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Estimating direct carbon emissions from Canadian wildland fires[1]

William J. de Groot[A,E], *Robert Landry*[B], *Werner A. Kurz*[C], *Kerry R. Anderson*[A], *Peter Englefield*[A], *Robert H. Fraser*[B], *Ronald J. Hall*[A], *Ed Banfield*[A], *Donald A. Raymond*[B], *Vincent Decker*[B], *Tim J. Lynham*[D] and *Janet M. Pritchard*[A]

[A]Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320 – 122nd Street, Edmonton, AB T6H 3S5 Canada.

[B]Natural Resources Canada, Earth Sciences Sector, Canada Centre for Remote Sensing, 588 Booth Street, Ottawa, ON K1A 0Y7 Canada.

[C]Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC V8Z 1M5 Canada.

[D]Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, ON P6A 2E5 Canada.

[E]Corresponding author. Email: bill.degroot@nrcan.gc.ca

Abstract. In support of Canada's National Forest Carbon Monitoring, Accounting and Reporting System, a project was initiated to develop and test procedures for estimating direct carbon emissions from fires. The Canadian Wildland Fire Information System (CWFIS) provides the infrastructure for these procedures. Area burned and daily fire spread estimates are derived from satellite products. Spatially and temporally explicit indices of burning conditions for each fire are calculated by CWFIS using fire weather data. The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) provides detailed forest type and leading species information, as well as pre-fire fuel load data. The Boreal Fire Effects Model calculates fuel consumption for different live biomass and dead organic matter pools in each burned cell according to fuel type, fuel load, burning conditions, and resulting fire behaviour. Carbon emissions are calculated from fuel consumption. CWFIS summarises the data in the form of disturbance matrices and provides spatially explicit estimates of area burned for national reporting. CBM-CFS3 integrates, at the national scale, these fire data with data on forest management and other disturbances. The methodology for estimating fire emissions was tested using a large-fire pilot study. A framework to implement the procedures at the national scale is described.

Additional keywords: fire behaviour, fuel consumption, remote sensing.

Introduction

Canadian wildland fire activity has increased over the last 30–40 years, the average area burned rising from 1.2 million ha during the 1970s to 2.8 million ha during the 1990s (Amiro *et al*. 2001; Stocks *et al*. 2002). The large amounts of carbon that these fires release into the atmosphere approach, in years of extreme fire activity, levels of industrial carbon emissions (Amiro *et al*. 2001). Most of the carbon is released in the form of CO_2 (90%), CO (9%), and CH_4 (1%) (Cofer *et al*. 1998; Kasischke and Bruhwiler 2002), all of which are greenhouse gases that contribute to global climate warming. The area burned by wildland fire is expected to increase across most of Canada as climate change progresses (Flannigan *et al*. 2005). Increasing fire weather severity is expected to result in longer fire seasons, greater fire intensity and fire severity (i.e. greater fuel consumption), and higher rates of lightning- and people-caused fires (Wotton and Flannigan 1993; Price and Rind 1994; Flannigan *et al*. 1998, 2005 Lyons *et al*. 1998; Wotton *et al*. 2003). To meet international reporting commitments under the United Nations Framework Convention on Climate Change (UNFCCC), Canada is required to estimate annual emissions and removals of carbon and non-CO_2 greenhouse gases, including emissions associated with wildfires within the managed forest and carbon uptake (removals) associated with regrowth in areas disturbed in prior years. In fire-dominated ecosystems such as Canada's boreal forest, wildland fires contribute significantly to annual emissions and their interannual variability. A joint Natural Resources Canada project involving the Canadian Forest Service and the

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Canada Centre for Remote Sensing was initiated in 2004 to develop an operational methodology to annually report direct wildfire emissions under Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS; Kurz and Apps 2006).

Direct carbon emissions from Canadian wildland fires for 1959–1999 were estimated by Amiro *et al*. (2001). Those results were based on the spatial large-fire database for Canada (Stocks *et al*. 2002; Parisien *et al*. 2006), weather data for days when fire was estimated to have spread, and basic fuel consumption models for standard fuel types of the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). The datasets were limited, and the Amiro *et al*. (2001) method therefore involved numerous assumptions about fuel, weather, and fire behaviour. For the purposes of ongoing annual UNFCCC and possible future Kyoto Protocol reporting, a new methodology for estimating carbon emissions was needed to capture variations in emissions between years, between fires, and even within a single large fire. Large fires typically burn a wide range of fuel types and fuel loads under weather conditions that change as the fire spreads across the landscape, with very large spatial and temporal variation in fuel consumption and carbon emissions (French *et al*. 2004). Here we report on the theory and approach of the new methodology being used to estimate carbon emissions from wildland fire in Canada.

Variability in fuel consumption is well documented by previous experimental burning projects in jack pine (*Pinus banksiana*) stands (Stocks 1987, 1989; Alexander *et al*. 2004; Stocks *et al*. 2004). Using Lambert *et al*. (2005) tree biomass equations and a carbon conversion factor of 0.5 for all fuel components (Mathews 1993; Yokelson *et al*. 1997; Nalder and Wein 1999; Kasischke *et al*. 2000; Richter *et al*. 2000), total carbon storage of fuel on the burned plots was 33.6–96.0 t ha^{-1}. A wide range in carbon emissions of 2.2–27.7 t ha^{-1} (fires intensities of 134–93 476 kW m^{-1}) was caused by variability in pre-fire fuel characteristics (fuel size, distribution, and total load) and fire weather, which affected fuel moisture and fire behaviour. The type of forest stand, or fuel type, also has a strong influence on carbon emission rates. For example, experimental burns conducted in jack pine (Quintilio *et al*. 1977) and black spruce (*P. mariana*) stands (Canadian Forest Service, Big Fish Lake, Alberta, M. E. Alexander, Big Fish Lake Experimental Burning Project unpubl. data) under very similar burning conditions (Fire Weather Index = 17) resulted in carbon emissions rates of 7 and 12 t ha^{-1}, respectively. This disparity was due to differences in physical fuel structure, which affected fire behaviour.

To account for the large variability of carbon emissions within fires, and the large interannual variability in the area burned (0.3–7.5 million ha $year^{-1}$; Stocks *et al*. 2002), a new methodology based on remote sensing and fire modelling was developed to estimate carbon emissions. The goal of the present project was to develop a scientifically supported method for timely, nationally consistent annual estimates of direct carbon emissions from wildland fires. The present paper summarises the procedure developed, presents a pilot study in which the method was applied to a large wildfire, and outlines the framework being used for national application.

Overview of procedures for estimating wildland fire carbon emissions

The information required to estimate direct wildland fire emissions is compiled from several sources and is processed by three interacting models. The Canadian Wildland Fire Information System (CWFIS) provides the procedural and data infrastructure needed to integrate fire and remote sensing information (Fig. 1). Remote sensing information on daily active fires (hot spots) guides the annual acquisition of images that are used to delineate fire perimeters and unburned islands, and to estimate area burned. CWFIS spatially models daily fire weather using the Canadian Forest Fire Weather Index (FWI) System to quantify burning conditions for locations and on days when hot spots are observed. CWFIS also hosts the operational procedures for estimating fire-related direct carbon emissions based on fuel, weather, and fire behaviour. Detailed pre-fire fuel load and tree species data are provided by NFCMARS through the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). The Boreal Fire Effects Model (BORFIRE), which operates as a submodel within the CWFIS host infrastructure, calculates stand-level carbon losses on the basis of fuel consumption and mortality (which are treated as carbon transfers from live biomass to dead organic matter pools). BORFIRE is driven by fuel type, FWI System, and fire rate-of-spread data from CWFIS and species-specific fuel load data from CBM-CFS3. CWFIS summarises the changes in carbon pools for all burned forest stands. Carbon emissions are represented by the net carbon loss of all carbon pools. These data are summarised for use in CBM-CFS3 as disturbance matrices (Kurz *et al*. 1992), which describe the fate of each carbon pool in the forest ecosystem during wildfire. Disturbance matrices can be specific to the daily area burned under specific burn conditions, but for the purposes of national reporting, disturbance matrices are calculated as averages for regions or time periods. The CBM-CFS3 then integrates information on forest growth and decomposition for all stands in the model with information about the impacts of management, land-use change, insects, and wildfires to calculate net annual carbon emissions and removals and emissions of non-CO_2 greenhouse gases.

Canadian Wildland Fire Information System

The CWFIS is a system for acquiring, storing, analysing, and disseminating current and historical fire information; it applies both the Canadian Forest Fire Danger Rating System (Stocks *et al*. 1989) and the Fire Monitoring, Mapping, and Modelling (FireM3) system at the national level (Lee *et al*. 2002; Englefield *et al*. 2004). Since 1995, the CWFIS has been providing a national view of daily fire potential and activity through the internet (http://cwfis.cfs.nrcan.gc.ca/, accessed 20 September 2007) for use by the public and by fire management agencies, and for national and international reporting. As an operational system, the CWFIS uses weather, topography, and fuel-type data to build daily fire danger maps, including maps for all of the FWI System components (Van Wagner 1987).

The component values of the FWI System (Fig. 1) are calculated using weather data collected at noon local standard time (LST) from over 1000 weather stations throughout Canada, including locations along the US border. Geographic

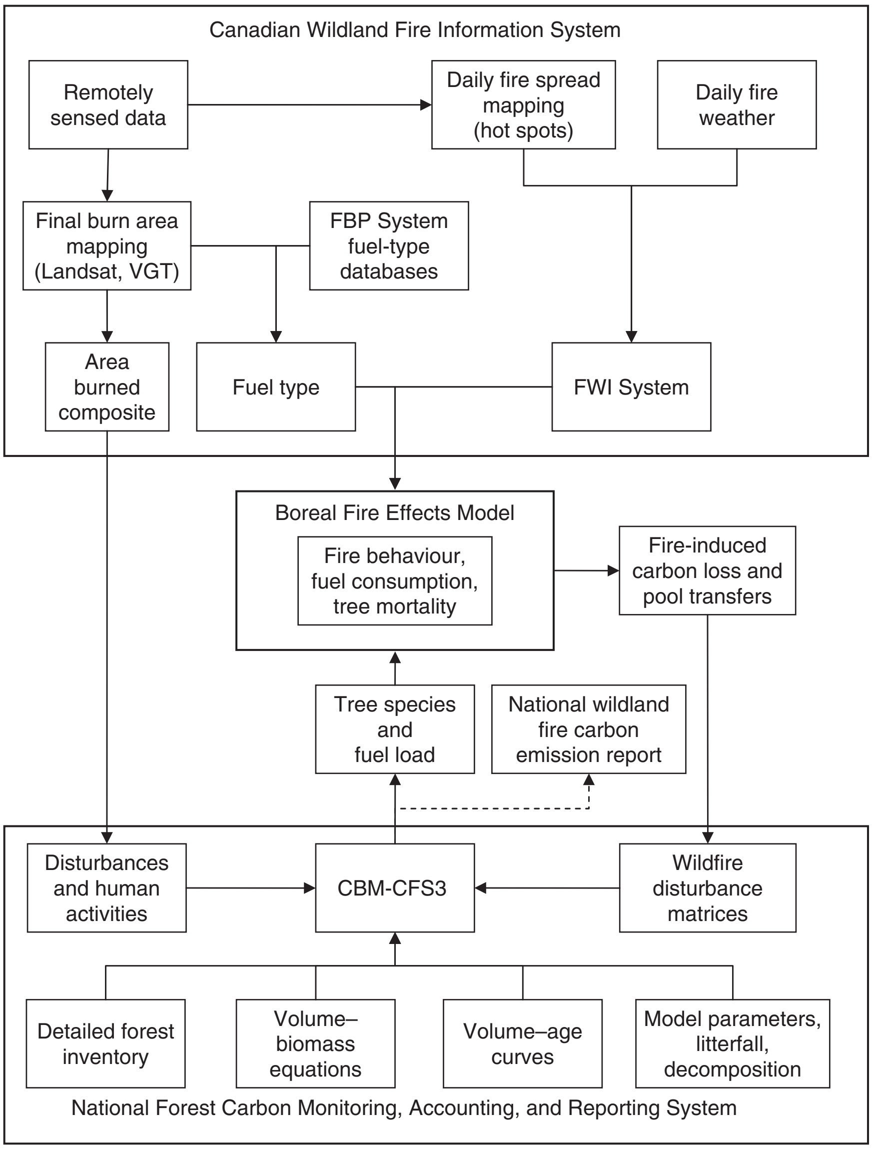

Fig. 1. National framework to estimate annual wildland fire carbon emissions. Dashed line indicates final step. FBP, Fire Behaviour Prediction; VGT, SPOT-VEGETATION sensor; FWI, Fire Weather Index; CBM-CFS3, Carbon Budget Model of the Canadian Forest Sector.

information systems (GIS) software is used to interpolate the weather data between stations, and an inverse-distance weighting scheme is used to produce gridded weather maps. The temperature and relative humidity maps are adjusted for elevation using GTOPO30, a global digital elevation model (available through the US Geological Survey website, http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html/, accessed 20 September 2007). The FWI System components are then calculated (Van Wagner and Pickett 1985) on a cell-by-cell basis to produce maps at a resolution (typically 0.1–5 km) matching that of other datasets.

Spatial fuel-type databases, which are available from numerous sources, have a variety of classification categories, scales (resolution), spatial coverage, and age. It was a priority of the present project to use nationally consistent products. Therefore, a recently developed national fuel-type map (Nadeau *et al*. 2005) was used for initial testing of the application. Fuel types were classified using the FBP System[2] at 1-km resolution. In comparison with five available provincial and territorial fuel-type maps, the national fuel-type map had an accuracy rate of 55–70%. Non-fuel-type categories were classified with the greatest certainty, whereas conifer fuels were the most difficult to classify into

[2] Fuel types include: C-1 (spruce-lichen woodland), C-2 (boreal spruce), C-3 and C-4 combined (mature and immature jack or lodgepole pine), C-5 (red and white pine), C-6 (conifer plantation), C-7 (ponderosa pine/Douglas-fir), D-1 (leafless aspen), M-1 and M-2 (boreal mixedwood), O-1 (grass).

Table 1. Comparison of forest stand fuel components of the Boreal Fire Effects Model (BORFIRE) and aboveground (above mineral soil) carbon pools of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)

BORFIRE fuel components	CBM-CFS3 carbon pools	Description
Live tree biomass		
Tree stem	Merchantable stemwood and bark	Stem wood, including bark
Tree branches	Other	Branch wood, including bark, tops, and trees of submerchantable size
Foliage	Foliage	Broadleaf and needle
Tree roots	Coarse root biomass	Coarse and medium roots
Fine roots	Fine roots	Live fine roots
Dead organic matter		
Forest floor litter (includes cured herbaceous material)	Aboveground very fast	Litterfall, dead fine woody material (<1-cm diameter)
Forest floor organic material	Aboveground slow	Forest floor fermentation and humus layers (duff)
Dead and downed medium woody debris	Aboveground fast	Fallen branches (1–7-cm diameter)
Dead and downed coarse woody debris	Aboveground medium	Fallen logs (>7-cm diameter)
Standing dead tree stem	Snag stem	Snag stem wood
Standing dead tree branches	Snag branches	Snag branch wood

the correct conifer fuel-type category. The fuel-type map was derived from three sources:

(1) Land Cover 2000, a satellite-image-based land cover classification of Canada at 1 × 1-km resolution (Latifovic *et al.* 2004), for which images were acquired in 2000 by the VEGETATION (VGT) sensor on the Système Probatoire pour l'Observation de la Terre (SPOT) satellite to produce a composite image representative of the summer months;
(2) ecozones and ecoregions of Canada (Ecological Stratification Working Group 1995), which were used to restrict the classified land cover map by excluding fuel types known to be absent from certain areas; and
(3) Canadian Forest Inventory (CanFI) data (Power and Gillis 2006), which were used to provide a coarse-resolution (10 × 10-km cell) indicator of the distribution of conifer species (Gray and Power 1997).

Carbon Budget Model of the Canadian Forest Sector

The CBM-CFS3 (Kurz *et al.* 1992; Kurz and Apps 1999), which is the core model of Canada's NFCMARS (Kurz and Apps 2006), is a stand- and landscape-level model of forest carbon dynamics[3]. For national-scale reporting, forest inventory and growth and yield data provided by provincial and territorial governments or obtained from CanFI 2001 are combined with data on forest management activities, natural disturbances, and land-use change to estimate carbon stock changes and non-CO_2 greenhouse gas emissions and removals.

For the current project, the CBM-CFS3 provided carbon data to calculate quantities of biomass and dead organic matter (or fuel load by species) in the inventory regions encompassing areas burned. The estimates of fuel consumption and mortality calculated by BORFIRE (according to burn conditions and other data), were summarised as carbon losses and transfers in wildfire disturbance matrices for use by CBM-CFS3. CWFIS provides the information on area burned by year and region, which is combined in CBM-CFS3 with all other relevant data on annual processes required to estimate carbon stock changes. The focus of the present paper is on the methods used to calculate fire emissions from a single large wildfire. The methods for estimating emissions at a national scale will be described in detail in a subsequent paper.

Boreal Fire Effects Model

BORFIRE is 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) according to plant vital attributes (Noble and Slatyer 1980; Pausas *et al.* 2004). The model has been used to simulate the long-term impacts of altered fire regimes on forest carbon storage under future climate change (de Groot *et al.* 2003) and the effects of different fire management strategies (de Groot *et al.* 2002). In the present project, it was used to model the immediate impacts of fire on forest carbon pools. BORFIRE is a stand-level model that keeps track of fire-related changes in fuel load in various stand compartments (Table 1). For this application, fuel load values in the model were initialised using carbon pool data from CBM-CFS3.

Modelling carbon emissions from wildland fire in BORFIRE

Total direct carbon emissions from wildland fires depend primarily on pre-fire fuel characteristics and burning (or fire weather) conditions during the fire itself (Amiro *et al.* 2001; French *et al.* 2004; Kasischke *et al.* 2005). Those data were provided by CWFIS and CBM-CFS3 in the form of FWI System, fuel, species, date, location and elevation input data (Fig. 2),

[3] An operational-scale version of the model, user's guide, and tutorials are freely available at http://carbon.cfs.nrcan.gc.ca/, accessed 20 September 2007.

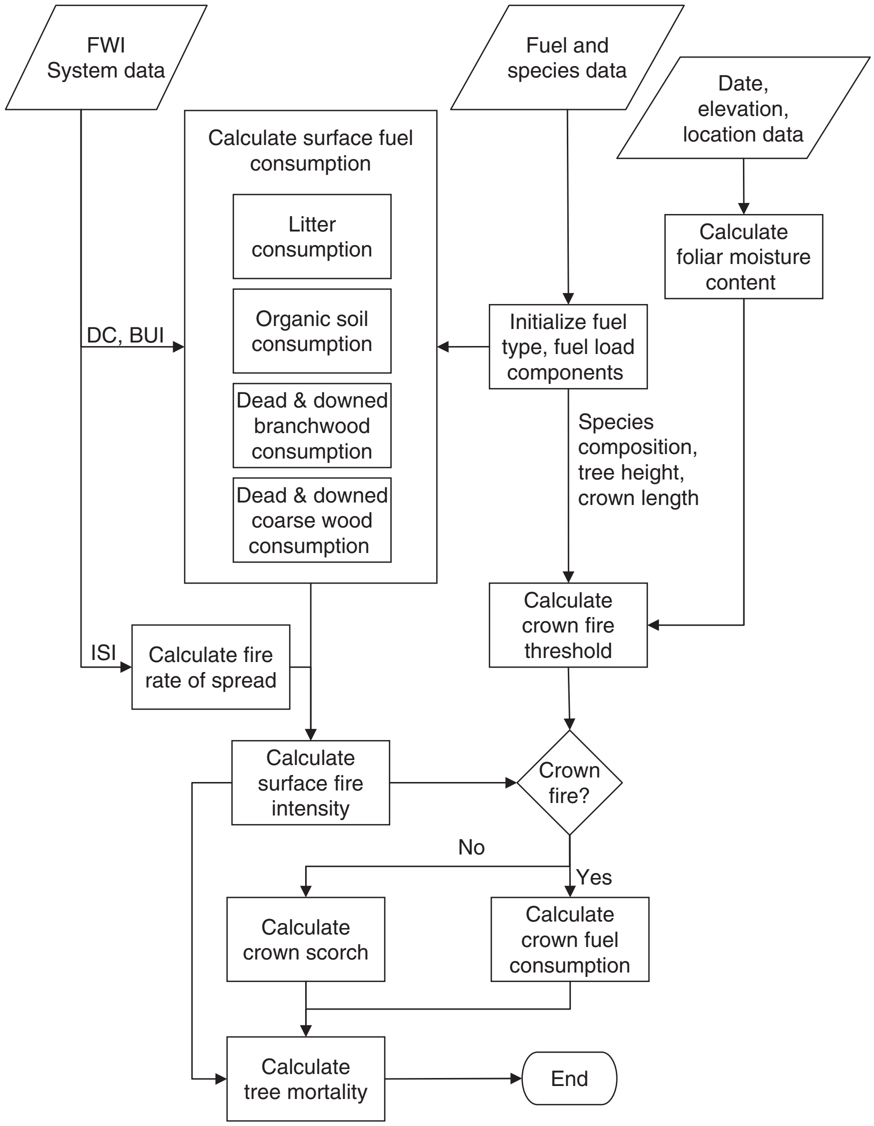

Fig. 2. Dataflow to calculate fuel consumption and tree mortality in the Boreal Fire Effects Model. FWI, Fire Weather Index; DC, Drought Code; BUI, Buildup Index; ISI, Initial Spread Index.

which were used to drive dynamic fuel-type-specific carbon emission algorithms. The amount of fuel consumed by fire and transferred between live trees and dead organic matter in the model was dependent on fire behaviour.

Large fires, most of which occur as crown fires, account for ~97% of the total area burned in Canada (Stocks 1991; Stocks *et al*. 2002). Overstorey fuel consumption is typically a limited amount (0–25%) of the total aboveground fuel load (Quintilio *et al*. 1977, 1991; Stocks 1987, 1989; Weber 1990; Alexander *et al*. 1991; Stocks *et al*. 2004), unless the trees are of very small diameter. The greatest uncertainty in modelling carbon emissions from wildland fire is estimating the forest floor source (French *et al*. 2004). In some boreal forest stand types, over half of the total fuel load may be stored in the forest floor (Nalder and Wein 1999; Kasischke *et al*. 2000), and fuel consumption of this substrate can range from near 0 to 100% (Dyrness and Norum 1983; Wein 1983; Nalder and Wein 1999; Kasischke *et al*. 2000; Richter *et al*. 2000). As part of the present project, a new forest floor carbon emission model was developed using experimental burn data from the FBP System database and post-fire field data from recent large wildfires (W. J. de Groot, J. M. Pritchard and T. J. Lynham unpubl. data). Wildfires that burned under high Drought Code (DC) values were targeted for sampling to extend the range of conditions currently represented in the FBP System database. Forest floor fuel consumption data from 128 plots in spruce, pine, aspen, and mixedwood fuel types were combined to develop a single algorithm for all fuel types. Estimates of forest floor fuel consumption with this new algorithm are generally higher than the FBP System estimates because there are more data at the high end of burning conditions and also because the new model accounts for higher emission rates that occur with higher pre-fire fuel loads.

Fire behaviour and stand-level direct carbon emissions

Fuel-specific fire behaviour algorithms within BORFIRE were driven by the codes and indices of the FWI System (Fig. 2). Overstorey (crown) fuel consumption was estimated with an algorithm developed from experimental burn data in the FBP System (Forestry Canada Fire Danger Group 1992) database (de Groot 2006). Slash burning models were used to estimate consumption of forest floor woody debris (McRae 1980). Consumption of organic forest floor material followed the new algorithm described in the previous section. Fire rate of spread was determined using the FBP System algorithms for the fuel type categories of the national fuel type map (Nadeau *et al.* 2005). This is the only point in the modelling process where FBP System fuel-type information was used. All other fuel-specific aspects of BORFIRE were based on tree species to model growth and yield and stand structure parameters important to fire behaviour (e.g. live-crown base height, crown length, foliage fuel load, bark and fine branch fuel load). BORFIRE can accommodate multiple-species stand composition in any proportion for the six boreal tree species currently available in the model (*Pinus banksiana*, *Picea glauca*, *Picea mariana*, *Populus tremuloides*, *Betula papyrifera*, and *Abies balsamea*), which represent the large majority of the boreal forest. Other tree species were simulated using the nearest similar species. Fire rate of spread was combined with surface fuel consumption to calculate surface fire intensity according to Byram's (1959) equation. This value was compared with the critical surface intensity to determine if the crown fire threshold had been reached (Fig. 2). If so, crown fuel consumption was also calculated. All fuel load and consumption values were converted to carbon using a factor of 0.5 carbon units per unit of fuel.

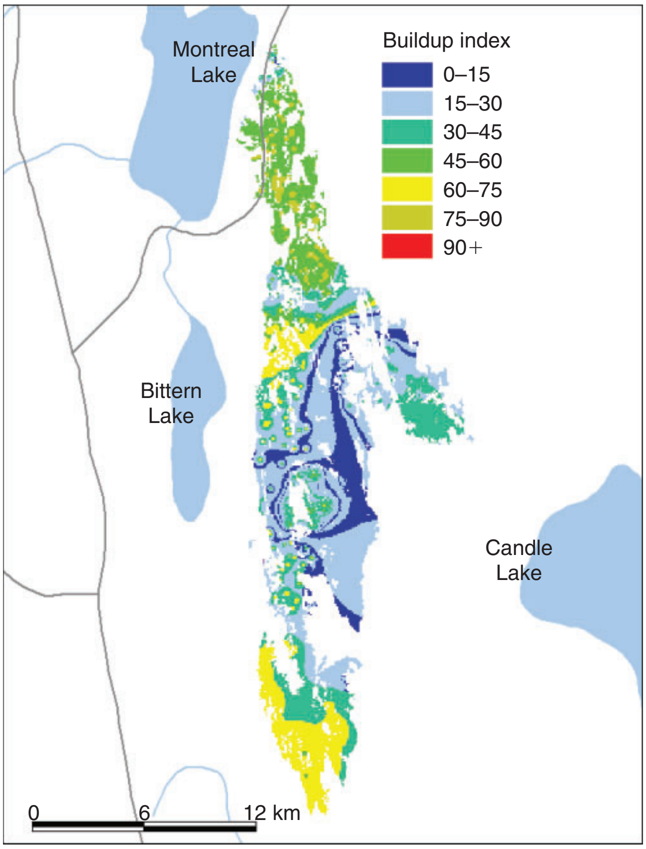

Fig. 3. Map of Buildup Index (BUI) values for the day each cell was burned for the 2003 Montreal Lake fire, Saskatchewan. BUI is an indicator of the total amount of fuel available for combustion.

Large-fire pilot study

Initial testing of the stand-level carbon emissions estimation procedure was conducted using a well-documented large wildfire. The 2003 Montreal Lake fire, located in the Boreal Plains ecozone (Ecological Stratification Working Group 1995) of central Saskatchewan, was selected for study because daily fire spread occurred over a broad range of burning conditions (Fig. 3) and it burned many different fuel types (Fig. 4) with varying fuel loads. Landsat imagery and detailed fuel, forest inventory, and weather datasets were also available for the area burned. The Montreal Lake fire burned 21 654 ha over a 70-day period. The final area burned actually represented three fires that coalesced during the period of the fire. Two carbon emission values were estimated for the fire using different fuel consumption models. The first estimate was obtained with the FBP System fuel consumption models, which were also used by Amiro *et al.* (2001). The second estimate was based on BORFIRE, with a new forest floor fuel consumption model developed from the FBP System database and wildfire field data.

Pilot study procedures

Daily fire progression maps were constructed to determine the date and associated weather conditions when each cell burned, prerequisites for accurate estimation of fuel consumption and carbon emissions. Fire spread was mapped using satellite-detected hot spot data provided by two sensors, the Advanced Very High Resolution Radiometer (AVHRR, available on National Oceanic and Atmospheric Administration 15, 16, and 17 satellites) and the Moderate Resolution Imaging Spectroradiometer (MODIS, available on the Aqua and Terra satellites). Each of these five polar-orbiting satellites makes two daily passes at different times throughout the day, providing repeated coverage that can take advantage of brief cloud-free views and can be used to monitor short fire-spread events. Hot spot dates and times were interpolated to produce a continuous grid (raster) map of burn progression. The fire-spread map was overlaid with FWI System grids (constructed from the archived daily fire weather data) to determine the values of the FWI System components that represented the burning conditions for the days that each cell burned. A 100×100-m cell size was used to match the resolution of the fuel-type map.

The fuel type of each burned cell was obtained from the provincial fuel-type map (Fig. 4). The tree species composition for burned stands was obtained by comparing fuel types with CanFI data for 2001. CanFI provided detailed national forest inventory data for each cell in a 10×10-km grid. The year in which the inventory data were collected can differ and CanFI 2001 data were therefore first brought to a common reference year (1990, the first reporting year under UNFCCC guidelines). The CBM-CFS3 was then used to simulate stand and carbon dynamics from 1990 to 2003, and the resulting stand conditions

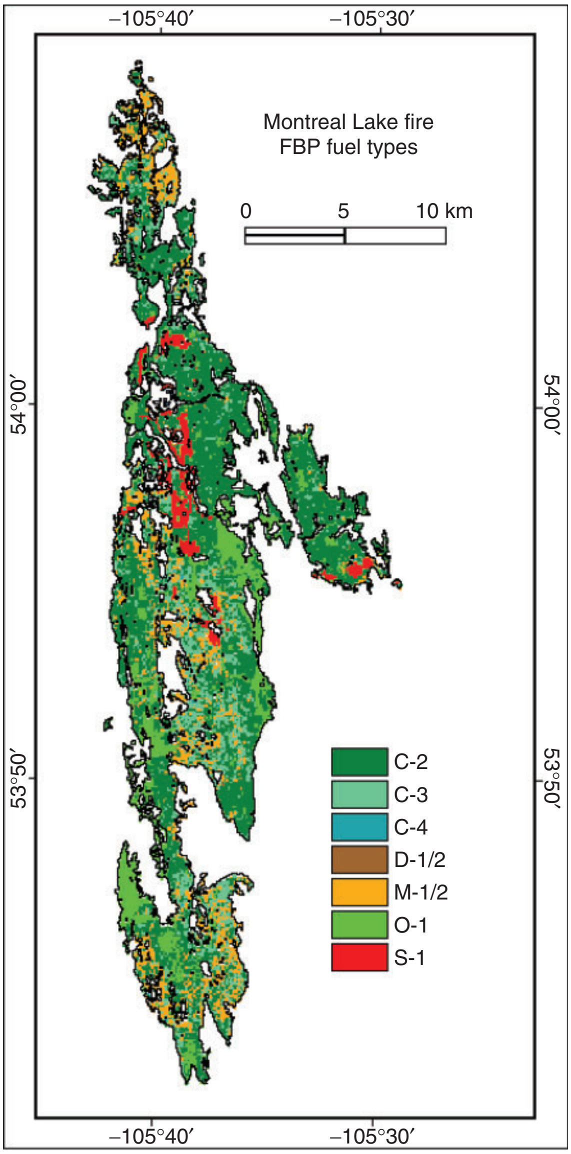

Fig. 4. Fuel-type map for the Montreal Lake fire (Saskatchewan Environment, Forest Fire Management Branch, Fuel Type Maps of Saskatchewan unpubl. data). Fuel types were classified using Landsat TM imagery and provincial forest inventory data originally obtained from aerial photography. FBP, Fire Behaviour Prediction System; C-2, boreal spruce; C-3, mature jack or lodgepole pine; C-4, immature jack or lodgepole pine; D-1/2, deciduous (leafless and leafed out); M-1/2, mixedwood (leafless and leafed out); O-1, grass; S-1, jack or lodgepole pine slash.

and fuel load estimates were provided to BORFIRE. The modelling procedure of CBM-CFS3 converts volume information into estimates of above- and below-ground biomass and estimates of carbon contained in several above- and below-ground dead organic matter and soil carbon pools (Table 1). Because CanFI is spatially referenced to 10 × 10-km grid cells (and is not truly spatially explicit at the forest polygon level), tree species and other forest attributes were determined by selecting stands that matched the provincial fuel type from a list of stands within the CanFI cell containing the area burned. For example, a C-2 (boreal spruce) FBP System fuel-type classification would require the random selection of forest stands from a list of all spruce stands within the CanFI cell until the area burned in that fuel type in that CanFI cell had been achieved.

Each stand selected from the CanFI database was then 'burned' using the BORFIRE model. Carbon pool data for each stand were provided by CBM-CFS3 and converted to fuel load data for the stand components in Table 1. CWFIS provided the remaining parameter values required to calculate fuel consumption by stand component and tree mortality resulting in transfers between components for each burned stand. These values included fuel type (to calculate fire rate of spread) and daily FWI System components that were interpolated by inverse distance weighting to the CanFI cell centroid. CWFIS compiled the fuel consumption and transfer data and converted them to changes in the carbon pools. Carbon emissions were estimated as the net carbon loss.

Pilot study results

Fuel consumption rates were higher with the BORFIRE method than with the FBP System method. Average fuel consumption rates for standing timber fuel types ranged from 3.0 to 4.6 kg m^{-2} with BORFIRE and from 0.9 to 3.2 kg m^{-2} with the FBP System (Table 2). The higher fuel consumption rates obtained with BORFIRE were primarily the result of the new fuel consumption algorithm for the forest floor. This new algorithm significantly increased the estimates of fuel consumption in hardwood and mixedwood stands, and most notably in spruce stands, which are characterised by deep organic soils contributing to high forest floor fuel loads. These stands are subject to deeper-burning fires after extended periods of dry weather, as indicated by high DC values. The Montreal Lake fire had DC values that ranged from 293 to 424 over the 70-day period that the fire spread. The BORFIRE method estimated total direct carbon emissions of 369 528 t for the Montreal Lake fire, whereas the FBP System estimated a value that was 30% lower (259 742 t). Fig. 5 illustrates the spatial variability in carbon emissions, which is typical of large fires.

National framework

To apply this methodology for estimating carbon emissions at a national scale, the procedures outlined in Fig. 1 were initiated in three distinct phases: daily monitoring and collection of active fire data, end-of-fire-season mapping, and end-of-year processing of burned-area polygon data to calculate carbon emissions. These phases are briefly summarised below and will be described in more detail in a subsequent paper.

Daily processes

Fire weather data are collected from across the country and archived daily during the fire season. In regions normally covered by snow during the winter, fire weather recording officially starts 3 days after snowmelt and typically ends when fire danger declines to very low levels near the end of the fire season, which usually occurs by late September or early October. In regions where snow cover is not a significant feature, only the start date changes. In that case, recording commences on the third consecutive day that noon temperature reaches 12°C or

Table 2. Mean (± standard deviation) total fuel consumption by fuel type for the 2003 Montreal Lake fire, Saskatchewan
As determined by the Fire Behavior Prediction (FBP) System and the Boreal Fire Effects Model (BORFIRE) methods for a total area burned of 21 654 ha

FBP System fuel type	Area of burn (ha)	FBP System		BORFIRE	
		No. of units burned[A]	Total fuel consumption ($kg\,m^{-2}$)	No. of units burned[A]	Total fuel consumption ($kg\,m^{-2}$)
Boreal spruce (C-2)	10 126	15	3.2 ± 0.5	844	4.3 ± 1.1
Mature pine (C-3)	3491	14	2.1 ± 0.4	482	3.2 ± 0.7
Immature pine (C-4)	156	6	2.9 ± 0.6	71	3.1 ± 0.6
Deciduous (D-1)	59	6	0.9 ± 0.1	97	3.4 ± 0.7
Mixedwood (M-1, M-2)	3120	12	1.1 ± 0.1	998	3.4 ± 0.8
Logging slash (S-1)	1055	6	6.7 ± 0.5	69	6.0 ± 1.2
Grassland (O-1)[B]	3618	15	0.3	223	0.3

[A]Refers to the total number of individual fuel-type polygons (FBP System method) or forest stands (BORFIRE method) burned per burning day. For example, one large fire might burn one large fuel-type polygon over 3 days in the FBP System method, resulting in three unique burned units; the same fire might burn 200 stands in the BORFIRE method, resulting in at least 200 burned units.
[B]In this case, fuel consumption rates are the same for the two methods because the BORFIRE model uses the FBP System algorithms as the default method when quantified fuel load values are unavailable.

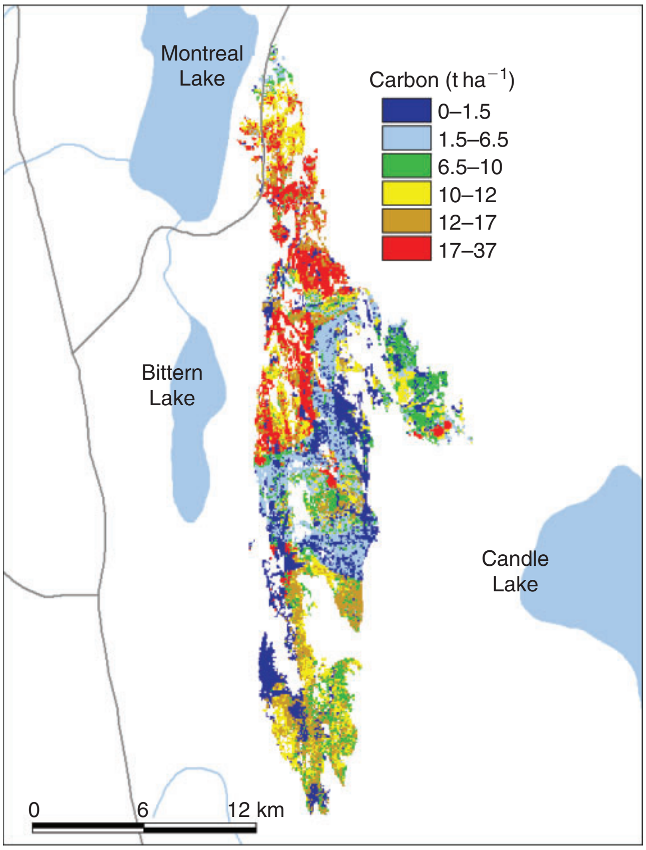

Fig. 5. Spatial map of carbon emissions from the 2003 Montreal Lake fire, Saskatchewan, as determined by the Fire Behavior Prediction System. This map was constructed using fuel-type and spatial weather data. A similar map based on the Boreal Fire Effects Model also requires fuel load data, which were not available in a spatially explicit form for the study area.

higher (Canadian Forest Service 1984). Fire hot spots are monitored daily with AVHRR and MODIS imagery, a process that indicates active fire perimeters to be used in plotting daily fire spread (Fig. 1). Daily fire monitoring also provides supplemental information for mapping burned areas (Fraser *et al.* 2000) and for planning of Landsat image acquisition.

End-of-season processes

Burned areas are mapped at the end of the fire season, when fire weather recording and active fire monitoring are complete. Fires are mapped using both coarse-resolution (SPOT-VGT) and fine-resolution (Landsat) satellite data; these products are supplemented with conventional maps from provincial and territorial agencies to produce a national burned-area composite.

A 1 × 1-km national-level burned-area product is generated by early October using a method dubbed Hot Spot and NDVI Differencing Synergy (HANDS), which combines multi-temporal change detection, and a cumulative mask of active fire hot spots (Fraser *et al.* 2000). Potential burned areas are first identified by differencing and statistical thresholding of a vegetation index derived from SPOT-VGT imagery composited from pre-fire and post-fire time periods. The combined AVHRR and MODIS hot spot mask is then used to create refined, spatially adaptive differencing thresholds and to identify falsely mapped areas. This method produced burned-area estimates at the national level that were similar to those from provincial and territorial forest fire agencies, which used sketch mapping, GPS, and digitising of aerial photos (Fraser *et al.* 2000, 2004). However, validation of the coarse-resolution product revealed that crown fire burned area was significantly overestimated because of spatial aggregation effects related to the inclusion of non-burned areas within the 1 × 1-km pixels (Fraser *et al.* 2004). Therefore, a simple regression calibration model was developed to remove the aggregation bias on estimates of crown fire burned area.

Although the SPOT-VGT burned area provides a national-level product suitable for estimating emissions, its accuracy is often limited by large spatial variability in aggregation bias, which can lead to poor results for small or highly fragmented burns. To improve mapping accuracy in regions of high fire activity, a sample of higher-resolution (30 × 30 m) Landsat scenes providing a 180-km swath is subjected to one of two mapping methods: the Single Acquisition Fire Mapping System (SAFiMS) and the Multi-Acquisition Fire Mapping System

Table 3. Comparison of total fuel consumption ($kg\,m^{-2}$) for several stand types, based on burning conditions[A] and fuel load at different stand ages[B]

As determined by Fire Behavior Prediction (FBP) System and Boreal Fire Effects Model (BORFIRE) methods; FWI, Fire Weather Index; na, not applicable

Species (FBP fuel type)	Average FWI System values				Extreme FWI System values			
	FBP System	BORFIRE[D]			FBP System	BORFIRE[D]		
		25 years	50 years	100 years		25 years	50 years	100 years
Immature pine (C-4)	2.1	2.7	na	na	3.6	3.1	na	na
Mature pine (C-3)	1.2	na	3.3	3.3	3.6	na	5.6	5.9
Black spruce (C-2)	2.7	3.0	4.1	5.9	3.8	3.5	4.6	6.8
White spruce (C-2)	2.7	2.2	3.8	4.9	3.8	3.7	4.4	5.7
Aspen (D-1)[C]	0.8	1.6	2.2	2.0	1.1	2.1	2.7	2.5

[A]Burning conditions were quantified by mean and extreme FWI System parameters during 1953–1980 for Prince Albert, Saskatchewan, using data from Harrington *et al*. (1983). FWI System values represent mid-June (summer) conditions for pine and spruce and mid-May (spring) conditions for aspen.
[B]Stand age was used to provide initial fuel load for stand components according to growth and yield algorithms derived from Alberta and Saskatchewan forests (Alberta Forest Service 1985) for pure, fully stocked stands on medium-productivity sites. Pre-fire forest floor fuel load was set at $4\,kg\,m^{-2}$ for all stand types except black spruce, which was set at $8\,kg\,m^{-2}$.
[C]Leafless aspen.
[D]For three stand ages.

(MAFiMS). SAFiMS is employed when an immediate post-fire Landsat image is available; it uses an integrated GIS and image analysis approach to identify change events within the image. The algorithm is adaptive because defining spectral changes that represent fire events is somewhat dependent on the conditions reflected in the image and the date that it was acquired. Some features such as wetlands and clear-cuts can cause confusion because of their spectral similarity to burned forest land. MAFiMS was devised to address this confusion and to improve consistency in identifying burned areas. This procedure is based on pre- and post-fire images and extends the temporal window for mapping fire events, especially when an immediate post-fire image is not available. Coarse-resolution burned-area estimates from SPOT-VGT in these regions are replaced by the Landsat burned-area estimates.

For post-fire mapping of burned areas, an automated procedure is used to identify and select Landsat images from the online archive of the Canada Centre for Remote Sensing. In that process, daily hot spot products are used to select scenes covering a maximal hot spot area on the earliest possible cloud-free date after burning (Fraser *et al*. 2004). A final burned-area composite for use in NFCMARS (to estimate national carbon emissions) is created by combining, in order of preference depending on spatial coverage, the 30×30-m Landsat-based products, fire agency burned-area maps deemed to be of sufficient accuracy, and the 1×1-km national satellite product.

End-of-year (annual) processes

The final annual procedures have been modified from those used for the Montreal Lake fire pilot study and are repeated for every fire. In the implementation of procedures in NFCMARS used for the 1990 to 2004 reporting period (Environment Canada 2006), estimates of annual area burned in each of over 500 spatial units are combined with regional disturbance matrices describing fuel consumption and tree mortality rates averaged for all fires within each ecozone. Future implementations could combine daily fire progression maps constructed from AVHRR and MODIS hot spot data with disturbance matrices describing the daily burn conditions. At present, the selection of forest stands eligible for burning from the inventory records contained in each of the over 500 spatial units occurs at random, but work is in progress to enhance record-selection procedures using national or provincial fuel-type maps to determine the fuel type of each burned stand. CBM-CFS3 uses CanFI 2001 or provincial inventory data to provide the pre-fire carbon pool status for each burned stand. CWFIS converts carbon data to fuel load data and burns each stand using BORFIRE. Fuel consumption is converted to direct carbon loss, and tree mortality is used to calculate carbon transfer from live to dead organic matter pools for each stand. From this procedure, average carbon loss and transfer data are summarised in regional disturbance matrices that are used in CBM-CFS3 to represent fire impacts and to calculate regional and national carbon emissions. Post-fire emissions and carbon uptake from forest regrowth are calculated by CBM-CFS3 and combined with all other processes that cause forest carbon emissions and removals in Canada's managed forest (Kurz and Apps 2006).

Discussion

According to the FBP System method, the mean fuel consumption rate for the Montreal Lake fire was $2.40\,kg\,m^{-2}$, which is very close to the average value of $2.35\,kg\,m^{-2}$ recorded by Amiro *et al*. (2001) for all fires in the Boreal Plains ecozone during the period 1959–1999. This result was expected because both estimates are based on the fuel consumption algorithms of the FBP System. In contrast, the mean total fuel consumption rate obtained with the BORFIRE method (with pre-fire fuel loads calculated by CBM-CFS3 with CanFI 2001 data) was $3.41\,kg\,m^{-2}$. The higher BORFIRE estimate is at least partly due to the new fuel consumption algorithms used in the model. Table 3 illustrates the difference in fuel consumption estimates between the FBP System and BORFIRE methods for standard fuel types. Unlike the FBP System method, BORFIRE fuel consumption estimates are influenced by pre-fire fuel loads, which

Table 4. Summary of mean (standard deviation) pre-fire fuel load (*a*) and fuel consumption (*b*) for surface fuels of the Montreal Lake fire

Pre-fire fuel loads were calculated using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) with Canadian Forest Inventory (CanFI) 2001 data; fuel consumption was calculated using the Boreal Fire Effects (BORFIRE) Model

FBP System fuel type	Litter (kg m^{-2})	Duff (kg m^{-2})	Dead woody debris (kg m^{-2})
(*a*) Pre-fire fuel load			
Boreal spruce (C-2)	0.61 (0.14)	0.98 (0.18)	3.36 (1.03)
Mature pine (C-3)	0.43 (0.05)	0.77 (0.06)	2.87 (0.93)
Immature pine (C-4)	0.28 (0.07)	0.61 (0.09)	3.26 (0.70)
Deciduous (D-1)	0.59 (0.07)	0.91 (0.08)	2.72 (0.61)
Mixedwood (M-1, M-2)	0.60 (0.12)	0.92 (0.14)	2.50 (0.50)
(*b*) Fuel consumption			
Boreal spruce (C-2)	0.61 (0.14)	0.67 (0.11)	1.84 (0.72)
Mature pine (C-3)	0.43 (0.05)	0.66 (0.11)	1.11 (0.41)
Immature pine (C-4)	0.28 (0.07)	0.59 (0.09)	1.39 (0.45)
Deciduous (D-1)	0.59 (0.07)	0.67 (0.09)	1.49 (0.39)
Mixedwood (M-1, M-2)	0.60 (0.12)	0.69 (0.11)	1.59 (0.53)

are represented by different stand ages in Table 3. In a sensitivity test with data from the Montreal Lake fire, a 10% increase or decrease in fuel load values for all forest stand fuel components resulted in a corresponding change of ~7% in total carbon emissions, which indicates that fuel consumption estimates are sensitive to pre-fire fuel load values based on Kercher and Axelrod's (1984) sensitivity criteria. The FBP System method had a relatively small number of units burned in the Montreal Lake fire (Table 2), but this did not have any influence on the fuel consumption estimate (i.e. owing to a limited sample size). Partitioning the original fuel-type polygons into a larger number of smaller polygons would not change the FBP System results. However, the large number of units burned by the BORFIRE method (using CanFI data provided by CBM-CFS3) illustrates the level of detail reached in providing a fuel consumption estimate from stand-level data.

In the Montreal Lake fire, almost half of the total fuel consumption occurred in the coarse and medium dead woody debris components on the forest floor (Table 4). Using the CBM-CFS3 with CanFI 2001 data, we calculated average pre-fire fuel loads for dead and downed woody debris at 2.5–3.4 kg m^{-2}. These values are higher than those recorded at experimental burning projects in jack pine stands in Ontario and the Northwest Territories (1.4–2.2 kg m^{-2}; Quintilio *et al*. 1977; Stocks 1987, 1989; Stocks *et al*. 2004), in northern Alberta white spruce, aspen, and mixedwood stands (1.5–2.3 kg m^{-2}; Ecosystem Management by Emulating Natural Disturbance (EMEND) Project, W. J. de Groot, Pre-fire Fuel Load unpubl. data; Spence *et al*. 2002), and numerous undisturbed stands surveyed across central Saskatchewan and Manitoba (1.1 $\pm$ 0.9 s.d. kg m^{-2}; Halliwell and Apps 1997). With BORFIRE, higher estimates of pre-fire dead and downed woody debris fuel loads will result in higher fuel consumption estimates.

Conversely, the average pre-fire forest floor (litter and duff) fuel load estimates of 0.9–1.6 kg m^{-2} (Table 4) were much lower than those reported by Nalder and Wein (1999) for jack pine (carbon storage of 1.3 kg m^{-2}, an approximate fuel load of 2.6 kg m^{-2}) and aspen (carbon storage of 2.8 kg m^{-2}, an approximate fuel load of 5.6 kg m^{-2}) stands of western Canada. Nalder and Wein (1999) also determined that decomposing coarse woody debris accounted for an additional 0.3–0.4 kg m^{-2} of the forest floor fuel load. An organic soil carbon inventory for central Saskatchewan showed an approximate forest floor fuel load of 5.0 ($\pm$2.1 s.d.) kg m^{-2} (based on carbon storage of 2.5 kg m^{-2}, Siltanen *et al*. 1997).

By these comparisons, it appears that one-third to one-half of the dead woody debris fuel load of the Montreal Lake fire, as calculated by the CBM-CFS3, should technically be included in the forest floor fuel component as decaying logs. The CBM-CFS3, like other ecosystem dynamics models, calculates the decay of woody dead organic matter but does not simulate the physical disintegration and redistribution of this material. Thus, although it is considered part of the medium or coarse woody debris pools, wood in advanced stages of decay may physically be incorporated in the forest floor layer. This redistribution would not change the total forest floor and dead woody debris fuel load estimated for the Montreal Lake fire (4.0–5.0 kg m^{-2}). However, it would decrease estimated fuel consumption of dead woody debris by 1.0–1.5 kg m^{-2} and increase estimated forest floor fuel consumption by 0.7–1.2 kg m^{-2}. The net effect of this redistribution would be a decrease of ~0.3 kg m^{-2} in the total fuel consumption estimate obtained with the BORFIRE method (with CBM-CFS3 and CanFI data). This would result in a final estimated fuel consumption rate of ~3.1 kg m^{-2} with BORFIRE.

The pilot study of the Montreal Lake fire demonstrated that fuel-type information is important for obtaining accurate pre-fire fuel load data. Fuel-type data are used to select the growth and yield equations for the species in each stand that is burned, which directly affects fuel load and its distribution between stand components. In the Montreal Lake fire pilot study, fuel-type maps were used to ensure that the correct species for each stand were selected from the list of CanFI stand records. By definition, fuel type affects fire behaviour (Merrill and Alexander 1987), which influences the fuel consumption rate. Species-specific fire behaviour algorithms are the primary component of BORFIRE. Fuel-type maps are important for spatial fire behaviour applications (Lee *et al*. 2002), but fuel-type mapping is difficult

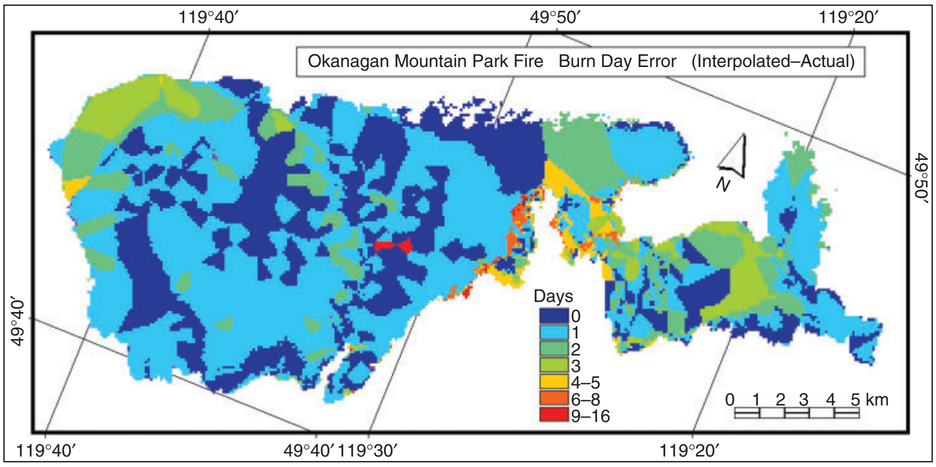

Fig. 6. Burn day anomalies (presented as absolute error, measured in days) for the 2003 Okanagan Mountain Park fire in British Columbia, with nearest neighbour interpolation. Burn perimeter information was provided by the British Columbia Ministry of Forest and Range Protection Program.

and complex (Keane *et al*. 2001), and no standard methods for creating these maps exist (Rollins *et al*. 2004). As a result, a plethora of approaches based on inventory (Tymstra and Ellehoj 1994; Woodall *et al*. 2004), remote sensing (Keane *et al*. 2001; Loveland 2001; Frank and Finnigan 2005), and multi-source datasets and models (Rollins *et al*. 2004; Falkowski *et al*. 2005; Nadeau *et al*. 2005) have been employed in generating fuel maps. In general, fuel-type maps tend to focus on the aboveground component.

The use of remote sensing to map fuel types is challenged by the complexities involved in the association between fuel type and image spectral response. At a fundamental level, we cannot expect to reliably map forest fuels from remote sensing directly; rather, we are mapping vegetative land cover as an indicator of forest fuels. A large body of studies has been directed at mapping land cover from remote sensing data (Cihlar 2000; Franklin and Wulder 2002; Wulder *et al*. 2003); thus, the development of methods for deriving fuel type from land cover may be a more promising approach to this problem. For a land mass as large as Canada, several criteria would ideally need to be addressed for successful mapping of forest fuel types:

(1) consistent use of a single approach to mapping fuel types over large areas;
(2) mapping products that reflect pre-fire fuel conditions;
(3) mapping methods that allow continuous updating to account for landscape disturbances such as fire, insects, disease, and harvesting; and
(4) maps that are variable in resolution but at a scale sufficiently fine to depict the spatial variability in fuel types within fire events (as spatial variability in fuel type affects fuel consumption and carbon emissions through effects on fire behaviour).

For application of the national framework to annually estimate wildfire carbon emissions across Canada, the complexities and challenges in generating fuel-type maps necessitate research for a method that meets the criteria listed above and that can be incorporated into the CWFIS. In the Montreal Lake fire pilot study, a simplified process was used, whereby records within a large spatial region (100-km^2 CanFI cell) were selected at random for burning (in the model) from a list of inventory records that contained the tree species representative of the fuel type that was burned (in the fire itself). In the future, it is envisioned that fuel-type maps will be integrated with satellite-derived burned-area maps to spatially depict the location and spatial distribution of pre-fire stand conditions and fire intensity, perhaps using remotely sensed estimates of burn severity. These spatial datasets, if integrated with BORFIRE, would provide the basis for more accurate accounting of the magnitude of, and spatial variability in, fuel consumption that typically occurs within boreal fires.

Initial application of this procedure for estimating carbon emissions using the Montreal Lake fire indicated that accurate mapping of daily fire spread is important because of the cumulative effect of fuel drying on fuel consumption. For example, if a fire burns over several months during a period of continuous drying, stands burned shortly after the start date will have less forest floor fuel consumption than stands burned near the end date. Although day-to-day changes in forest floor fuel moisture are small, daily drying effects accumulate, and significant drying can occur during a full week. Daily fire spread can be mapped using satellite-detected hot spots, but there are a few technical challenges. For instance, fires burning under cloud, smoke cover, or forest canopy cannot be detected. Similarly, small areas of flaming combustion and low-intensity fire are unlikely to be detected. Mapping fire growth also requires interpretation between available observations because fires do not spread at a constant rate. Fires often smoulder or spread very slowly for 1 or more days, then surge forward during mid-afternoon for a few hours in response to increased drying and wind events. If a fire flares up between satellite passes, hot spots are not captured and fire spread for that day is not documented. Using multiple sources of hot spot data can minimise this problem. Resolution of hot spot data can be an issue because AVHRR and MODIS imagery has a pixel size of 1 km^2 at nadir, and much coarser resolution at the edges of the swath. A hot spot means that fire is burning somewhere within the pixel, but it is impossible to tell exactly where. The uncertainty of fire location is increased by the difficulty in accurately georectifying coarse-resolution imagery. Depending on the position of the pixel in the swath, the hot spot location (taken as the centre of the pixel) may be up to 2 km away from the actual burning area, although it usually is within 1 km.

Despite these challenges, hot spot data can be used to map fire spread at the level of accuracy needed for this application. This is clearly illustrated in Fig. 6, which indicates the difference in spread of the 2003 Okanagan Lake fire in south-central British Columbia when mapped by interpolated hot spots and by daily aerial reconnaissance using digital thermal infrared imagery from the Airborne Wildfire Intelligence System (further information at www.awis.ca, accessed 20 September 2007) and helicopter with GPS. The fire burned more than 25 000 ha during a 23-day period, and fire spread was interpolated using 502 AVHRR and MODIS hot spot observations. Fig. 6 shows that 80% of the total fire area was correctly interpolated to within 1 day, 90% of the fire area was correct to within 2 days, and 95% was correct to within 3 days. Various interpolation methods were tested (nearest neighbour, inverse distance weighting, spline, linear kriging, universal kriging), but the resulting differences in total fuel consumption of the entire fire were extremely small ($<0.4\%$). This test case demonstrated that it is possible to map daily fire spread for large, long-burning fires with sufficient accuracy to account for the effect of cumulative drying on fuels and subsequent fuel consumption and carbon emissions.

Since the Montreal Lake fire pilot study, a modified version of the BORFIRE method of estimating wildland fire carbon emissions has been operationally applied at the national scale using CWFIS-derived data for Canada-wide reporting under NFCMARS. Initial application was completed for the 2004 fire season, and the procedure is now being used annually in Canada. National application required modification of the procedures used for the Montreal Lake fire because of the scale and databases involved. The methodology used for national inventory reporting under NFCMARS will be reported in a subsequent paper.

Conclusions

Accurate estimation of carbon emissions from large fires requires pre-fire fuel data and fire weather data for the entire burn period. All data must be spatially explicit, and, in the case of fire weather data, daily information is required. Hot spot data can be used to map fire growth, to ensure that correct daily burning conditions are used for each forest stand burned. Carbon emission estimates are sensitive to pre-fire fuel loads, so the methods used to establish initial fuel conditions should be tested and verified for the area of study. Fuel-type mapping is also important for ensuring reliable estimates of carbon emissions, because it influences the selection of stand data from forest inventory databases, as well as the growth and yield model used to establish pre-fire fuel conditions. If these potential sources of error are minimised, it is possible to capture the wide variation in carbon emissions rate within a fire and to more accurately estimate total direct carbon emissions from wildland fires. It appears that the biggest challenge to applying this methodology within an operational national framework will be to acquire and annually update the necessary fuel type, fuel load, and burn area databases, at the appropriate spatial and temporal resolution.

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