studies for benchmark fuel and stand types, supplemented with observations on wildfires and operational prescribed fires.

The FBP System predicts ground and surface fuel consumption or the combined consumption of forest floor and dead woody debris fuel components, so direct comparisons between the models generated by this study and those of the FBP System are not possible. However, de Groot et al. (2007) found that average total fuel consumption for the 2004 Montreal Lake, Saskatchewan, fire was 2.4 kg·m^{-2} according to the FBP System and about 3.1 kg·m^{-2} (after adjustment for decomposition of dead woody debris) according to the BORFIRE model with preburn data for fuel load. The difference was attributed primarily to the fuel-load-based forest floor consumption model that was used in BORFIRE, and developed from this study. Smouldering combustion could also be causing differences between forest floor fuel consumption models in the FBP System and those in this study. The FBP System represents fuel consumption by a moving flame front. It is not known how much, if any, forest floor fuel consumption occurred by smouldering combustion at the wildfires, but the high preburn forest floor fuel loads and moderate DC values in the wildfire data set suggest this possibility.

Carbon density for live tree biomass is commonly taken as 0.5 carbon units per unit of fuel (Mathews 1993). Studies of organic forest floor material have indicated that the percentage of carbon ranges from 18% to 55%, depending on the soil layer and amount of decomposition, although most values are between 40% and 50% (Yokelson et al. 1997; Nalder and Wein 1999; Kasischke et al. 2000). The total carbon values for the forest floor measured in the current wildfire field study ranged from 40.9% to 53.9%. Kasischke et al. (2000) measured carbon content values of 18.5%–48.0% in Alaskan black spruce, white spruce, and aspen stands. Simard et al. (2001) reported organic carbon values of 43.8%–53.3% for black spruce forest floor in the Quebec boreal forest, and Bauer et al. (2006) found that total carbon ranged from 26.3% for lacustrine peat to 48.8% for sedge–moss peat in Alberta, Saskatchewan, and Manitoba. Total carbon values include both organic carbon from decomposing plant and animal residues and inorganic carbon, which originates from carbonate minerals (calcite, dolomite, and carbonate salts) of the parent material (Nelson and Sommers 1982), and comparing such values may be impossible. However, if soils are from noncalcareous parent material, the amount of inorganic carbon is generally low, and total carbon can be considered equivalent to the amount of organic carbon (Nelson and Sommers 1982). For this reason, we consider the total carbon values obtained in the wildfire study to be very close to organic carbon values, even though inorganic carbon was not measured. Kasischke et al. (2000) and Neff et al. (2005) reported a general trend of decreasing percent carbon with soil depth in black spruce stands of interior Alaska, but no statistically significant trend ($\alpha = 0.05$) was found in the field data from the present wildfire study.

The ranges in forest floor fuel consumption (0.59–5.05 kg·m^{-2}) and carbon emissions (0.29–2.43 kg·m^{-2}) determined in this study are consistent with values for boreal forest measured elsewhere. In other North American boreal studies, reported forest floor fuel consumption rates have ranged from less than 1 kg·m^{-2} (Weber et al. 1987; French et al. 2000) to 7.86 kg·m^{-2} (French et al. 2000; Kasischke and Bruhwiler 2002; Neff et al. 2005). The highest carbon emission values to date are those reported by Kasischke and Johnstone (2005), who estimated carbon emission of 0.56–5.67 kg·m^{-2} for wildfires in Alaskan black spruce forest. Their highest values were attributed to late-season fires that occurred after extended drying, warmer temperatures, and permafrost melting. Carbon emission estimates for boreal peatland have ranged from 2.1 to 7.57 kg·m^{-2} (Zoltai et al. 1998; Kasischke et al. 2000; Turetsky and Wieder 2001; Benscoter and Wieder 2003). Data from northern Europe and Asia are sparse, but McRae et al. (2006), who carried out experimental fires on dry Scots pine (*Pinus sylvestris* L.) sites in central Siberia, found forest floor fuel consumption rates of 0.9–2.6 kg·m^{-2}. FWI System data were available for those fires, so it was possible to plot the Russian fuel consumption data with Canadian data using the original eq. 1 from this study (Fig. 7). Although there are only six data points from the Siberian sites, the data scatter suggests that the fuel-load-based forest floor fuel consumption model developed in this study may be applicable to other circumpolar boreal forests.

Use of these models to estimate forest floor fuel consumption requires either preburn data on the forest floor fuel load or data on the depth and bulk density of the forest floor. To estimate national carbon emissions associated with wildland fire, preburn fuel load values are provided by the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al. 2008). The forest floor fuel consumption models can also be used in other applications if the required preburn data can be obtained from other sources. For example, in landscape-level applications with many burned units or stands, preburn fuel load could be modeled from the basic forest inventory (similar to CBM-CFS3) or estimated from field survey data. For small-scale applications such as prescribed fires or single-wildfire events, preburn forest floor data could be obtained by direct sampling within the area of concern.

Acknowledgments

Vernon Peters assisted with project planning and field logistics. Elizabeth Farries, Kari Willer, Ruth Errington, and Rene Beaulieu collected field data on wildfires. Field support was provided by the Saskatchewan Department of Ecosystem and Resource Management, Manitoba Conservation, Parks Canada, the Ontario Ministry of Natural Resources, and Yukon Community Services, Wildland Fire Management. Peter Englefield, Richard Carr, Kerry Anderson, and John Little helped collect the FWI System data for the wildfire study. Robert Landry, Vincent Decker, Robert Fraser, Ron Hall, Michael Gartrell, and Jason Freeburn prepared imagery for the wildfires. Yonghe Wang assisted with data analysis. Werner Kurz, Ed Banfield, and Brian Simpson provided consultation on the Carbon Budget Model of the Canadian Forest Sector. Presubmission reviews by Marty Alexander and Mike Wotton were very helpful. Funding support was provided by the Government Related Initiatives Program (GRIP) of the Canadian Space Agency, the Program of Energy Research and Development (PERD), and the federal government of Canada.

References

Abbott, K.A., Alexander, M.E., MacLean, D.A., Leblon, B., Beck, J.A., and Staples, G.C. 2007. Predicting forest floor moisture for burned and unburned *Pinus banksiana* forests in the Canadian Northwest Territories. Int. J. Wildland Fire, **16**: 71–80. doi:10.1071/WF06021.

Alexander, M.E., Stocks, B.J., and Lawson, B.D. 1991. Fire behavior in black spruce–lichen woodland: the Porter Lake project. For. Can. North. For. Cent. Inf. Rep. NOR-X-310.

Amiro, B.D., Todd, J.B., Wotton, B.M., Logan, K.A., Flannigan, M.D., Stocks, B.J., Mason, J.A., Martell, D.L., and Hirsch, K.G. 2001. Direct carbon emissions from Canadian forest fires, 1959–1999. Can. J. For. Res. **31**: 512–525. doi:10.1139/cjfr-31-3-512.

Baskerville, G.L. 1972. Use of logarithmic regression in the estimation of plant biomass. Can. J. For. Res. **2**: 49–53. doi:10.1139/x72-009.

Bauer, I.E., Bhatti, J.S., Cash, K.J., Tarnacai, C., and Robinson, S.D. 2006. Developing statistical models to estimate the carbon density of organic soils. Can. J. Soil Sci. **86**: 295–304.

Benscoter, B.W., and Wieder, R.K. 2003. Variability in organic matter lost by combustion in a boreal bog during the 2001 Chisholm fire. Can. J. For. Res. **33**: 2509–2513. doi:10.1139/x03-162.

Chrosciewicz, Z. 1989. Prediction of forest-floor moisture content on jack pine cutovers. Can. J. For. Res. **19**: 239–243. doi:10.1139/x89-033.

Cottam, G., and Curtis, J.T. 1956. The use of distance measures in phytosociological sampling. Ecology, **37**: 451–460. doi:10.2307/1930167.

de Groot, W.J. 2006. Modeling Canadian wildland fire carbon emissions with the Boreal Fire Effects (BORFIRE) model. *In* Proceedings of the 5th International Conference on Forest Fire Research, Figueira da Foz, Portugal, 27–30 November 2006. *Edited by* D.X. Viegas. Elsevier BV, Amsterdam. CD-ROM.

de Groot, W.J., Bothwell, P.M., and Logan, K.A. 2003. Simulating the effects of future fire regimes on western Canadian boreal forests. J. Veg. Sci. **14**: 355–364. doi:10.1658/1100-9233(2003)014[0355:STEOFF]2.0.CO;2.

de Groot, W.J., Landry, R., Kurz, W.A., Anderson, K.R., Englefield, P., Fraser, R.H., Hall, R.J., Banfield, E., Raymond, D.A., Decker, V., Lynham, T.J., and Pritchard, J.M. 2007. Estimating direct carbon emissions from Canadian wildland fires. Int. J. Wildland Fire, **16**: 593–606. doi:10.1071/WF06150.

Dyrness, C.T., and Norum, R.A. 1983. The effects of experimental fires on black spruce forest floors in interior Alaska. Can. J. For. Res. **13**: 879–893. doi:10.1139/x83-118.

Englefield, P., Lee, B.S., and Suddaby, R.M. 2000. Spatial Fire Management System. *In* Proceedings of the 20th ESRI International User Conference, San Diego, Calif. Paper No. 489. Environmental Systems Research Institute, Redlands, Calif.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., and Stocks, B.J. 2005. Future area burned in Canada. Clim. Change, **72**: 1–16. doi:10.1007/s10584-005-5935-y.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can. Inf. Rep. ST-X-3.

Frandsen, W.H. 1997. Ignition probability of organic soils. Can. J. For. Res. **27**: 1471–1477. doi:10.1139/cjfr-27-9-1471.

French, N.H.F., Kasischke, E.S., Stocks, B.J., Mudd, J.P., Martel, D.L., and Lee, B.S. 2000. Carbon release from fires in the North

American boreal forest. *In* Fire, climate change and carbon cycling in the North American boreal forest. *Edited by* E.S. Kasischke and B.J. Stocks. Springer, New York. pp. 377–388.

French, N.H.F., Goovaerts, P., and Kasischke, E.S. 2004. Uncertainty in estimating carbon emissions from boreal forest fires. J. Geophys. Res. **109**: D14S08. doi:10.1029/2003JD003635.

Harden, J.W., Neff, J.C., Sandberg, D.V., Turetsky, M.R., Ottmar, R., Gleixner, G., Fries, T.L., and Manies, K.L. 2004. Chemistry of burning the forest floor during the FROSTFIRE experimental burn, interior Alaska, 1999. Global Biogeochem. Cycles, **18**: GB3014. doi:10.1029/2003GB002194.

Hartford, R.A. 1989. Smoldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density. *In* Proceedings of the 10th Conference on Fire and Forest Meteorology, Ottawa, Ontario, 17–21 April 1989. *Edited by* D.C. MacIver, H. Auld, and R. Whitewood. Forestry Canada and Environment Canada, Ottawa, Ont. pp. 282–286.

Kalra, Y.P., and Maynard, D.G. 1991. Methods manual for forest soil and plant analysis. For. Can. North. For. Cent. Inf. Rep. NOR-X 319. pp. 25–27.

Kane, E.S., Kasischke, E.S., Valentine, D.W., Turetsky, M.R., and McGuire, A.D. 2007. Topographic influences on wildfire consumption of soil organic carbon in interior Alaska: Implications for black carbon accumulation. J. Geophys. Res. **112**: G03017. doi:10.1029/2007JG000458.

Kasischke, E.S., and Bruhwiler, L.P. 2002. Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. J. Geophys. Res. **107**: 8146. [printed 108(D1), 2003.] doi:10.1029/2001JD000461.

Kasischke, E.S., and Johnstone, J.F. 2005. Variation in postfire organic layer thickness in a black spruce forest complex in interior Alaska and its effects on soil temperature and moisture. Can. J. For. Res. **35**: 2164–2177. doi:10.1139/x05-159.

Kasischke, E.S., O'Neill, K.P., French, N.H.F., and Bourgeau-Chavez, L.L. 2000. Controls on pattern of biomass burning in Alaskan boreal forests. *In* Fire, climate change and carbon cycling in the North American boreal forest. *Edited by* E.S. Kasischke and B.J. Stocks. Springer, New York. pp. 173–196.

Kasischke, E.S., Hyer, E.J., Novelli, P.C., Bruhwiler, L.P., French, N.H.F., Sukhinin, A.I., Hewson, J.H., and Stocks, B.J. 2005. Influences of boreal fire emissions on northern hemisphere atmospheric carbon and carbon monoxide. Global Biogeochem. Cycles, **19**: GB1012. doi:10.1029/2004GB002300.

Kurz, W.A., Dymond, C.C., White, T., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., and Apps, M.J. 2008. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Model. In press. doi:10.1016/j.ecolmodel.2008.10.018.

Kurz, W.A., and Apps, M.J. 2006. Developing Canada's national forest carbon monitoring, accounting and reporting system to meet the reporting requirements of the Kyoto Protocol. Mitig. Adapt. Strategies Glob. Change, **11**: 33–43. doi:10.1007/s11027-006-1006-6.

Lawson, B.D. 1973. Fire behavior in lodgepole pine stands, related to the Canadian Fire Weather Index. Can. For. Serv. Pac. For. Cent. Inf. Rep. BC-X-76.

Lawson, B.D., and Dalrymple, G.N. 1996. Ground-truthing the Drought Code: field verification of overwinter recharge of forest floor moisture. Can. For. Serv. For. Resour. Dev. Agree. Rep. 268.

Lentile, L., Morgan, P., Hardy, C., Hudak, A., Means, R., Ottmar, R., Robichaud, P., Sutherland, E., Way, F., and Lewis, S. 2007. Lessons learned from Rapid Response Research on wildland fires. Fire Manage. Today, **67**: 24–31.

Mathews, G. 1993. The carbon content of trees. For. Comm. Tech. Pap. 4. [Edinburgh, Scotland.]

McRae, D.J., Conard, S.G., Ivanova, G.A., Sukhinin, A.I., Baker, S.P., Samsonov, Y.N., Blake, T.W., Ivanov, V.A., Ivanov, A.V., Churkina, T.V., Hao, W.M., Koutzenogij, K.P., and Kovalena, N. 2006. Variability of fire behaviour, fire effects, and emissions in Scotch pine forests of central Siberia. Mitig. Adapt. Strategies Glob. Change, **11**: 45–74. doi:10.1007/s11027-006-1008-4.

Miyanishi, K., and Johnson, E.A. 2002. Process and patterns of duff consumption in the mixedwood boreal forest. Can. J. For. Res. **32**: 1285–1295. doi:10.1139/x02-051.

Mueller-Dombois, D., and Ellenberg, H. 1974. Aims and methods of vegetation ecology. John Wiley & Sons, New York. pp. 111–114.

Nalder, I.A., and Wein, R.W. 1998. A new forest floor corer for rapid sampling, minimal disturbance and adequate precision. Silva Fenn. **32**: 373–382.

Nalder, I.A., and Wein, R.W. 1999. Long-term forest floor carbon dynamics after fire in upland boreal forests of western Canada. Global Biogeochem. Cycles, **13**: 951–968. doi:10.1029/1999GB900056.

Neff, J.C., Harden, J.W., and Gleixner, G. 2005. Fire effects on soil organic matter content, composition, and nutrients in boreal interior Alaska. Can. J. For. Res. **35**: 2178–2187. doi:10.1139/x05-154.

Nelson, D.W., and Sommers, L.E. 1982. Total carbon, organic carbon, and organic matter. *In* Methods of soil analysis. Part 2. Chemical and microbiological properties. 2nd ed. *Edited by* A.L. Page, R.H. Miller, and D.R. Kenney. Am. Soc. Agron. Soil Sci. Soc. Am. Agron. Ser. 9. pp. 539–579.

Otway, S.G., Bork, E.W., Anderson, K.R., and Alexander, M.E. 2007. Relating changes in duff moisture to the Canadian Forest Fire Weather Index System in *Populus tremuloides* stands in Elk Island National Park. Can. J. For. Res. **37**: 1987–1998. doi:10.1139/X07-055.

Quintilio, D., Fahnestock, G.R., and Dubé, D.E. 1977. Fire behavior in upland jack pine: the Darwin Lake Project. Can. For. Serv. North. For. Cent. Inf. Rep. NOR-X-174.

Quintilio, D., Alexander, M.E., and Ponto, R.L. 1991. Spring fires in a semimature trembling aspen stand in central Alberta. For. Can. North. For. Cent. Inf. Rep. NOR-X-323.

Simard, D.G., Fyles, J.W., Paré, D., and Nguyen, T. 2001. Impacts of clearcut harvesting and wildfire on soil nutrient status in the Quebec boreal forest. Can. J. Soil Sci. **81**: 229–237.

Sprugel, D.G. 1983. Correcting for bias in log-transformed allometric equations. Ecology, **64**: 209–210. doi:10.2307/1937343.

Stocks, B.J. 1987*a*. Fire behavior in immature jack pine. Can. J. For. Res. **17**: 80–86. doi:10.1139/x87-014.

Stocks, B.J. 1987*b*. Fire potential in the spruce budworm-damaged forests of Ontario. For. Chron. **63**: 8–14.

Stocks, B.J. 1989. Fire behavior in mature jack pine. Can. J. For. Res. **19**: 783–790. doi:10.1139/x89-119.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., and Skinner, W.R. 2002. Large forest fires in Canada, 1959–1997. J. Geophys. Res. **107**: 8149. [printed 108(D1), 2003.] doi:10.1029/2001JD000484.

Stocks, B.J., Alexander, M.E., Wotton, B.M., Stefner, C.N., Flannigan, M.D., Taylor, S.W., Lavoie, N., Mason, J.A., Hartley, G.R., Maffey, M.E., Dalrymple, G.N., Blake, T.W., Cruz, M.G., and Lanoville, R.A. 2004. Crown fire behavior in a northern jack pine – black spruce forest. Can. J. For. Res. **34**: 1548–1560. doi:10.1139/x04-054.

SYSTAT Software Inc. 2004. SYSTAT version 11. SYSTAT Software Inc., Richmond, Calif.

Turetsky, M.R., and Wieder, R.K. 2001. A direct approach to quantifying organic matter lost as a result of peatland wildfire. Can. J. For. Res. **31**: 363–366. doi:10.1139/cjfr-31-2-363.

Van Wagner, C.E. 1963. Prescribed burning experiments: red and white pine. Publ. 1020, Department of Forestry, Forest Research Branch, Ottawa, Ont.

Van Wagner, C.E. 1972. Duff consumption by fire in eastern pine stands. Can. J. For. Res. **2**: 34–39. doi:10.1139/x72-006.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech. Rep. 35.

Weber, M.G., Hummel, M., and Van Wagner, C.E. 1987. Selected parameters of fire behavior and *Pinus banksiana* Lamb. regeneration in eastern Ontario. For. Chron. **64**: 340–346.

Wein, R.W. 1983. Fire behaviour and ecological effects in organic terrain. *In* The role of fire in northern circumpolar ecosystems. *Edited by* R.W. Wein and D.A. MacLean. John Wiley & Sons, Toronto, Ont. pp. 81–95.

Wotton, B.M., Stocks, B.J., and Martell, D.L. 2005. An index for tracking sheltered forest floor moisture within the Canadian Forest Fire Weather Index System. Int. J. Wildland Fire, **14**: 169–182. doi:10.1071/WF04038.

Yokelson, R.J., Susott, R., Ward, D.E., Reardon, J., and Griffith, D.W.T. 1997. Emissions from smoldering combustion of biomass measured by open-path Fourier transform infrared spectroscopy. J. Geophys. Res. **102**(D15): 18 865 – 18 877. doi:10.1029/97JD00852.

Zoltai, S.C., Morrissey, L.A., Livingston, G.P., and de Groot, W.J. 1998. Effects of fires on carbon cycling in North American boreal peatlands. Environ. Rev. **6**: 13–24. doi:10.1139/er-6-1-13.