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A comparison of Canadian and Russian boreal forest fire regimes ☆

William J. de Groot [a,*], Alan S. Cantin [a], Michael D. Flannigan [b], Amber J. Soja [c], Lynn M. Gowman [a], Alison Newbery [a]

[a] Canadian Forest Service, Natural Resources Canada, 1219 Queen St. East, Sault Ste. Marie, ON, Canada P6A 2E5
[b] University of Alberta, Dept. of Renewable Resources, 713A General Services Building, Edmonton, AB, Canada T6G 2H1
[c] National Institute of Aerospace, NASA Langley Research Center, Climate Science and Chemistry and Dynamics Branches, 21 Langley Boulevard, Mail Stop 420, Hampton, VA 23681-2199, United States

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ABSTRACT

Boreal forest dynamics are largely driven by disturbance, and fire is a prevalent force of change across the boreal circumpolar region. North American and Eurasian boreal fire regimes are known to be very different but there are few quantitative comparison studies. Russian and Canadian boreal fire regimes are compared using fire weather, fire statistics, fire behaviour, and C emissions data from two large study areas. Fuel consumption, head fire intensity, and C emissions were modelled using fire weather data, fuels data and burned area polygons for all large (200+ ha) fires that occurred in the study areas during 2001–2007. Fire behaviour and C emissions of each large fire were simulated with the Canadian Fire Effects Model (CanFIRE) using fuel type and fuel load data of the burned areas, and Canadian Forest Fire Weather Index System parameters, as interpolated to the fire from the weather station network on the average active fire date. In the Russian study area located in central Siberia, there was an annual average of 1441.9 large fires per 100 M ha of forest land that burned 1.89 M ha (average large fire size = 1312 ha, mean fire return interval = 52.9 years) with an average fire intensity of 4858 kW m^{-1}. In the western Canada study area, there was an annual average of 93.7 large fires per 100 M ha of forest land that burned 0.56 M ha of forest (average large fire size = 5930 ha, mean fire return interval = 179.9 years) with an average fire intensity of 6047 kW m^{-1}. The 2001–2007 fire size distribution and annual area burned in the Canadian study area were very similar to 1970–2009 statistics, although large fire frequency was higher and average large fire size was smaller. Similar long-term fire statistics for Russia currently do not exist for comparison. The C emissions rate (t ha^{-1} of burned area) was 53% higher in the Canadian study area due to higher pre-burn forest floor fuel loads and higher fuel consumption by crown fires. However, the Russian study area had much higher total C emissions (per 100 M ha of forest area) because of greater annual area burned. The Russian C emissions estimate in this study is likely conservative due to low forest floor fuel load estimates in available datasets. Fire regime differences are discussed in terms of fuel, weather, and fire ecology.

1. Introduction

The boreal forest covers about 1.3 B ha of northern circumpolar land (FAO, 2001) representing the largest forest biome and one third of global forest cover. Wildland fire is a prevalent natural disturbance across the boreal forest region (Wein and MacLean, 1983; Goldammer and Furyaev, 1996). Although fire statistics for northern Asia are unsure, it is estimated that 5–20 M ha of the boreal forest is burned every year (Conard and Ivanova, 1999; French et al., 2000; Kasischke and Bruhwiler, 2003; Stocks et al., 2003; Zhang et al., 2003; Sukhinin et al., 2004). The boreal region stores about 800 Pg C (Apps et al., 1993), or one-third of all terrestrial C due to its vast size and extensive peatlands. Boreal wildland fire emits an annual average of 182 Tg C, about 9.1% of global fire emissions (van der Werf et al., 2010). Fire also has an important role as a process driving physical and ecological dynamics that are critical in maintaining boreal ecosystems (Weber and Flannigan, 1997; Ryan, 2002).

Over 70% of the boreal forest is in Eurasia, and the remainder in North America. The northern circumpolar limit is defined by the July 13 °C isotherm, and the southern boundary by the July 18 °C isotherm (Kuusela, 1990). The boreal forest is characterized by relatively few tree genera commonly found across the entire region (primarily *Abies*, *Betula*, *Larix*, *Picea*, *Pinus*, and *Populus*) although tree species are different between Eurasia and North America. This distinct continental separation in forest species composition is matched by the marked difference in continental fire regimes.

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* Corresponding author. Tel.: +1 705 541 5538; fax: +1 705 541 5700.
E-mail address: bill.degroot@nrcan.gc.ca (W.J. de Groot).

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The historical fire record in Russia is poorly documented, but all literature suggests that most fire in Russia occurs as surface fire (e.g., ~77% by area burned; Korovin, 1996) which is usually of low to moderate intensity. In Canada, most fire occurs as high intensity crown fire (Stocks et al., 2004).

The connection between plant species and fire regime is well-known (Heinselman, 1981; Malanson, 1987). Vegetation is fuel, which affects flammability (Mutch, 1970) and fire behaviour through fuel consumption. Each species also has unique physical and ecological characteristics (Gill, 1981; Trabaud, 1987) or plant vital attributes (Noble and Slatyer, 1980) that determine how it survives in an environment of recurrent fire disturbance. Boreal plant species have various strategies for surviving periodic fire (Rowe, 1983) but it is not known why there is such strong continental divergence in tree species and fire regimes. Whether boreal tree species adapted to the local fire regime, or if boreal fire regime is dictated by local tree species as fuel (e.g., through morphological and physiological characteristics over its life cycle) is unclear.

Fire regimes are usually described by fire frequency, fire intensity, fire severity, season of burn, type of fire, and spatial pattern (size, shape) to provide a general summary of the history of fire events over large areas and long timeframes (Gill and Allan, 2008). Fire events are generally summarized in terms of size, burning period (dates or season) and fire behaviour characteristics, which are descriptors of stand-level fire activity. Fire behaviour parameters typically include components of Byram's (1959) fire intensity model (rate of fire spread, fuel consumption, and fire intensity) and the type of fire (ground, surface, or crown fire). Fire regime contains all of these fire behaviour parameters, either directly (fire intensity, fire severity/fuel consumption, type of fire) or indirectly in time (fire frequency, seasonality) and space (fire size, pattern) (Table 1). In other words, fire regime is a historical summary of the timing and extent of fire behaviour accumulated on a landscape over many years by many fires. The connection between fire behaviour (small scale) and fire regimes (large scale) is important because it can be used to scale-up stand-level fire behaviour models to serve as fire regime models (e.g., de Groot et al., 2003). In this way, the history of fire events and associated fire behaviour are used to assess fire regime.

The purpose of this study is to compare fire regimes of boreal Eurasia and North America using two study areas in Canada and Russia. The null hypothesis is that there is no difference in fire frequency (annual number of fires per forested area), mean fire return interval (MFRI, area burned per forested area), average fire intensity ($kW\,m^{-1}$), seasonal trend (monthly fire frequency and area burned), fire severity (fuel consumption, $kg\,m^{-2}$; and resulting C emissions rate, $t\,ha^{-1}$), type of fire (crown or surface) and average fire size. The literature suggests that the North American boreal region has substantially more crown fire. If this is correct, there should also be greater average fire intensity in North America. The existing literature on Russian fire statistics and fire behaviour is weak, so comparisons of fire frequency, MFRI, season of burn, fire severity and fire size are unprecedented.

Table 1
Comparison of typical fire behavior and corresponding fire regime characteristics (after Byram, 1959; Gill and Allan, 2008).

Fire behaviour		Fire regime	
Characteristic	Descriptor	Characteristic	Descriptor
Fire intensity	$kW\,m^{-1}$	Fire intensity	Low, moderate, high
Fuel consumption	$kg\,m^{-2}$	Fire severity	Low, moderate, high
Fire type	Ground, surface or crown (passive or active)[a]	Type of fire	Surface or crown
Rate of fire spread	$m\,min^{-1}$	Fire size	General size classes
		Season of burn	Spring, summer, autumn
		Fire frequency	Infrequent, moderate frequency, frequent

[a] Van Wagner (1977).

2. Methods

Current boreal fire regimes were assessed by comparing fire statistics, fire weather conditions, and modeled fire behaviour and C emissions between study areas in Canada and Russia. Study areas were selected using ecological and geo-political boundaries to represent large contiguous forest with known history of significant fire activity. The study areas were used to provide a large representative sample of fire weather, and of boreal fires with which to compare fire behaviour and C emissions. One study area was identified in western Canada that was comprised of boreal forest in the provinces of Alberta, Saskatchewan, Manitoba and the Northwest Territories (Fig. 1). This 234.36 M ha area contained 156.66 M ha of forest area (natural vegetation only; non-fuel and agricultural area removed). The study area was represented by the Boreal Plains, Boreal Shield, Taiga Plains, and Taiga Shield ecozones of Canada, with small portions of the Hudson Plains and Taiga Cordillera (Ecological Stratification Working Group, 1995). The study area is bounded to the north by the arctic tundra, and to the south by the Prairie grasslands. The Russian study area was located in central Siberia (Fig. 2). The boundaries (50–65°N, 90–125°E) were selected to have similar ecozonal range as the Canadian study area. The Russian study area was 327.55 M ha (forest area = 299.64 M ha) and was represented by nine ecozones (Alexeyev and Birdsey, 1998): montane subarid territories, montane subboreal territories, forest-steppe (broad-leaved deciduous forests), southern taiga, montane boreal territories, middle taiga, northern taiga, montane territories of the sub-arctic, and forest-tundra and sparse sub-arctic forests. The Russian study area contained 28 ecoregions and 11 primary administrative units (oblasts).

Five datasets were acquired for each study area: fuel type (or forest cover), fuel load (biomass), fire weather, satellite-detected active fires (hot spots) and area burned polygons. The fuel type and fuel load data were obtained from national sources, so there are differences in spatial characterization and data resolution. The area burned polygons were obtained from nationally-compiled databases that were developed from different remotely sensed global datasets. The Moderate Resolution Imaging Spectroradiometer (MODIS) provided all active fire data for both study areas.

For the Russian study area, fuel load and fuel type data were obtained using non-spatial forest C and tree species data from Alexeyev and Birdsey (1998). Seven fuel types were classified in the Russian study area based on the major species or genera in the forest composition data: *Pinus sylvestris* L., *Pinus sibirica* Du Tour, *Populus tremula* L., *Larix* spp. (*L. sibirica* Ledeb. and *L. gmelinii* (Rupr.) Litv.), *Betula* spp. (*B. pendula* Roth. and *B. pubescens* Ehrh.), *Picea* spp. (primarily *P. obovata* Ledeb.), and *Abies* spp. (primarily *A. sibirica* Ledeb.). The study area had minor components of shrub types (1.8% of total fuels), *Quercus mongolica* Fisch. Ex Ledeb. (0.3% of total fuels) and pasture (0.4% of total area), so these fuels were not included in the analyses. Forest litter C data were available by ecoregion and were used to provide fuel load values for organic forest floor material by ecoregion. All C data used in this study was converted to fuel load using a fuel:carbon conversion factor of 2. Other forest C data were available for most oblasts, which were converted to average ecoregion values using an oblast area-weighted

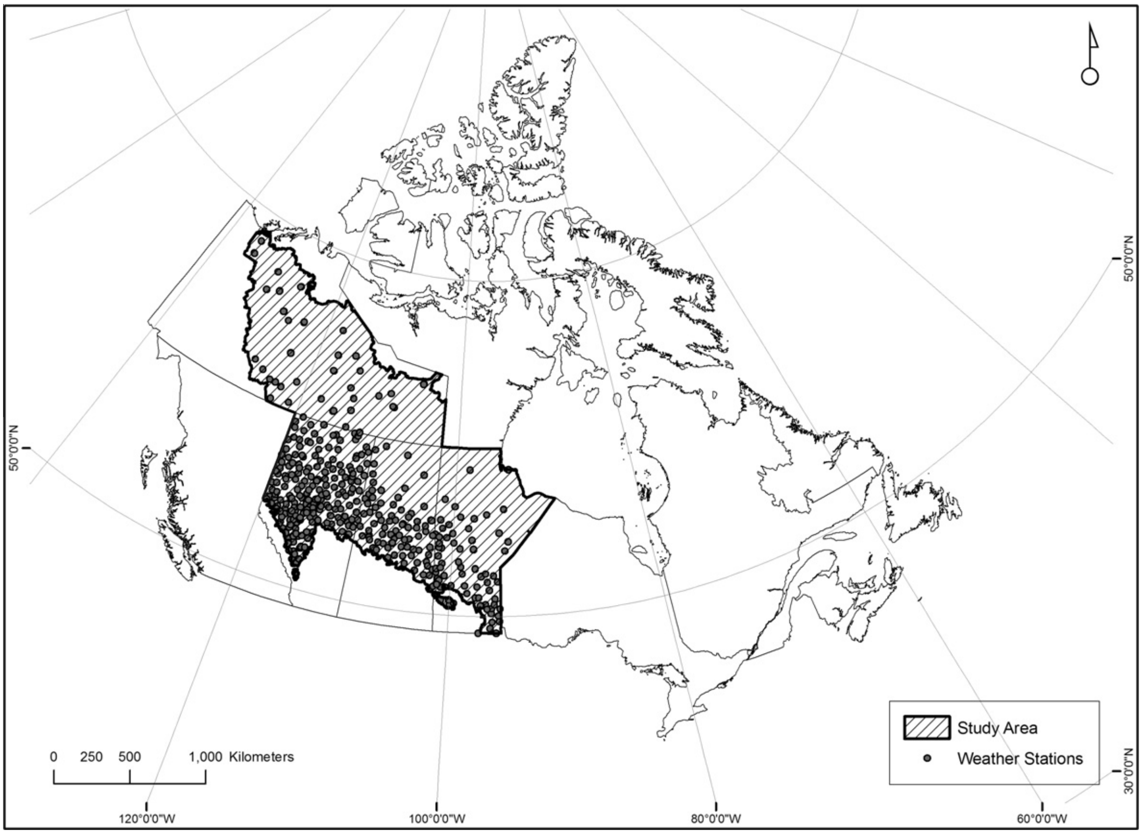


Fig. 1. Location of Canadian study area and weather stations.

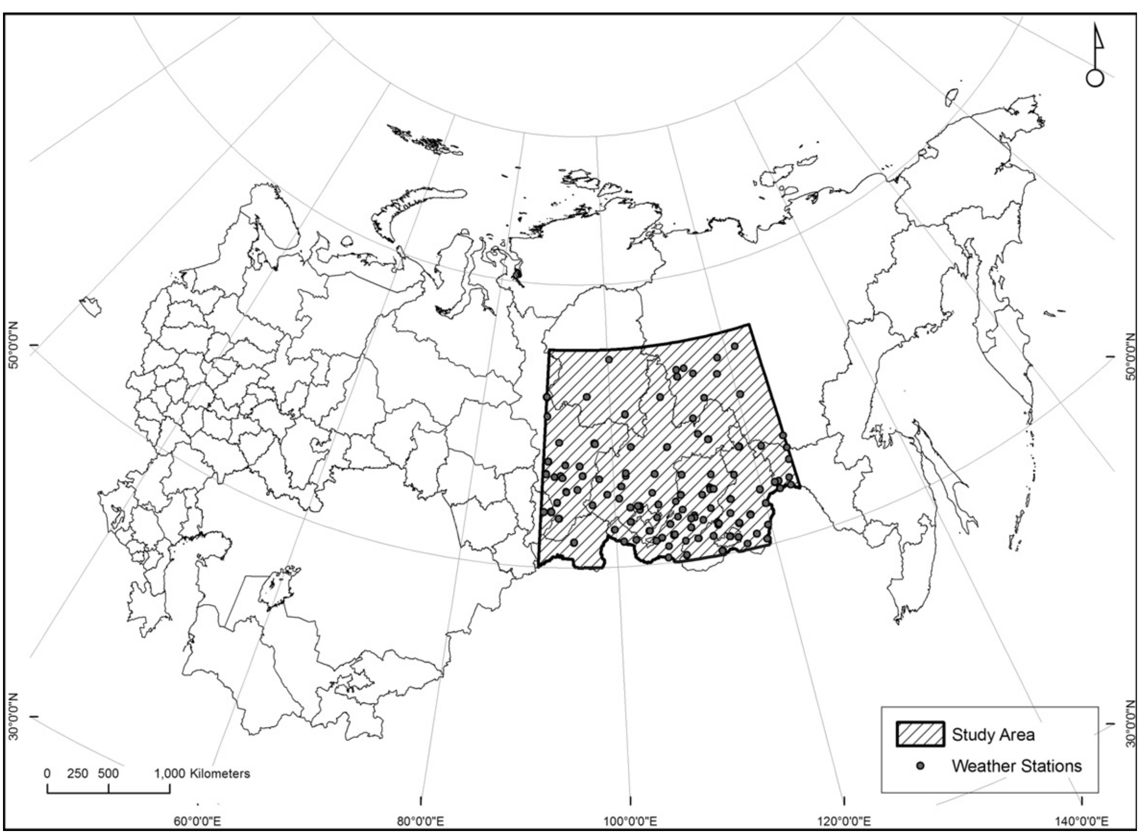


Fig. 2. Location of Russian study area and weather stations.

Table 2
Fuel loads and area of representation in the Russian study area.

Ecoregion (forest province/Taiga district)	Area (ha × 1000)	Aboveground tree fuel load (kg m^{-2})								Coarse woody debris fuel load (kg m^{-2})	Forest floor fuel load (kg m^{-2})
		Abies spp.	*Betula* spp.	*Larix* spp.	*Picea* spp.	*Pinus sibirica*	*Pinus sylvestris*	*Populus tremula*	Stand total		
Aldan	4877	0.001	0.023	2.986	0.015	0.017	0.308	0.005	3.355	0.79	2.6
Angara–Tunguska/Angara southern	20,818	0.306	0.646	2.676	0.408	1.175	2.003	0.177	7.392	0.77	3.4
Angara–Tunguska/Lower Tunguska northern	30,011	0.195	0.392	2.774	0.251	0.644	1.137	0.099	5.491	1.85	2.2
Angara–Tunguska/Stony Tunguska middle	25,817	0.260	0.561	2.740	0.355	1.036	1.816	0.155	6.922	1.05	3.2
Baikal–Stanovoi	19,073	0.039	0.405	3.371	0.035	0.446	0.767	0.061	5.124	0.39	3.6
Chikoi-Ingodin	21,632	0.011	0.447	3.524	0.009	0.373	0.643	0.040	5.045	0.18	3.8
Dahurain	8858	0.000	0.479	3.593	0.004	0.328	0.573	0.033	5.010	1.39	2.6
Eastern Sayan	14,313	0.208	0.557	2.731	0.331	1.054	1.580	0.147	6.606	1.4	3
Eastern Tuva	5798	0.004	0.191	3.815	0.044	2.043	0.120	0.021	6.237	0.62	2.8
Jidin	3435	0.082	0.233	3.054	0.041	0.674	1.112	0.090	5.286	1.53	2.4
Kansk–Kransoyarsk–Biryusa (forest-steppe)	8873	0.352	0.667	2.600	0.426	1.049	1.617	0.163	6.875	1.81	2.8
Khakass-Minusinsk	5778	0.447	0.710	2.448	0.463	0.793	0.835	0.135	5.831	2.61	2.4
Khetsk-Kotui-Olenek (forest-tundra)	3164	0.001	0.023	2.986	0.015	0.017	0.308	0.005	3.355	1.04	5
Lena–Vilyui	40,486	0.011	0.046	2.976	0.030	0.070	0.395	0.013	3.542	0.62	2.8
Near-Baikal	12,082	0.114	0.310	2.999	0.110	0.806	1.390	0.111	5.840	1.58	2.4
Near-Enisey	19,075	0.447	0.710	2.448	0.463	0.793	0.835	0.135	5.831	1.81	3.2
Northern Altai-Sayan	8912	0.207	0.427	3.183	0.235	1.459	0.452	0.073	6.036	0.75	3.4
Putoran	3174	0.001	0.023	2.986	0.015	0.017	0.308	0.005	3.355	0.37	3.8
Salair-Kuznetsk	518	0.049	0.399	3.272	0.210	1.545	0.379	0.493	6.347	1.18	2.4
Selenga	4396	0.080	0.235	3.062	0.041	0.667	1.102	0.089	5.275	1.91	2.4
Southern Altai–Tuva	4576	0.005	0.191	3.812	0.044	2.042	0.120	0.021	6.235	1.42	2
TransUrals-Enisey/Middle	1051	0.447	0.710	2.448	0.463	0.793	0.835	0.135	5.831	1.81	3.2
TransUrals-Enisey/Southern	5370	0.447	0.710	2.448	0.463	0.793	0.835	0.135	5.831	1.81	3.2
TransUrals-Enisey/sub taiga	938	0.447	0.710	2.448	0.463	0.793	0.835	0.135	5.831	1.81	3.2
Upper Angara	6192	0.246	0.619	2.772	0.385	1.338	2.498	0.195	8.053	1.37	2.8
Upper Lena	12,527	0.238	0.600	2.787	0.368	1.304	2.430	0.190	7.917	0.98	3.2
Vitim–Olekma Tableland	32,009	0.001	0.023	2.986	0.015	0.017	0.308	0.005	3.355	0.79	2.6
Zeya-Uda	3801	0.306	0.646	2.676	0.408	1.175	2.003	0.177	7.392	0.77	3.4
Total	327,554										

basis within each ecoregion. Carbon data was not available for four oblasts (Agin-Buryat Okrug, Evenk Autonomous Okrug, Khakass Republic, and Ust-Orda Buryat Okrug) so data from the largest neighbouring oblast was used. Total tree C was summarized by fuel type using an average of the five available age classes (early regeneration, late regeneration, middle, maturing and mature/overmature) for stocked stands within oblasts, and then calculated by ecoregion. Aboveground tree C was calculated by reducing total tree C values by the average root C: total tree C density (20%). Dead woody debris fuel load was calculated for each ecoregion by subtracting ecoregion litter C from the ecoregion total dead C values (mortmass C in Alexeyev and Birdsey, 1998) and converted to fuel load. By this method, the Russian fuel database contained average litter and coarse woody debris fuel load by ecoregion, and average tree fuel load and average stand composition by ecoregion (Table 2) as weighted by the average area of the seven fuel types within oblasts. For the purpose of fire behaviour simulations in this study, average tree heights of the Russian fuel types were determined from the literature (Nikolov and Helmisaari, 1992; Sullivan, 1993, 1994; Richardson, 1998; Scherer-Lorenzen et al., 2005; Myking et al., 2011) (Table 3). Live crown base height for each species was calculated using tree height and a standard crown length factor of 0.8 for *Picea* and *Abies* spp., and 0.4 for *Pinus* spp., *Betula* spp., *Larix* spp. and *P. tremula* (cf. Keane et al., 1989).

The Canadian study area used the fuel type classification scheme of the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992). The following seven fuel types are found in the Canadian study area: Spruce–Lichen Woodland (C-1), Boreal Spruce (C-2), Mature Jack or Lodgepole Pine (C-3), Immature Jack or Lodgepole Pine (C-4), Deciduous (D-1, leafless condition), Mixedwood (M-1, leafless condition), and O-1b (standing grass; assumed fully cured in this study). The M-1 fuel type was assumed to have equal composition of *Picea glauca* (Moench) Voss and *Populus tremuloides* Michx. The national fuel type database of Nadeau et al. (2005) provided spatial fuel type distribution at 1 km resolution (fuel types, corresponding species and area are summarized in Table 4). Although other databases were available (e.g., provincial and territorial forest inventories), this database was selected because it used a uniform fuels classification across the entire study area and provided complete coverage including boreal forest area beyond the commercial forest management zone. All fuels data related to C-1 were summarized from Alexander et al. (1991). For all other fuel types, tree fuel loads were determined using the Alberta Phase III Forest Inventory (Anon, 1985) algorithms for 75-year old fully stocked stands for *Picea mariana* (Mill.) BSP (C-2), *Pinus banksiana* Lamb. (C-3), *P. tremuloides* (D-1 and M-1), and *P. glauca* (M-1). Tree data for the C-4 fuel type was similarly determined using 25-year old *P. banksiana*. Forest floor fuel loads were obtained from Letang and de Groot (2012) and dead woody debris fuel loads were from national unpublished data (on file).

The time period of this study was determined by the availability of MODIS active fire data and area burned polygon data. The first year of complete active fire data during the entire fire season

Table 3
Vegetation, proportion of study area, canopy characteristics, and Canadian Forest Fire Behavior Prediction System fire rate of spread (ROS) model used to calculate fire behaviour in the Canadian and Russian study areas.

	Proportion[a] of fuels within study area (%)	Foliage characteristics	Tree height (m)	Live crown base height (m)	ROS model[b]
Canadian study area					
Picea mariana-Spruce Lichen Woodland	11.6	Evergreen needle	4.7	0.9	C-1
Picea mariana-Boreal Spruce	41.4	Evergreen needle	11.5	2.3	C-2
Pinus banksiana	6.2	Evergreen needle	16.8	10.1	C-3
Pinus banksiana	3.9	Evergreen needle	7.9	4.7	C-4
Populus tremuloides	22.5	Deciduous broadleaf	19.7	11.8	D-1
Populus tremuloides/*Picea glauca*	6.6	Deciduous broadleaf and evergreen needle	19.7/15.9	11.8/3.2	M-1
Grass	7.9	NA	NA	NA	O-1b
Russian study area					
Abies spp.	2.0	Evergreen needle	24	4.8	C-2
Betula spp.	7.9	Deciduous broadleaf	21	12.6	D-1
Larix spp.	56.0	Deciduous needle	26	15.6	D-1
Picea spp.	2.8	Evergreen needle	34	6.8	C-2
Pinus sibirica	13.4	Evergreen needle	23	13.8	C-3
Pinus sylvestris	14.4	Evergreen needle	23	13.8	C-3
Populus tremula	1.4	Deciduous broadleaf	30	18	D-1

[a] Proportion of fuels calculated by fuel type area in the Canadian study area, and by fuel type load in the Russian study area (area by species data not available).
[b] C-1, Spruce–Lichen Woodland; C-2, Boreal Spruce; C-3, Mature Jack or Lodgepole Pine; C-4, Immature Jack or Lodgepole Pine; D-1, Deciduous (leafless condition); M-1, Mixedwood (leafless condition); and O-1b Grass (standing), fully cured condition for this study.

Table 4
Fuel loads and area of representation in the Canadian study area.

Fuel type	Species	Total area within study area (ha × 1000)	Aboveground tree fuel load (kg m^{-2})	Dead woody debris fuel load (kg m^{-2})	Forest floor fuel load (kg m^{-2})
C-1	*Picea mariana*	18,128	1.8	0.4	1.5
C-2	*Picea mariana*	64,798	9.7	1.3	12.3
C-3	*Pinus banksiana*	9725	13.3	1.6	4.5
C-4	*Pinus banksiana*	6091	4.1	1.6	4.5
D-1	*Populus tremuloides*	35,193	11.3	1.7	8.4
M-1	*Picea glauca*, *Populus tremuloides*	10,339	10.7	1.0	10.4
O-1	Grass	12,383	0	0	0.3
	Total	156,657			

(April–October) from both Terra and Aqua MODIS satellites was available in 2001. MODIS active fire data were obtained from the University of Maryland Fire Information for Resource Management System (Davies et al., 2009) and was used to determine the period of burning for fires in both study areas. Area burned polygons for Russia were only available up to and including 2007. Fire weather data were available for many weather stations across both study areas from March 15 to October 31 during 2001–2007 and were used to calculate codes and indices of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987).

This study used only fires that burned 200+ ha of forest land based on the burn area product, which accounts for 97% of total area burned in Canada (Stocks et al., 2003) and an estimated 50–70% of area burned in Russia (Valendik, 1996). Fire perimeters for the Canadian study area were obtained by selecting polygons in the Canadian National Fire Database (CNFDB; National Forestry Database, 2012). Since 2004, most large fires in the CNFDB have been mapped using Landsat and SPOT-VGT. A larger proportion of earlier fires in the database were mapped by helicopter-mounted GIS, aerial photogrammetry, or were hand-drawn on post-fire mapping flights. The Russian fire perimeters were obtained from AVHRR fire mapping (Sukhinin et al., 2004). In general, the Canadian fire perimeters have higher resolution than the Russian dataset.

The Canadian Fire Effects Model (CanFIRE; de Groot, 2006, 2010) was used to calculate fire behaviour and fire effects in both study areas. In the Canadian study area, the national fuel-type map was overlaid with fire perimeters to determine fuel types and fuel loads that were burned within each fire. Active fire data were used to determine burning days for each fire, and corresponding fire weather data. Daily FWI System values were calculated for every hot spot by interpolating (thin plate spline) fire weather data from the weather station network. Each fire was burned in a CanFIRE simulation using the average FWI System values for all hot spots that occurred within the fire perimeter. CanFIRE used fuels and fire weather data to calculate rate of fire spread, fuel consumption, head fire intensity and total C emissions for all fires individually.

Fire regimes during 2001–2007 were compared using summary statistics for FWI System components, fire numbers, area burned, fire behaviour and C emissions in the two study areas. The 2001–2007 fire regime was also compared to the recent long-term fire regime of the past four decades (1970–2009) in the Canadian study area (similar long-term data for Russia was not available). Area burned and numbers of fire data were normalized by total burnable (forest) area within each study area. All data were summarized by month and compared for seasonal trends. Total number of fires, area burned and C emissions were similarly summarized for annual comparison. MFRI was calculated using all area burned data for 2001–2007.

3. Results

FWI System calculations normally begin three days after snowmelt and end when snow covers the ground or fire danger becomes negligible in late autumn. The data collection period varied each year but complete daily fire weather records for both study areas were available for 19 April–30 October during 2001–2007. In general, the FWI System data summary statistics (not presented) indicated that fire weather conditions were slightly higher in the Canadian study area during the 7-year period of the study, although DC values were substantially higher. Daily Fine Fuel Moisture Code (FFMC) values, which indicate the moisture content of dead fine fuels and is used as a general indicator of potential for human-caused fire starts (Wotton, 2009) showed a general decreasing trend from spring to autumn with the exception of a late autumn increase in the Canadian study (Table 5). The Duff Moisture Code (DMC) represents the moisture content of the moderately deep, loosely compacted soil organic layer (upper duff, or F layer) and the Drought Code (DC) represents the moisture content of deep compact soil organic matter (deep duff, or H layer). The DMC, which is often used as an indicator of lightning fires (Wotton, 2009) showed higher late spring and mid-summer values in both study areas. The DC was consistently higher in the Canadian study area by 50–100 points throughout the entire fire season (Fig. 3). The Buildup Index (BUI) is a combination of the DMC and DC, providing a general indication of the total amount of fuel available for combustion during a fire. It is primarily influenced by the DMC, and therefore, the seasonal BUI trend in both study areas (Fig. 4) is very similar to the seasonal DMC trend. The Initial Spread Index (ISI) indicates potential rate of fire spread and is calculated using FFMC and wind speed. Average monthly ISI values were highest in the early spring in the Canadian study area and in later spring in the Russian study area. Low to moderate ISI values (e.g., <8) are not critical in relation to fire behaviour, but the high variability in some months of both study areas indicates greater frequency of high and extreme ISI values, which often represents the days when most area burned occurs. The Fire Weather Index (FWI) is a general indicator of landscape-level fire danger and fire intensity, and is calculated using ISI and BUI. FWI values decreased from spring to autumn in the Canadian study area, whereas the Russian FWI data had a similar range but peak average values occurred May to July. The Daily Severity Rating (DSR) was designed to indicate general fire control difficulty in Canadian forests, and is an exponential function of the FWI (Van Wagner, 1970, 1987). The DSR had similar range in both study areas, but followed the respective FWI trends of each study area.

There were 1028 large fires in the Canadian study area, which burned 6.10 M ha (Fig. 5a), and 30,243 large fires in the Russian study area, which burned 39.67 M ha (Fig. 5b) during 2001–2007 (Table 6a). Fire frequency and area burned data were normalized by forest area (Table 6b). During 2001–2007, there was an annual average of 93.7 and 1441.9 large fires per 100 M ha of forest, which

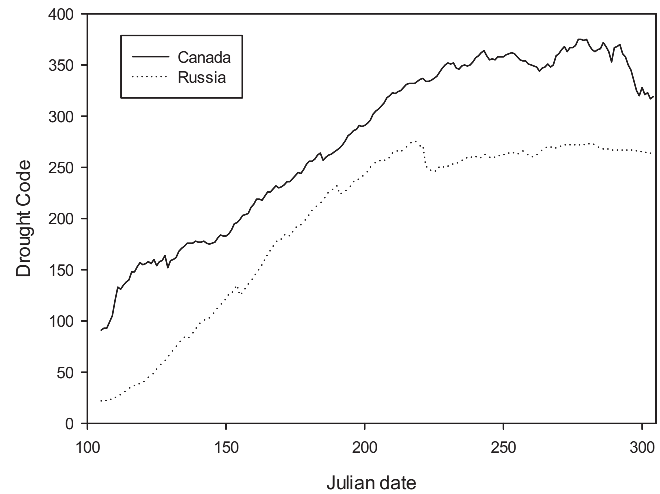


Fig. 3. Average daily DC during the fire season for 2001–2007 in the Canadian and Russian study areas.

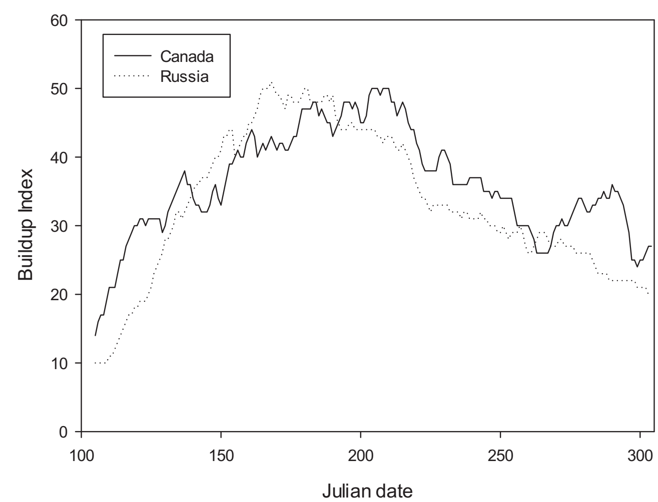
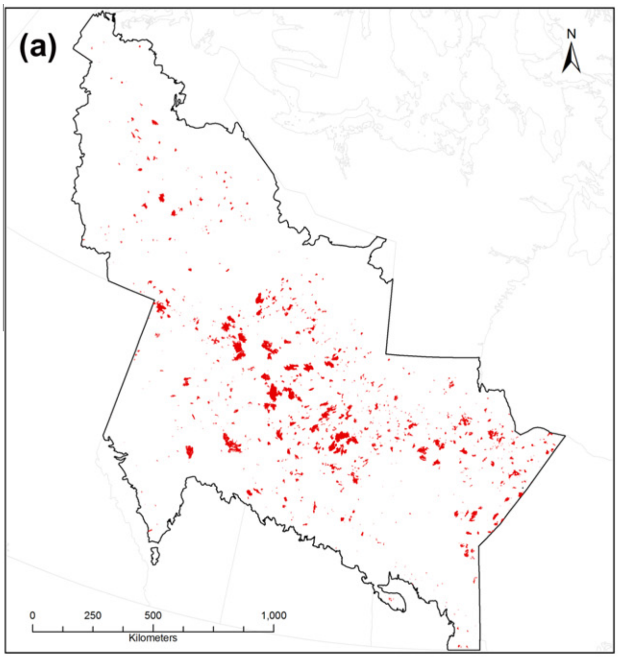


Fig. 4. Average daily BUI during the fire season for 2001–2007 in the Canadian and Russian study areas.

Table 5
Summary of Canadian Forest Fire Weather Index System data (mean, SD) for 2001–2007 in the study areas (based on April 1–October 31 data from weather stations within the study areas).

	FFMC	DMC	DC	ISI	BUI	FWI	DSR
Canadian study area							
April	83 (14)	19 (11)	141 (112)	7.8 (6.4)	26 (15)	12.2 (9.5)	3.2 (4.4)
May	76 (21)	24 (16)	172 (117)	6.0 (6.6)	33 (20)	11.3 (11.2)	3.3 (5.6)
June	76 (19)	30 (23)	226 (130)	4.7 (8.0)	42 (29)	10.8 (10.7)	3.0 (5.2)
July	77 (17)	32 (25)	288 (145)	4.3 (4.4)	47 (32)	10.5 (10.0)	2.8 (4.6)
August	72 (19)	25 (22)	343 (157)	3.3 (9.2)	40 (31)	7.8 (9.2)	1.9 (8.2)
September	70 (20)	19 (20)	356 (173)	2.8 (3.5)	31 (30)	5.9 (7.7)	1.3 (3.1)
October	74 (18)	19 (19)	361 (173)	3.3 (6.2)	32 (29)	6.8 (8.2)	1.5 (6.5)
Russian study area							
April	80 (13)	14 (12)	33 (19)	5.4 (10.2)	14 (12)	6.9 (8.3)	1.6 (4.2)
May	80 (15)	29 (23)	84 (50)	5.7 (6.7)	31 (23)	10.6 (11.0)	3.0 (6.0)
June	78 (17)	39 (34)	166 (94)	4.8 (5.0)	47 (35)	11.6 (12.0)	3.5 (6.2)
July	75 (19)	32 (31)	239 (135)	3.7 (6.1)	45 (37)	9.3 (10.8)	2.6 (7.9)
August	73 (19)	22 (22)	259 (154)	3.0 (3.3)	34 (29)	6.7 (8.2)	1.5 (3.4)
September	73 (19)	18 (18)	265 (165)	2.9 (3.4)	29 (26)	5.9 (7.5)	1.3 (2.9)
October	70 (19)	15 (18)	268 (166)	2.3 (3.2)	23 (28)	4.4 (6.6)	0.9 (2.4)



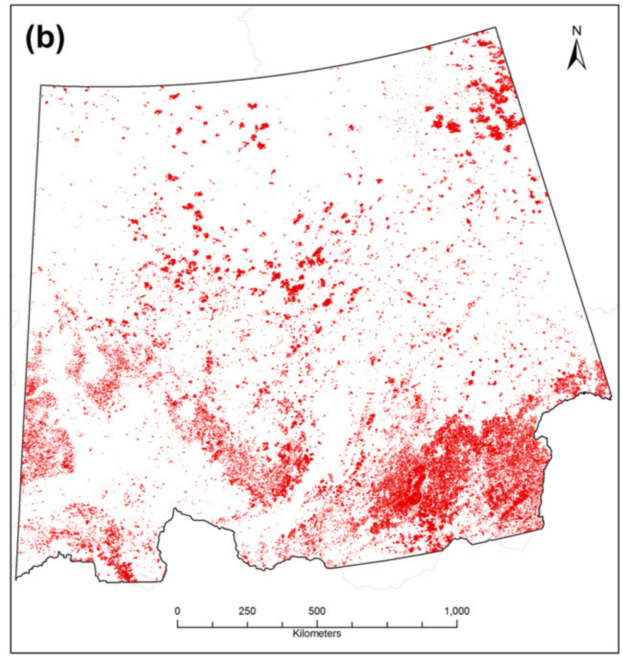


Fig. 5. Area burned in the Canadian (a) and Russian (b) study areas during 2001–2007.

Table 6
Summary of annual large (200+ ha) fire frequency and area burned (a) for the entire Canadian and Russian study areas, and (b) normalized per 100 M ha of forest area in each study area.

Year	Number of fires		Area burned (ha)	
	Total Canadian study area	Total Russian study area	Total Canadian study area	Total Russian study area
(a)				
2001	94	1513	346,766	1,420,693
2002	134	3009	1,261,254	4,968,075
2003	193	6706	1,109,618	14,093,693
2004	200	1585	904,388	1,315,519
2005	133	4901	492,195	3,759,078
2006	157	5914	947,572	7,455,900
2007	117	6615	1,034,499	6,655,575
Total	1028	30,243	6,096,293	39,668,534
	Canadian study area (100 M ha^{-1})	Russian study area (100 M ha^{-1})	Canadian study area (100 M ha^{-1})	Russian study area (100 M ha^{-1})
(b)				
2001	60.0	504.9	221,354	474,140
2002	85.5	1004.2	805,105	1,658,039
2003	123.2	2238.1	708,311	4,703,611
2004	127.7	529.0	577,305	439,040
2005	84.9	1635.7	314,186	1,254,550
2006	100.2	1973.7	604,870	2,488,322
2007	74.7	2207.7	660,359	2,221,223
Total	656.2	10093.3	3,891,491	13,238,924

burned an annual average of 0.56 M ha and 1.89 M ha per 100 M ha of forest in the Canadian and Russian study areas, respectively. This corresponds with an MFRI = 52.9 years in the Russian study area and an MFRI = 179.9 years in the Canadian study area. Large fires in the Canadian study area were distributed more towards the larger fire sizes than in the Russian study area (Fig. 6). There was an average large fire size of 5930 ha and 1312 ha in the Canadian and Russian study areas, respectively. In comparison to fire statistics of the past 4 decades for the Canadian study area, the 2001–2007 period had a slightly higher average number of large fires and area burned was slightly lower. During 1970–2009, there was an average of 74.7 large fires per year that burned 0.60 M ha per 100 M ha of forest (average large fire size = 7994 ha, MFRI = 167.4 years).

There were 122 fires (representing 87,947 ha) in the Canadian study area for which the date of burn could not be determined because there were no satellite-detected active fires within a 1-km buffer of the burn perimeter; 10,247 fires (representing 4.82 M ha) were similarly not dated in the Russian study area. Since fire weather was unknown on these fires, they were not used to calculate fire behaviour and C emissions statistics.

Most fires and area burned occurred mid-summer in the Canadian study area (Table 7). Russian fire occurrence and area burned data was bimodal with the largest peak occurring in May and a lower peak in July. Average monthly fuel consumption of forest floor and dead woody debris steadily increased during the fire season in the Canadian study area, but crown fuel consumption was more variable and showed no seasonal trend (Table 7). In the Russian study area, forest floor fuel consumption showed very little seasonal variability, but dead woody debris fuel consumption was very low in the spring and increased sharply for the remainder of the fire season with a peak in mid-summer. Crown fuel consumption was much lower in the Russian study area, with a peak in late spring and early summer. The C emissions rate steadily increased during the fire season in the Canadian study area with a late autumn decline, but varied little during the fire season in the Russian study area. The greatest total C emissions occurred in June and July in the Canadian study area, and in May and July in the Russian study area.

Modeled crown fires accounted for 57.1% of the area burned in the Canadian study area, and average fire intensity was 6047 kW m^{-1}. In the Russian study area, crown fires only accounted for 6.5% of all area burned and average fire intensity was 4858 kW m^{-1}. In the Canadian study area, the average fuel consumption rate (5.68 kg m^{-2}) and C emissions rate (28.4 t ha^{-1}) were much higher than in the Russian study area (3.73 kg m^{-2} fuel consumption, 18.5 t ha^{-1} C emissions). Based on these average rates and annual area burned in the study areas, the annual average C emissions rate (per 100 M ha of forest) in the Canadian and Russian study areas was 15.8 and 35.0 Mt C, respectively.

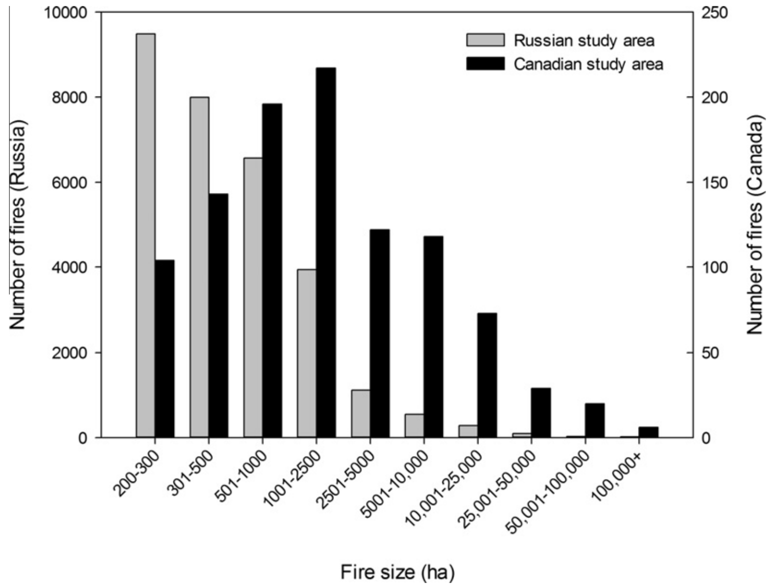


Fig. 6. Size distribution of 2001–2007 fires in the Canadian and Russian study areas.

Table 7
Average (SD) monthly fire statistics for all fires in the two study areas for 2001–2007, and fire behaviour characteristics, and carbon emissions for fires with known burning dates.

	Number of fires	Area burned (ha)	Fire behaviour				Carbon emissions rate (t ha^{-1})	Total carbon emissions (Mt)
			Forest floor fuel consumption (kg m^{-2})	Dead woody debris fuel consumption (kg m^{-2})	Crown fuel consumption (kg m^{-2})	Fire intensity (kW m^{-1})		
Canadian study area								
March	0	0	NA	NA	NA	NA	NA	NA
April	1	2,202	1.20	0.24	0.81	5,438	11.3	0.021
	(1)	(3,066)	(0.52)	(0.09)	(1.83)	(12,605)	(11.1)	(0.003)
May	6	63,323	2.14	0.34	1.78	12,542	21.3	1.669
	(5)	(110,992)	(0.68)	(0.08)	(1.96)	(19,284)	(12.0)	(0.135)
June	32	312,501	3.19	0.41	1.84	8,053	27.2	9.473
	(16)	(286,500)	(1.39)	(0.16)	(1.62)	(9,959)	(13.9)	(0.100)
July	69	338,646	3.80	0.54	1.31	4,447	28.2	10.768
	(41)	(215,282)	(1.67)	(0.18)	(1.34)	(6,608)	(12.8)	(0.054)
August	19	129,118	4.36	0.62	1.54	6,390	32.6	4.286
	(24)	(199,643)	(1.99)	(0.24)	(1.44)	(9,106)	(14.7)	(0.071)
September	2	11,560	6.13	0.86	1.53	6,361	42.6	0.452
	(3)	(23,068)	(1.30)	(0.16)	(1.64)	(8,539)	(12.2)	(0.046)
October	0.1	986	5.63	0.91	0.00	272	32.7	0.032
	(0.4)	(2,610)	(0.00)	(0.00)	(0.00)	(0)	(0.0)	(0.000)
Unknown	17	12,564						
	(9)	(10,732)						
Russian study area								
March	67	51,801	3.26	0.11	0.00	359	16.8	0.874
	(107)	(84,785)	(0.61)	(0.14)	(0.00)	(582)	(2.4)	(1.476)
April	604	628,972	3.01	0.27	0.07	4210	16.7	10.655
	(576)	(621,680)	(0.59)	(0.17)	(0.22)	(6478)	(2.6)	(10.708)
May	1113	1,961,488	3.03	0.44	0.21	8209	18.4	37.001
	(910)	(3,177,555)	(0.50)	(0.16)	(0.38)	(9869)	(2.7)	(60.076)
June	236	378,146	3.18	0.57	0.18	8113	19.7	7.569
	(308)	(618,161)	(0.49)	(0.24)	(0.30)	(8374)	(2.4)	(12.520)
July	379	1,024,468	3.13	0.74	0.10	5514	19.8	20.058
	(312)	(1,146,086)	(0.45)	(0.28)	(0.21)	(5169)	(2.2)	(23.522)
August	189	495,703	3.21	0.68	0.05	4866	19.7	9.293
	(138)	(675,915)	(0.50)	(0.33)	(0.09)	(4906)	(1.9)	(12.053)
September	190	304,564	3.15	0.66	0.03	3733	19.2	5.919
	(178)	(355,630)	(0.53)	(0.36)	(0.07)	(3915)	(1.6)	(7.089)
October	77	132,597	3.19	0.61	0.02	3863	19.1	2.461
	(92)	(181,137)	(0.57)	(0.38)	(0.10)	(5169)	(1.7)	(3.421)
Unknown	1464	689,196						
	(747)	(410,504)						

4. Discussion

The boreal fire regimes of central Siberia and western Canada are distinctly different. During 2001–2007, the Canadian study area was characterized by higher long-term dryness as represented by consistently higher DC values during the entire fire season. Canadian DC values were much higher at the start of most fire seasons because it was adjusted for low overwinter precipitation (Lawson and Armitage, 2008), whereas this was not done in the Russian study area because winter precipitation data was not available. It is likely that the spring DC values in Russia were artificially low because of this, but to what degree is unknown. However, the effect of overwinter drought declines exponentially with time. In the case of the DC, the drought effect would be 36.8% remaining after a standard weather timelag of 52 days (Van Wagner, 1987), although the time period to self-correct is much shorter when there are significant rainfall events. Therefore, the higher DC values ($\sim$100 points) in the Canadian study area during August to October, which is usually the period of highest DC values during the fire season, can be considered representative. Higher DC values substantially increase fuel consumption and C emissions. Regarding the other fire weather indicators, the Canadian study area had slightly higher FWI System values overall indicating slightly more severe fire weather. In terms of fire behaviour, the highest FWI System values are most important, so standard deviation in combination with mean is a better indicator of fire weather severity than the means alone, which are generally low to moderate. Both study areas have weather conditions that can periodically support high to extreme fire behaviour, but this occurs most frequently in April and May in the Canadian study area and a little later (May and June) in the Russian study area, as indicated by the FWI and DSR values.

The Russian study area had a number of large fires in March but there were none in the Canadian study area, suggesting there may be an earlier start to the Russian fire season. Most large fires occurred during spring in the Russian study area, and during summer in the Canadian study area. Shvidenko and Nilsson (2000) indicated that 86% of Russian fires are human-caused, which is consistent with the spring-dominated fire season found in this study. Human-caused fires typically occur in spring (and sometimes autumn) when there are extensive areas of dead light surface fuels (e.g., cured grass, leaf litter) available for combustion before understory plants green-up and trees leaf-out. Lightning fires occur most frequently during the summer months and are responsible for 80% of the area burned by large fires in Canada (Stocks et al., 2003), which corresponds with the majority of area burned in this study. Large fires occur most frequently in northern Canada where fires in these remote areas are usually started by lightning, and direct suppression action is limited (or not taken) because there are few values at risk. There are many human-caused fires in southern areas

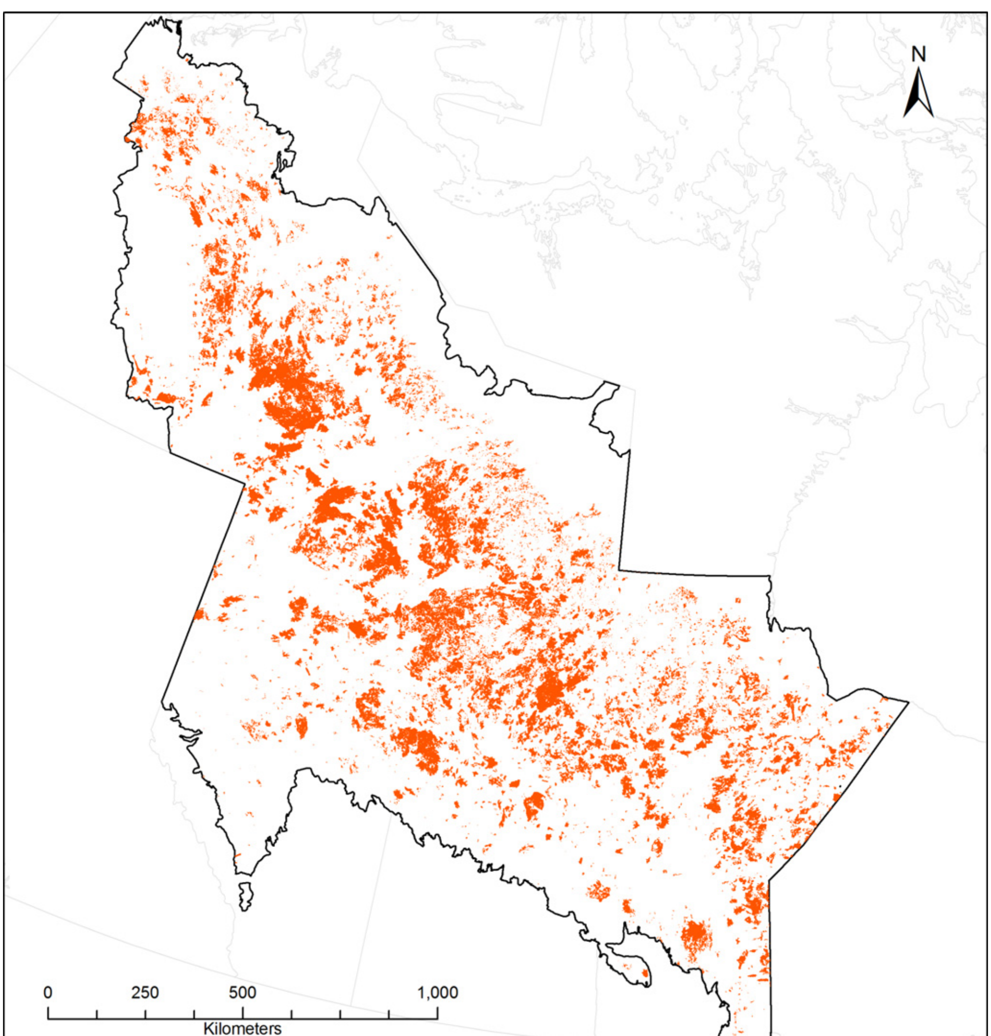


Fig. 7. Area burned in the Canadian study area during 1970–2009.

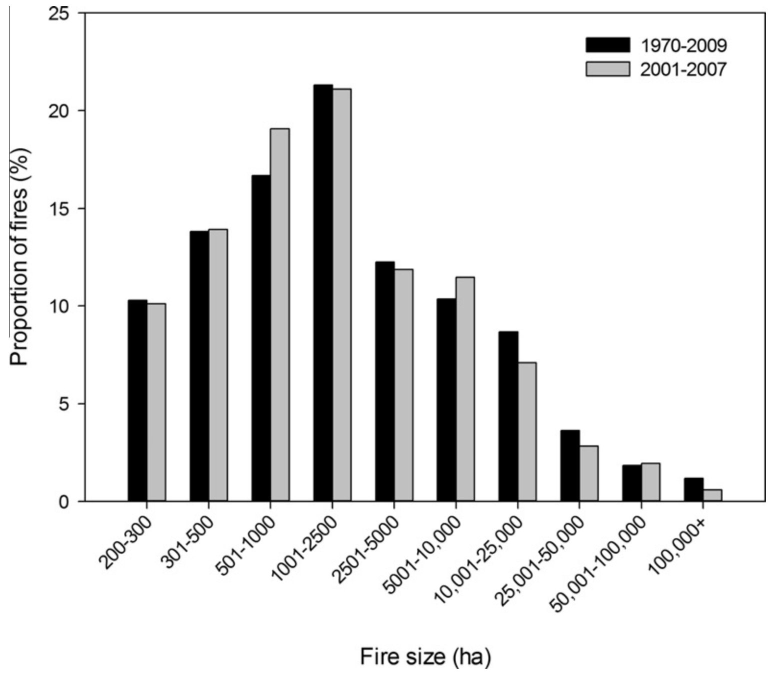


Fig. 8. Comparison of fire size distributions in the Canadian study area during 2001–2007 and 1970–2009.

of Canada in the spring and autumn (Stocks et al., 2003) but few of these fires become large because they are usually easily accessible for rapid initial attack.

The fire frequency and area burned was vastly different between the two study areas. The Russian study area had many more large fires and a greater amount of area burned. However, Canadian fires were larger in average size. Canadian fires also had higher average intensities and fuel consumption rates. The latter resulted in higher C emission rates (t ha^{-1} of burned area) in the Canadian study area, but the Russian study area produced over twice as much total annual C emissions over the same amount of forest area because of the higher rate of annual area burned. Total C emissions were closely aligned with area burned in both study areas, and followed seasonal area burned trends. As previously mentioned, the early season DC values for Russia are likely low because they were not adjusted for overwinter precipitation deficit. Because most area burned in the Russian study area occurred during the first half of the fire season, the net effect of low spring DC estimates would be a slightly low C emissions estimate for the Russian study area. If the spring and early summer DC values in Russia were higher, the values would still be in the low to moderate range, which would not dramatically increase the C emissions rate. The relatively low MFRI in the Russian study area (52.9 years) corresponds well with previous estimates (others cited in Sannikov and Goldammer, 1996; Shvidenko and Nilsson, 2000). The very long MFRI of 179.9 years during 2001–2007 in the Canadian study area was slightly longer than the long-term (1970–2009) record of 167.4 years for western boreal Canada.[1] The 2001–2007 fires were widely-distributed across the study area (Fig. 5a), similar to the historical pattern (Fig. 7). The fire size distribution from this study was also very similar to the long-term statistics (Fig. 8). However, there was a greater annual fire frequency during 2001–2007 with 93.7 large fires per 100 M ha of forest (74.7 large fires during 1970–2009) and large fires were smaller with an average size of 5930 ha (7994 ha during 1970–2009). Historical fire statistics do not currently exist for Russia, so no comparison can be made between the 2001–2007 data and the long-term fire regime for the Russian study area.

The total fuel consumption rate was higher in the Canadian study area because forest floor fuel consumption was higher due to greater pre-burn forest floor fuel loads, and because crown fuel consumption was higher. The Russian data did not include any deep organic sites, which appears to be a weakness in that dataset. Therefore, it is most likely that fuel consumption and C emissions in the Russian study area are underestimated. Although it is generally acknowledged that the vast majority of area burned in Canadian northern forests are by crown fire (Stocks et al., 2004), this study shows that the proportion of area burned by crown fire is highly dependent on forest composition, or fuel type. Pure coniferous stands represented 63.0% of the total forest land in the Canadian study area, and 57.1% of the total area burned during the study period occurred as crown fire. Crown fire is not possible in deciduous forest or grasslands, and can only occur in mixedwood stands if the coniferous component is >50% and the conifer component is capable of crowning. Therefore, even though the North American boreal forest is dominated by a high intensity crown fire regime, there are many areas within the fire perimeter that are burned as surface fire, or remain unburned, depending on forest composition and weather conditions during the fire. Crown fires in Russia occur mostly in the dark coniferous forest, which are dominated by *Picea*, *Abies*, and *P. sibirica*. *P. sylvestris* and *Larix* exist primarily in surface fire regimes, although crown fire can occur in *P. sylvestris* if the stand is young and surface fire intensity is high enough. Dark coniferous forest species represented 16.4% of the total study area and are concentrated in the southwest and west-central regions (a small amount occurs towards the west). A substantial amount of fire occurred in the dark coniferous forest region but it did not represent a majority of the area burned. In the context of the entire Russian forest, dark forest species represent 27.7% of the total growing stock, so there was a smaller proportional representation in this study area.

The large number of fires in the Russian study area that had no active fire detected by satellite (10,185 or 33.8% of all fires) in comparison to the Canadian study area (122 or 11.9% of all fires) was

[1] Fire statistics for Manitoba, Saskatchewan, Alberta, and Northwest Territories not including National Parks (National Forestry Database, 2012)

surprising. This may be partly related to the coarser scale mapping of the Russian fires, or due to greater potential for active fire detection on larger Canadian fires. For fires in both study areas, a certain amount of fire is obscured by cloud and water vapour in smoke, and some fires may not be burning actively at the time of satellite overpass. However, it is believed that with all conditions being equal, more active fire is detected on North American boreal wildfires because they characteristically burn as high intensity crown fires (Wooster and Zhang, 2004). Low to moderate intensity surface fires, which are characteristic of Eurasian boreal fires, are more difficult to detect because there is lower energy output and the fire front can be obscured by live tree canopy.

Boreal fire regime differences between North America and Eurasia appear closely related to forest composition and species fire ecology. There is a consistent component of deciduous broadleaf species across the circumpolar boreal forest. *Betula* and *Populus* represent 14% and 18% of the boreal forest in Canada and Russia, and all species are relatively short-lived (100–150 years). Neither tree genus supports crown fire due to the high moisture content of their broadleaf foliage. Trees are easily killed by low intensity surface fire, which girdles the stem, but the species survive in fire-dominated ecosystems by quickly re-sprouting from root stock. *Betula* and *Populus* thrive under short fire frequencies by quickly occupying new growing space that becomes available when fire disturbance removes competing vegetation. Pure stands of *Betula* and *Populus* typically only burn in the spring and autumn during the leafless stage when cured understory plant material can be dried by solar radiation. On the other hand, the conifer components of Eurasian and North American boreal forests are very different, and exemplify the cause and/or effect of divergent boreal fire regimes. For example, the Russian boreal forest is dominated by *Larix* (32% of growing stock, versus <2% of Canadian forest by area), and the Canadian boreal forest is dominated by *Picea* (64% of forest area, versus 15% of growing stock in Russia) (Alexeyev and Birdsey, 1998; National Forest Inventory System, 2012). *Larix* does not support crown fire because of high moisture content of deciduous needles, but *Picea* promotes crown fire by having highly flammable needle foliage and a low live branch habit, which acts as a ladder fuel that enables a surface fire to become a crown fire. *Abies* promotes crown fire similar to *Picea*, and the Canadian and Russian boreal forests have the same amount of *Abies* composition (3%). *Pinus* also has highly flammable needle foliage, but species in this genus self-prune lower branches, which reduces ladder fuels and the possibility of a surface fire transitioning to a crown fire. By self-pruning, live branches are typically restricted to the top 40% of the tree. Self-pruning is of lesser importance for its influence on potential crowning in North American *P. banksiana* stands because of the relatively low total tree height, but self-pruning ladder fuels on the taller *P. sylvestris* and *P. sibirica* can have a very significant effect on reduced crowning potential. *Pinus* represents much more boreal forest cover in Russia than Canada (29% versus 7%). All of these forest composition factors are consistent with a crown-fire dominated fire regime in boreal North America and a surface fire dominated fire regime in boreal Eurasia.

The fire ecology of Eurasian boreal conifers is also distinctly different from North American conifers. Eurasian species have much longer maximum lifespan (400–600+ years, versus 150–250 years in North America), which provides those species with greater reproductive opportunity for individual trees that survive a fire. The Eurasian boreal conifers *P. sylvestris*, *Larix sibirica*, *Larix gmelinii*, and to a lesser degree, *P. sibirica*, are characterized by thick bark to protect stem cambium from heat injury by surface fires. There are many North American tree species with this trait but none occur in the boreal forest region. *P. banksiana* has bark that is capable of providing moderate stem cambium protection, although trees are usually killed by needle loss during crown fire. Thick bark is characteristic of species adapted to frequent low to moderate intensity surface fire, and is consistent with the short MFRI found in the Russian study area. North American boreal conifers survive in crown-fire dominated ecosystems by storing seeds in the canopy (*P. banksiana*, *P. mariana*) or as fire avoiders (*P. glauca*, *Abies balsamifera*) that grow in infrequently burned areas, and/or are able to re-invade burned areas as a shade tolerant species growing in the understory of pioneer species.

5. Conclusions

Comparison of the 2001–2007 fire regimes in the Russian and Canadian study areas shows exceptional differences. Most large fires occurred during spring in the Russian study area, and during summer in the Canadian study area. In the Russian study area, the annual area burned was over three times greater, and the annual large fire frequency was an order of magnitude greater. Average large fire size was over four times greater in the Canadian study area. The proportion of area burned by crown fire was almost an order of magnitude greater in the Canadian study area, which contributed to higher average fire intensities. The average fuel consumption and C emission rates (within burned areas) was about 50% greater in the Canadian study area due to higher forest floor fuel loading and a greater amount of crown fire. However, total C emissions (per 100 M ha of forest area) was twice as high in the Russian study area due to a higher annual area burn rate. It is likely that the Russian C emissions estimate in this study is conservative due to low forest floor fuel load estimates in available datasets. The 2001–2007 fire regime of western Canada was very similar to the 1970–2009 record in terms of fire size distribution and annual area burned, although large fire frequency was greater and average large fire size was smaller. Historical fire statistics do not exist for Russia, so it is not known how closely the 2001–2007 data represents the long-term fire regime in the Russian study area.

Acknowledgements

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