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Climate change impacts on future boreal fire regimes ☆

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ABSTRACT

Fire disturbance is a primary driver of forest dynamics across the circumpolar boreal region, although there are major differences in continental fire regimes. Relatively infrequent, high intensity crown fires dominate North American boreal forests, and low to moderate intensity surface fires of moderate frequency are typical of northern Asia boreal forests. Climate change will result in future altered fire regimes, which will be realized through changes in fire weather, fire behaviour and C emissions. The impacts of climate change on 2091–2100 fire regimes were simulated in two large boreal study areas in central Russia and western Canada using three global climate models (CGCM3.1, HadCM3 and IPSL-CM4) and three climate change scenarios (A1B, A2 and B1). The severity of future fire weather conditions increased in both study areas but was more extreme in the Canadian study area. The CGCM model and the B1 scenario indicated the smallest increases, and the IPSL model and the A2 scenario indicated the greatest increases. Daily Severity Rating (DSR) and head fire intensity (HFI), which are indicators of fire control difficulty, increased in both boreal regions but were more extreme in western Canada. DSR seasonally peaked near the middle of the fire season in both regions at levels much higher than currently experienced. HFI similarly peaked at extreme levels in the late spring or early summer in central Russia. In western Canada, HFI peaked once in the spring at its most extreme level, and again in the late summer at a slightly lower extreme level. Fuel consumption rate changed very little in central Russia, but it increased in western Canada and exhibited a seasonal increasing trend as fuels dried out as the fire season progressed. There was a higher C emissions rate for fires in western Canada, but total C emissions were higher in central Russia due to the greater amount of annual area burned. Future changes in the fire regime will affect forest composition as some species will be favoured over others by fire ecology traits. Fire management will be challenged in the future by increased fire weather severity that could push current suppression capacity beyond a tipping point, resulting in a substantial increase in large fires.

1. Introduction

Fire has been a prevalent disturbance in the circumpolar boreal forest for millennia (Tolonen, 1983) and it is a primary driving force of ecosystem dynamics (Weber and Flannigan, 1997; Ryan, 2002). Fire regimes, which describe historical fire, show distinct continental divergence in the boreal region. Fire regime is usually characterized by fire frequency, fire intensity, fire severity (including physical and ecological aspects), season of burn, type of fire (crown, surface and ground), and fire size (including shape or pattern) (Weber and Flannigan, 1997; Gill and Allan, 2008). In boreal North America, the fire regime is characterized by infrequent high intensity crown fires, while relatively frequent, low to moderate intensity surface fires dominate the boreal forest of northern Asia (Korovin, 1996; Stocks et al., 2004). Large fires (>200 ha) are common across the entire circumpolar boreal region and account for the large majority of annual area burned, although fires are larger and fewer in North America (de Groot et al., 2013). The mean fire return interval in North America is also much longer, being about 167–180 years in western Canada and 53 years in central Russia.

The boreal forest is comprised mostly of *Abies*, *Betula*, *Larix*, *Picea*, *Pinus*, and *Populus* but tree species differ between North America and Eurasia. The North American boreal region is dominated by *Picea* (64%), and the Eurasian region is dominated by *Larix* (32%) and *Pinus* (29%) (Alexeyev and Birdsey, 1998; Bourgeau-Chavez et al., 2000; National Forest Inventory System, 2012). The boreal forest is characterized by very low arboreal diversity, and tree species have a few simple but diverse strategies to surviving recurrent fire which are closely tied to fire regime (Rowe, 1983). For example, the fire ecology of Russian tree species (e.g., *Larix* and *Pinus*) is largely driven by a thick-barked stem trait, which supports an individual tree survival strategy in a surface fire-dominated environment. Conversely in North America, aerial

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seed banks are protected by cone serotiny (*Pinus banksiana* Lamb.) and by semi-serotinous cones grouped in large clumps at the tops of trees (*Picea mariana* (Mill.) BSP) to ensure post-fire regeneration in an environment dominated by crown fire. Rapid re-sprouting after disturbance is a common survival trait by *Betula* and *Populus* species across the circumpolar boreal region, representing 16–18% of the forest on both continents.

Tree species have adapted to boreal fire regimes over a very long time. For example, there is support for correlated evolution of tree flammability and cone serotiny in pines (Keeley and Zedler, 1998; Schwilk and Ackerly, 2001) as found in *P. banksiana* of North America, but not in the thick-barked *Pinus sylvestris* L. of boreal Eurasia, which usually burns by surface fire. Fire regimes are dynamic and have varied markedly in history. As fire regime changes, the balance in species composition shifts according to fire ecology traits that developed over an evolutionary timescale. As current climate change progresses, there will be a substantial shift in fire regime that will have both ecological and fire management implications.

In general, there is expected to be an increase in fire behaviour and area burned across the boreal region during this century (Flannigan et al., 2009, 2013). Area burned has been linked to temperature (Gillett et al., 2004) and under current climate change scenarios, global temperature increase is predicted to be greatest at northern high latitudes (IPCC, 2007). There are several studies indicating that annual area burned by the end of this century will increase 2–5.5 times over current values for Canada and Alaska (Flannigan et al., 2005; Balshi et al., 2009), fire severity will increase, and fire seasons will be longer (Flannigan et al., 2013). The impacts of climate change on fire regimes will not be consistent across the boreal region with some areas experiencing greater change than others. The purpose of this study was to quantify the expected change in current boreal fire regimes by the end of this century, and to compare differences in future continental fire regimes.

2. Methods

Fire regimes were compared using fire weather, fire behaviour, and C emissions criteria. Future fire regimes were estimated by using future climate conditions to calculate future fire weather. Those data were applied to a large sample of typical boreal fires from study areas in Russia and Canada (Fig. 1) to calculate fire behaviour and C emissions. Fire and weather data for 2001–2007 were available from a recent study of two large study areas in western Canada and central Russia (de Groot et al., 2013) to represent current conditions in this study. The Canadian study area was 234.36 M ha in size (forest area = 156.66 M ha) and the Russian study area was 327.55 M ha (forest area = 299.64 M ha). The Canadian study area was comprised of 53% *P. mariana*, 10% *P. banksiana*, 22% *Populus tremuloides* Michx., 7% mixedwood stands (mostly *P. tremuloides* and *Picea glauca* (Moench) Voss), and 8% grassland. The Russian study area was 56% *Larix*, 28% *Pinus*, 8% *Betula*, 2% *Abies*, 3% *Picea*, 1% *Populus*, and 2% shrubland (as a proportion of total fuel load; spatial fuel data not available). During the 2001–2007 study period, the Russian study area had 30,243 large (200+ ha) fires that burned a total of 39.67 M ha (average fire size = 1312 ha, mean fire return interval = 52.9 years). The Canadian fire study area had 1028 large fires that burned 6.10 M ha (average fire size = 5930 ha, mean fire return interval = 179.9 years). The average C emissions rate (t ha^{-1} within burned areas) was 53% higher in the Canadian study area due to higher pre-burn forest floor fuel loads and higher fuel consumption by crown fires. The Russian study area produced much higher total C emissions because of greater annual area burned. The 2001–2007 fire statistics for the Canadian study area were very similar to historical fire data (1970–2009) for that area (de Groot et al., 2013). Similar long-term data for Russia do not exist for comparison, but the current data does not conflict with general descriptions in the published literature of numerous large surface fires and large area burned rates (Goldammer and Furyaev, 1996; Conard and Ivanova, 1999; Zhang et al., 2003; Sukhinin et al., 2004). A detailed description of fuels and 2001–2007 fire statistics, fire weather, fire behaviour, and C emissions is provided in de Groot et al. (2013).

There were nine sets of future fire weather conditions applied to each study area, which were based on three Global Climate Models (GCMs) and three climate change scenarios. The Canadian (CGCM3.1; Scinocca et al., 2008), Hadley (HadCM3; Gordon et al., 2000), and France (IPSL-CM4; Marti et al., 2006) GCM's provided future fire weather data. There are four emissions scenario storylines (A1, A2, B1, and B2) that set out distinct directions for global development through the year 2100 (IPCC, 2000). A1 is described by a world of very rapid economic growth, with the global population peaking mid-century. In this scenario, there is a rapid introduction of new and more efficient technologies. A1 is further divided into three groups. A1F1 is fossil-fuel intensive, A1T assumes non-fossil energy resource use and A1B is a balance across all energy sources. A2 is a world with increased population growth, slow economic development and slow technological change. B1 shares the same population as A1, but a more rapid change in economic structure, moving towards service and information technology. Lastly, B2 has an intermediate population and economic growth. It emphasises local solutions to economic, social and environmental sustainability. We selected the A1B, A2 and B1 scenarios for evaluation in this study.

Future climate simulation procedures were similar to those used globally by Flannigan et al. (2013), but were restricted to these specific study areas. In brief, future fire weather was simulated by each GCM for each climate change scenario, interpolated to a 2.5° grid over the study areas (Fig. 1) using an area weighted interpolation in XConv/convsh 1.91 (Cole, 2009). Changes in monthly temperature, precipitation, relative humidity and wind speed between the GCM baseline data (1971–2000 for CGCM3.1 and IPSL-CM4; 1971–1999 for HadCM3) and future GCM data was summarized by decade until 2100 (only the 2091–2100 data is reported here). To calculate future fire weather data, these monthly values were applied to the 2001–2007 daily weather data by month for the period April 1–October 31, which were interpolated to the same gridpoints using a thin-plate spline interpolation method. The resulting new daily weather was used to calculate the Canadian Forest Fire Weather Index (FWI) System components at each gridpoint location. For precipitation, the decadal future monthly GCM averages were divided by the GCM monthly baselines to get a ratio of future precipitation over baseline precipitation. This ratio was used as a multiplier to the daily precipitation amount in the 2001–2007 data. The Drought Code (DC) was set to standard spring conditions each year, and was not adjusted for possible overwinter precipitation deficit.

To calculate future fire behaviour and C emissions, the change in monthly temperature, precipitation, relative humidity and wind speed between baseline and future GCM data was summarized by decade and then interpolated to the hot spot locations within each fire. Interpolated values were applied to the 2001–2007 daily fire weather dataset, which was also interpolated to the hot spot locations within each fire, to calculate future FWI System parameters at the location of each hotspot. From the 2001–2007 large fire datasets, there were 906 large fires in the Canadian study area and 19,996 large fires in the Russian study area containing a minimum of one hot spot within a buffer of 1 km around the fire perimeter, which were used in this study. The 2001–2007 large

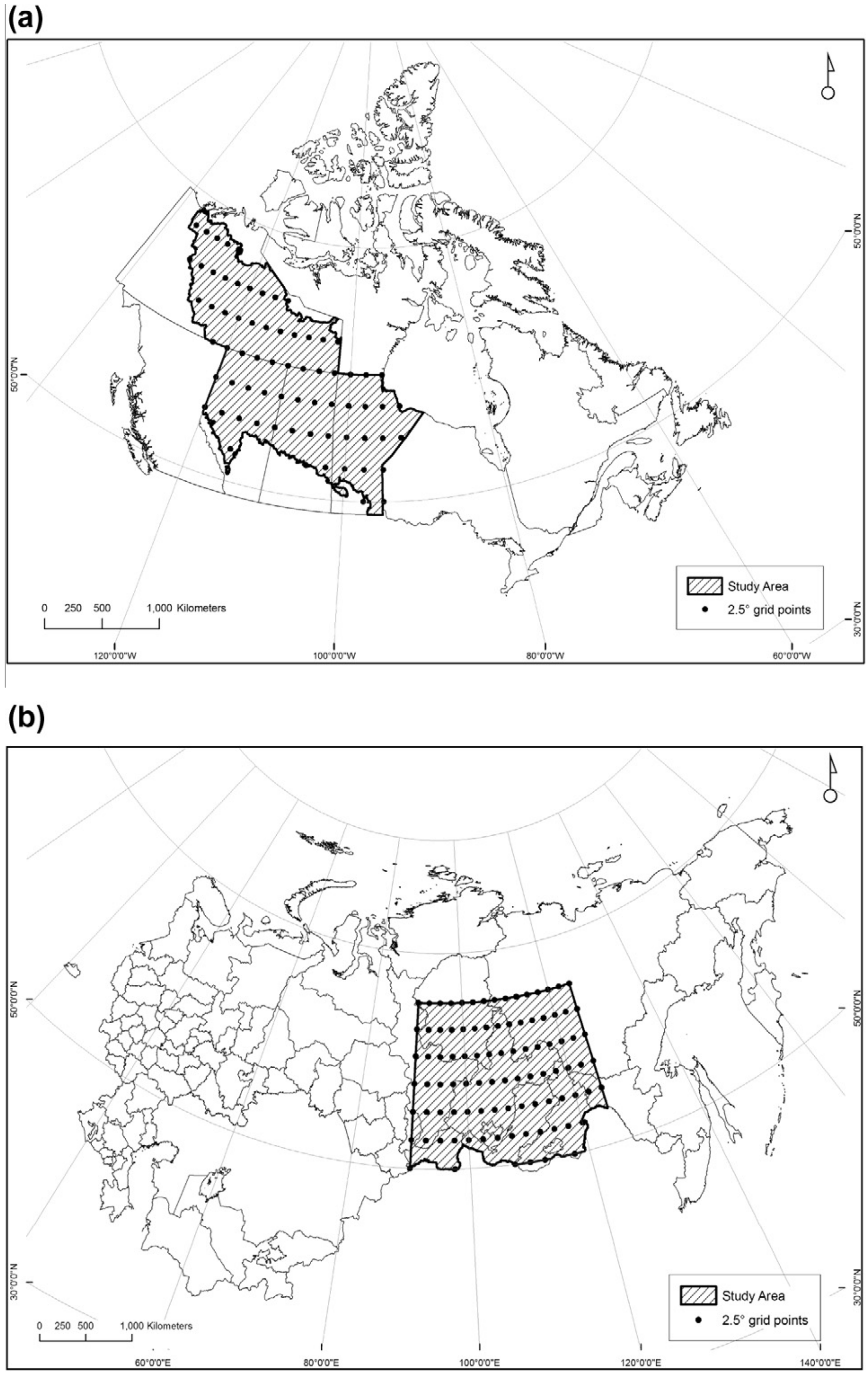

Fig. 1. Location of weather data gridpoints in (a) Canadian study area and (b) Russian study area.

fires for both study areas were burned using these new FWI System values for 2091–2100. Fires were simulated in the Canadian Fire Effects Model (CanFIRE; de Groot, 2006, 2010) using the future FWI System data with the 2001–2007 fire and fuels data to calculate future rate of fire spread, fuel consumption rate, head fire intensity, and C emissions rate for each fire. Fuels data were obtained from de Groot et al. (2013), which was interpreted from forest vegetation data. The simulated future fires were burned on the same Julian date as the original fire for each GCM and climate change scenario using the average FWI System conditions interpolated (thin plate spline) from the gridpoints to the original hot spot locations on each fire. By this method, all of the 2001–2007 large fires in the Russian study area (19,996 fires) and in the Canadian study area (906 fires) were re-burned individually in a CanFIRE simulation using future fire weather conditions for each model and climate change scenario (nine combinations). The net influence of climate change on fire regimes during this century was then assessed by determining the change in fire weather (using FWI System components), fire behaviour, and C emissions rate between 2001–2007 and 2091–2100 for both study areas.

All parameters were examined by monthly statistics for seasonal changes in future fire regimes. Differences in the 2091–2100 parameters were also compared between the two study areas to assess differences between continental boreal fire regimes.

3. Results

3.1. Fire weather

In general, 2091–2100 fire weather conditions under all models and scenarios were predicted to be slightly or moderately higher in the Canadian study area for all FWI System components except for the Fine Fuel Moisture Code (FFMC) and DC, which were usually slightly higher in the Russian study area (Table 1). This is the same pattern found in the 2001–2007 data. Fire weather conditions were predicted to generally increase by the end of this century in both study areas, although the CGCM indicated some minor decreases under the three scenarios, but mostly in the Canadian study area. In both study areas, the CGCM produced the lowest severity of future fire weather conditions and the IPSL produced the highest future severity conditions under each climate change scenario. Future fire weather conditions in both study areas were most severe under the A2 scenario, and the B1 scenario was least severe for all climate change models, with the exception that the CGCM produced highest values for Russia under the B1 scenario and lowest for Russia under the A2 scenario. Some FWI System parameters increased quite substantially in both study areas by the Hadley and IPSL models under all scenarios, particularly for the FWI and Daily Severity Rating (DSR) but also to a lesser degree for the Duff Moisture Code (DMC), Initial Spread Index (ISI) and Buildup Index (BUI). Increases in DC and FFMC were generally much smaller. This study did not make any adjustments to the DC for overwinter precipitation deficit, so the values presented here will underestimate future DC during periods of multi-year drought. The Canadian study area showed slightly higher DC values than the Russian study area during the first half of the fire season, and lower values near the end of the season (Fig. 2).

The 2091–2100 monthly DSR in the Canadian study area followed the 2001–2007 trend of peak values in June and much lower values in spring and autumn by all model and scenario combinations (Table 2). However, in the Russian study area, the peak monthly DSR shifted from June (in the 2001–2007 fire regime) to July in all future CGCM and Hadley scenarios, but the IPSL model showed an extended peak period from May through July. In both study areas, the highest DSR values were produced by the IPSL model (peak values were exceptionally higher than other models) and lowest values by CGCM. The A2 scenario also had the highest DSR values and the B1 was generally lowest in both study areas.

3.2. Fire behaviour and C emissions

3.2.1. Fuel consumption

In the Canadian study area, future total fuel consumption rate increased under all models and scenarios, although some increases were small (Fig. 3). Total fuel consumption increased due to higher forest floor fuel consumption and crown fuel consumption rates. The IPSL showed the greatest total fuel consumption rate increase under A1B and A2 scenarios, and the Hadley showed the greatest increase under the B1 scenario. Total fuel consumption rate generally increased the greatest under the A2 scenario. Current and future fuel consumption rate in the Canadian study area was consistently and substantially higher than the Russian study area. All models and scenarios indicated very little change in future fuel consumption rate in the Russian study area. Similar to current (2001–2007) monthly trends, all models and future scenarios of total fuel consumption rate showed a strong seasonal trend in the Canadian study area, with the lowest values at the start of the fire season (2.9–5.2 kg m^{-2}) and the highest values at the end of the fire season (8.1–13.7 kg m^{-2}) (data not presented). There was also a slight decrease in crown and total fuel consumption that occurred in July in most model and scenario combinations. In the Russian study area, future total fuel consumption rate by all models and scenarios was much less variable (3.4–5.0 kg m^{-2}) with highest values often occurring in mid-fire season.

3.2.2. Head fire intensity

Future HFI results showed a bi-modal trend in the Canadian study area with a large peak in May or June and a second lower peak in August or September (Table 3). This was consistent across all models and scenarios, except the IPSL A1B scenario which showed a peak in April and steady decline in HFI during the rest of the fire season. Future monthly HFI values in the Russian study area were lowest in the spring and autumn and highest in May or June across all models and scenarios. The IPSL model produced the

Table 1
Comparison of current (2001–2007) actual and future (2091–2100) estimated values of Canadian Forest Fire Weather Index System components (mean, SD).

Month	2001–2007	2091–2100								
		A1B			A2			B1		
		CGCM3.1	HadCM3	IPSL-CM4	CGCM3.1	HadCM3	IPSL-CM4	CGCM3.1	HadCM3	IPSL-CM4
Canadian study area										
FFMC[a]	71.4 (19.1)	70.8 (19.9)	74.4 (18.6)	77.4 (17.3)	71.4 (19.7)	75.2 (17.9)	78.3 (17.1)	70.4 (20.0)	73.0 (18.8)	75.0 (18.1)
DMC	19.6 (18.3)	18.8 (17.6)	26.5 (23.6)	34.8 (31.3)	19.6 (18.1)	27.1 (23.7)	38.4 (35.1)	18.8 (17.9)	23.1 (20.8)	27.4 (25.5)
DC	247 (173)	234 (163)	274 (186)	311 (201)	238 (168)	274 (193)	326 (201)	236 (164)	259 (182)	272 (180)
ISI	3.3 (3.9)	3.4 (4.0)	4.4 (5.0)	5.8 (7.5)	3.5 (4.1)	4.5 (5.1)	6.3 (8.0)	3.2 (3.8)	3.8 (4.5)	4.6 (5.5)
BUI	28.3 (24.2)	26.9 (22.9)	37.1 (30.3)	46.7 (36.7)	28.1 (23.7)	38.0 (30.6)	50.7 (39.8)	26.9 (23.1)	32.8 (26.9)	37.4 (30.9)
FWI	6.3 (7.7)	6.3 (7.9)	9.4 (10.7)	12.8 (14.0)	6.8 (8.3)	9.7 (10.9)	14.3 (15.3)	6.0 (7.6)	7.8 (9.1)	9.6 (11.1)
DSR	1.4 (2.8)	1.4 (3.0)	2.6 (4.9)	4.4 (8.1)	1.6 (3.2)	2.7 (5.1)	5.2 (9.3)	1.3 (2.7)	1.9 (3.7)	2.8 (5.2)
Russian study area										
FFMC	71.5 (17.3)	71.5 (17.9)	74.6 (16.6)	77.3 (15.6)	71.2 (18.1)	75.5 (16.2)	78.6 (15.5)	72.4 (17.0)	73.4 (16.6)	75.2 (16.2)
DMC	17.5 (18.9)	18.6 (19.5)	23.6 (23.6)	31.2 (29.8)	18.4 (18.9)	24.7 (22.8)	35.9 (33.6)	19.5 (20.2)	20.6 (20.3)	25.5 (25.3)
DC	259 (165)	259 (166)	275 (186)	330 (203)	256 (162)	284 (176)	346 (212)	271 (173)	267 (174)	300 (186)
ISI	2.5 (2.8)	2.6 (2.8)	3.3 (5.0)	4.2 (5.1)	2.5 (2.8)	3.4 (3.8)	4.8 (5.8)	2.7 (3.0)	2.9 (3.1)	3.4 (3.9)
BUI	26.1 (24.9)	27.6 (26.0)	34.2 (30.3)	43.8 (35.8)	27.4 (25.5)	35.7 (29.4)	49.4 (40.3)	28.9 (26.7)	30.5 (27.0)	36.5 (31.4)
FWI	5.0 (7.0)	5.3 (7.2)	7.4 (10.7)	10.0 (12.1)	5.2 (7.1)	7.9 (9.6)	11.9 (13.7)	5.6 (7.5)	6.2 (8.0)	7.8 (9.8)
DSR	1.0 (2.4)	1.1 (2.5)	1.8 (4.9)	3.1 (6.3)	1.1 (2.3)	2.0 (4.0)	4.0 (7.6)	1.2 (2.7)	1.4 (2.9)	2.1 (4.2)

[a] FFMC = Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, ISI = Initial Spread Index, BUI = Buildup Index, FWI = Fire Weather Index, DSR = Daily Severity Rating.

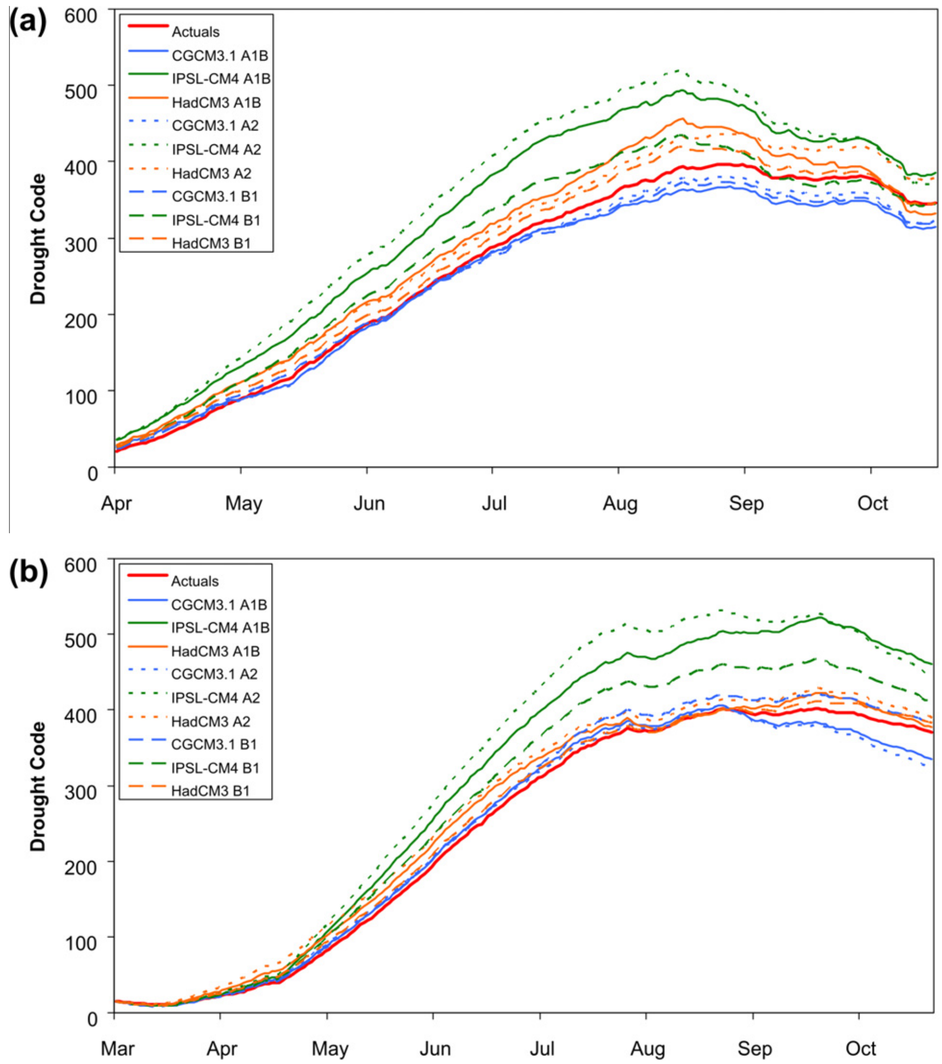

Fig. 2. Comparison of seasonal DC trend (a) in Canadian study area and (b) in Russian study area. Models = CGCM3.1, HadCM3, IPSL-CM4; scenarios = A2, A1B, B1.

Table 2
Comparison of current (2001–2007) actual and future (2091–2100) estimated Daily Severity Rating (mean, SD).

Month	2001–2007	2091–2100								
		A1B			A2			B1		
		CGCM3.1	HadCM3	IPSL-CM4	CGCM3.1	HadCM3	IPSL-CM4	CGCM3.1	HadCM3	IPSL-CM4
Canadian study area										
March	0.04 (0.1)	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)	0.04 (0.0)	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)
April	0.94 (1.9)	0.72 (1.5)	1.22 (2.4)	3.65 (7.1)	0.66 (1.4)	1.24 (2.7)	3.94 (7.6)	0.66 (1.4)	1.03 (2.3)	1.60 (1.6)
May	1.92 (3.4)	1.13 (1.8)	2.53 (3.4)	6.83 (8.5)	1.24 (1.9)	2.64 (3.6)	8.52 (9.9)	1.39 (2.1)	2.00 (2.8)	3.45 (3.4)
June	2.47 (3.7)	3.48 (5.0)	5.23 (6.8)	10.07 (13.6)	3.76 (5.6)	5.45 (7.4)	12.30 (16.0)	3.43 (5.4)	4.63 (6.4)	6.87 (6.9)
July	1.99 (3.2)	2.16 (3.1)	3.87 (4.9)	5.97 (7.2)	2.46 (3.6)	3.77 (4.8)	7.02 (8.3)	1.61 (2.6)	2.77 (3.8)	4.27 (4.3)
August	1.18 (2.5)	0.54 (1.1)	1.89 (2.9)	1.75 (2.6)	0.65 (1.2)	1.75 (3.2)	2.08 (2.9)	0.47 (0.9)	1.00 (1.6)	1.20 (1.2)
September	0.73 (1.9)	0.22 (0.7)	0.59 (1.7)	0.52 (1.4)	0.29 (0.8)	0.97 (2.6)	0.53 (1.4)	0.21 (0.7)	0.31 (0.9)	0.31 (0.3)
October	0.37 (1.3)	0.29 (0.9)	0.37 (1.2)	0.46 (1.3)	0.35 (1.1)	0.76 (2.1)	0.50 (1.4)	0.23 (0.7)	0.35 (1.1)	0.47 (0.5)
Russian study area										
March	0.03 (0.1)	0.01 (0.0)	0.02 (0.1)	0.02 (0.0)	0.01 (0.0)	0.03 (0.1)	0.02 (0.0)	0.02 (0.1)	0.02 (0.0)	0.02 (0.0)
April	0.28 (0.9)	0.63 (1.4)	1.10 (2.5)	0.83 (2.0)	0.62 (1.4)	1.38 (2.8)	0.88 (2.1)	0.60 (1.5)	0.72 (1.6)	0.58 (1.4)
May	1.51 (2.8)	1.16 (2.5)	1.91 (3.9)	5.96 (10.8)	1.10 (2.3)	2.24 (4.4)	8.03 (12.5)	1.28 (2.7)	1.40 (2.8)	3.12 (5.8)
June	2.18 (3.6)	1.44 (3.3)	2.27 (4.7)	4.03 (6.7)	1.21 (2.7)	2.44 (5.4)	5.17 (7.8)	1.50 (3.4)	1.75 (3.9)	2.85 (5.6)
July	1.70 (2.9)	2.09 (2.9)	3.37 (4.5)	4.74 (5.8)	2.06 (2.9)	3.94 (5.1)	6.57 (7.2)	2.61 (3.6)	2.61 (3.8)	3.39 (4.5)
August	0.81 (1.8)	1.17 (2.4)	1.75 (3.4)	2.31 (3.9)	1.12 (2.2)	1.87 (3.4)	3.08 (5.1)	1.24 (2.6)	1.43 (2.8)	1.57 (2.9)
September	0.55 (1.5)	1.06 (2.5)	1.80 (3.6)	1.98 (3.4)	0.99 (2.4)	1.65 (3.4)	2.26 (3.8)	0.91 (2.1)	1.30 (2.8)	1.52 (2.9)
October	0.26 (1.0)	0.48 (1.6)	0.77 (2.1)	0.77 (2.2)	0.39 (1.3)	0.70 (2.0)	0.87 (2.5)	0.40 (1.3)	0.58 (1.7)	0.68 (2.0)

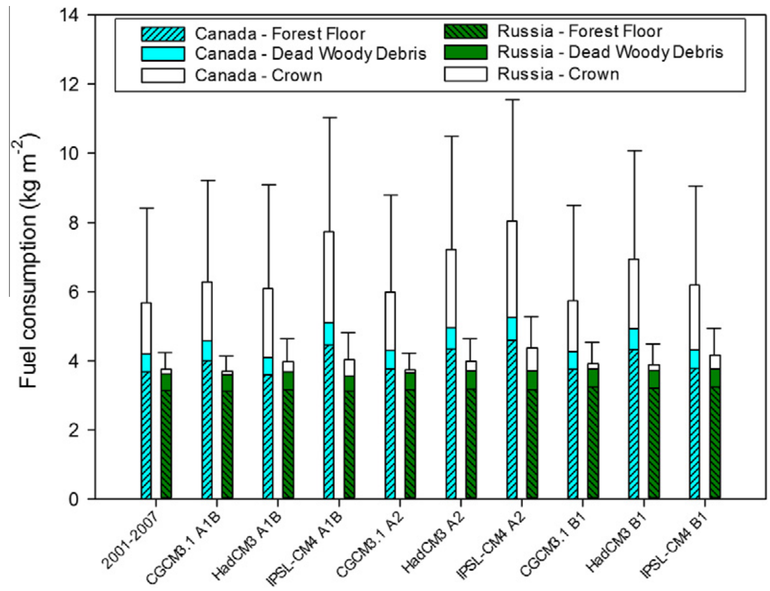

Fig. 3. Average forest floor, dead woody debris, crown and total fuel consumption under current (2001–2007) and future (2091–2100) climate change model scenarios (kg m^{-2}; SD of total indicated). Models = CGCM3.1, HadCM3, IPSL-CM4; scenarios = A2, A1B, B1.

Table 3
Comparison of current (2001–2007) actual and future (2091–2100) estimated average (SD) monthly head fire intensity (kW m^{-1}).

Month	2001–2007	2091–2100								
		A1B			A2			B1		
		CGCM3.1	HadCM3	IPSL-CM4	CGCM3.1	HadCM3	IPSL-CM4	CGCM3.1	HadCM3	IPSL-CM4
Canadian study area										
March	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
April	5438	6028	11,247	45,339	1227	13,997	42,472	3698	8956	24,344
	(12,605)	(14,270)	(24,584)	(66,266)	(3183)	(30,869)	(62,882)	(7885)	(18,743)	(40,089)
May	12,541	13,518	16,424	35,413	13,973	21,171	45,709	9794	19,333	28,944
	(19,284)	(20,419)	(24,589)	(45,007)	(20,829)	(30,202)	(56,861)	(16,439)	(27,577)	(37,540)
June	8053	11,882	12,696	18,318	11,070	16,480	21,010	7054	15,049	11,332
	(9959)	(13,341)	(14,946)	(20,297)	(13,007)	(17,167)	(22,314)	(9086)	(15,561)	(13,308)
July	4447	5519	8601	16,765	5969	11,755	19,072	4058	6997	7269
	(6608)	(8037)	(14,084)	(20,913)	(9780)	(17,586)	(24,380)	(5583)	(10,474)	(10,786)
August	6390	8133	17,377	16,121	7677	14,332	23,741	7439	13,743	13,243
	(9106)	(11,841)	(20,229)	(18,680)	(11,358)	(18,938)	(27,860)	(9855)	(15,558)	(17,585)
September	6361	10,694	15,671	16,135	12,140	20,316	17,935	8045	12,651	10,421
	(8539)	(12,797)	(22,227)	(17,712)	(14,705)	(24,636)	(26,432)	(11,870)	(16,500)	(15,477)
October	272	1840	1537	1267	258	2920	2078	126	1152	1441
	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
Russian study area										
March	359	248	968	804	308	283	1463	409	444	1163
	(582)	(549)	(1348)	(1055)	(628)	(712)	(1760)	(865)	(796)	(1458)
April	4210	3842	9770	5547	4056	9236	7850	7634	4802	4226
	(6478)	(5704)	(12,232)	(8132)	(5889)	(12,421)	(9842)	(10,849)	(7059)	(6407)
May	8210	6046	14,711	28,290	6270	13,588	46,669	7506	9703	25,869
	(9870)	(7527)	(15,496)	(27,199)	(7998)	(13,699)	(34,320)	(9417)	(10,278)	(22,481)
June	8114	7758	19,721	12,294	6614	14,798	17,296	9063	7923	16,719
	(8379)	(8064)	(15,789)	(11,212)	(5808)	(13,870)	(15,713)	(8035)	(8472)	(14,416)
July	5514	4728	9030	10,992	5527	12,054	13,501	7575	7642	9717
	(5169)	(4858)	(8723)	(10,713)	(4784)	(9707)	(11,676)	(6521)	(6353)	(9025)
August	4865	5530	7813	8189	4372	8903	9022	6375	8005	7933
	(4906)	(4973)	(8075)	(7827)	(4750)	(8492)	(9139)	(6127)	(5863)	(6210)
September	3733	3595	5523	5060	2555	5885	5449	3184	6450	5286
	(3915)	(4017)	(5103)	(5779)	(2917)	(4566)	(5704)	(3600)	(4764)	(5426)
October	3863	3130	4240	6173	4033	5096	5321	2716	5445	4349
	(5169)	(4626)	(6373)	(9531)	(5883)	(7551)	(8101)	(3979)	(7739)	(6308)

highest HFI values and the CGCM produced the lowest HFI values in all scenarios in both study areas. In general, the A2 scenario had the highest HFI values and the B1 had the lowest in both study areas. These values reflect a general future increase in HFI by the Hadley and IPSL models, under all scenarios and in both study areas. The IPSL produced the highest future HFI increases. However, the CGCM indicated a general decrease in future HFI under A1B and A2 scenarios in the Russian study area. It also indicated

Table 4
Comparison of current (2001–2007) actual and future (2091–2100) estimated average (SD) monthly wildland fire C emissions rate (t ha^{-1} of burned area).

Month	2001–2007	2091–2100								
		A1B			A2			B1		
		CGCM3.1	HadCM3	IPSL-CM4	CGCM3.1	HadCM3	IPSL-CM4	CGCM3.1	HadCM3	IPSL-CM4
Canadian study area										
March	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
April	11.3 (11.1)	12.0 (11.7)	13.9 (14.0)	24.6 (16.6)	7.9 (5.1)	14.7 (15.0)	23.4 (16.6)	10.5 (10.0)	13.4 (13.0)	18.7 (14.9)
May	21.3 (12.0)	22.9 (12.6)	23.9 (12.6)	32.1 (15.8)	21.3 (12.2)	26.3 (13.8)	32.0 (17.4)	18.6 (11.3)	25.3 (13.3)	28.5 (14.7)
June	27.2 (13.9)	31.1 (15.0)	29.4 (14.5)	34.7 (15.7)	29.4 (14.7)	34.9 (15.4)	37.0 (15.8)	25.8 (13.3)	35.0 (14.7)	30.6 (14.3)
July	28.2 (12.8)	31.0 (13.5)	29.4 (13.8)	39.3 (15.5)	30.0 (13.0)	36.2 (15.5)	40.4 (16.4)	28.8 (12.5)	33.6 (14.6)	30.1 (13.6)
August	32.6 (14.7)	35.4 (16.0)	37.0 (16.8)	43.8 (18.2)	33.0 (14.9)	40.5 (17.9)	47.0 (20.2)	35.5 (15.2)	40.6 (17.5)	34.9 (15.6)
September	42.6 (12.2)	47.6 (14.1)	47.0 (17.0)	54.9 (15.8)	44.4 (14.1)	53.2 (16.9)	54.3 (20.4)	44.2 (14.1)	52.9 (14.2)	41.6 (15.1)
October	32.7 (0.0)	44.7 (0.0)	40.1 (0.0)	47.2 (0.0)	33.1 (0.0)	53.6 (0.0)	43.9 (0.0)	32.5 (0.0)	43.7 (0.0)	36.5 (0.0)
Russian study area										
March	16.8 (2.4)	16.8 (2.5)	16.9 (2.4)	16.9 (2.4)	16.8 (2.4)	16.8 (2.5)	16.9 (2.4)	16.8 (2.5)	16.9 (2.4)	16.9 (2.4)
April	16.7 (2.6)	16.8 (2.5)	17.5 (3.0)	16.9 (2.8)	16.8 (2.5)	17.3 (3.0)	17.3 (2.8)	17.1 (2.9)	16.8 (2.6)	16.7 (2.6)
May	18.4 (2.7)	18.2 (2.3)	19.8 (3.3)	21.8 (4.6)	18.1 (2.3)	19.6 (3.2)	24.6 (4.7)	18.4 (2.4)	18.8 (2.8)	21.4 (4.2)
June	19.7 (2.4)	19.8 (2.4)	22.5 (3.6)	20.3 (3.1)	19.6 (2.1)	21.3 (3.2)	21.9 (3.6)	20.3 (2.6)	19.7 (2.4)	21.6 (3.4)
July	19.8 (2.2)	19.1 (2.3)	21.9 (3.5)	20.5 (3.6)	21.1 (2.5)	22.2 (3.6)	22.5 (3.8)	22.0 (2.8)	19.8 (2.6)	22.0 (3.3)
August	19.7 (1.9)	18.8 (1.9)	19.6 (2.3)	19.1 (2.3)	20.1 (2.1)	21.3 (2.9)	21.1 (2.8)	23.4 (2.9)	21.1 (2.4)	22.8 (2.8)
September	19.2 (1.6)	18.6 (1.8)	18.4 (1.9)	18.1 (2.2)	18.3 (1.7)	19.7 (1.8)	19.0 (1.8)	21.7 (3.3)	23.5 (2.3)	22.7 (3.2)
October	19.1 (1.7)	18.5 (1.9)	18.0 (2.2)	19.1 (2.7)	18.2 (2.0)	20.3 (2.8)	18.8 (2.0)	19.5 (2.6)	24.7 (2.5)	21.9 (3.3)

primarily increasing HFI values in the Canadian study area for A1B and A2 scenarios, and mixed results under the B1 scenario for both study areas. The Hadley and IPSL showed increasing HFI for almost all months in both study areas under all scenarios, with many months showing dramatic increases. IPSL and A2 showed the greatest increases overall.

3.2.3. Type of fire

Crown fuel consumption, total fuel consumption and HFI are closely related to the amount of crown fire vs. surface fire. In comparison to the current (2001–2007) amount of crown fire in the Canadian study area (57%), the CGCM indicates little change in the amount of future crown fire (54–60%), while the Hadley (62–65%) and IPSL (61–69%) indicate slightly higher values under the three climate change scenarios. In the Russian study area, which currently has 6% crown fire, future amounts are estimated at 6–8% by CGCM, 8–12% by HadCM3, and 15–22% by IPSL.

3.2.4. Carbon emissions rate

The C emissions rate followed the same patterns as the total fuel consumption rate. In the Canadian study area, the lowest monthly future C emissions rate occurred in April and values steadily increased during the fire season until reaching the highest rates in September by all models and scenarios (Table 4). Overall, the future average monthly C emissions rate was much higher and more variable in the Canadian study area (7.9–54.3 t ha^{-1}) than the Russian study area (16.7–24.7 t ha^{-1}). The lowest C emissions rate in the Russian study area occurred in the spring under all simulations, but peak values occurred at various months during the fire season, depending on the model and scenario. In the Canadian study area, the IPSL model produced the greatest C emissions rate increases under A1B and A2 scenarios, and the Hadley produced the greatest increase under B1. Overall, changes in the future Russian C emissions rate were mixed and smaller than in the Canadian study area.

4. Discussion

All models and climate change scenarios indicate that future fire weather conditions are predicted to become more severe in both continental boreal forest regions, although fire weather is expected to be more severe in western Canada than central Russia. The degree of increase is dependent on the model and scenario, but in general, the IPSL model and A2 scenario indicate the greatest increases in severity, and the CGCM model and B1 scenario the lowest increases. The CGCM indicates only a relatively small increase (<18%) in future average DSR for most scenarios in both study areas, but exceptionally large increases are indicated by the Hadley (34–97%) and IPSL models (98–288%). At the peak DSR periods in early to mid-fire season, the IPSL model indicated monthly average DSR values under the A2 scenario that are 4–5 times greater than the highest average values currently experienced. If the Hadley and IPSL models are correct, this will place a huge increasing demand on fire management in the future, regardless of climate change scenario.

The HFI is another key indicator of fire control difficulty because it indicates the type of suppression resources and/or strategy needed to contain wildfire. For example, firefighters with handtools are only effective on fires <500 kW m^{-1}, power pumps and hoselines are useful up to 1000–2000 kW m^{-1}, heavy line-building equipment (e.g., dozers) are needed on fires up to 2000–3000 kW m^{-1}, and air tankers are required for fires of greater intensity (Alexander and de Groot, 1988; de Groot et al., 2007). At HFI values greater than 4000–5000 kW m^{-1}, indirect attack is often used by burning out with helitorch from control lines often constructed by heavy ground equipment or fire retardant dropped by air tankers. The HFI is a fire behaviour-based indicator of fire suppression capacity that accounts for fire weather and fuel types, making it a better indicator than DSR, which it is based on fire weather alone. In this study, the change in future HFI was wide-ranging and mixed by the various model and scenario combinations. However, the peak average monthly HFI values were beyond the air tanker control limit in all future model and scenario combinations in both study areas. This limit was far-exceeded in many cases in both study areas, and confirms the expected future extreme conditions indicated by the future DSR results.

An interesting trend in the future simulations of the Canadian study area was a bi-modal peak of HFI values in 8 of 9 model-scenario combinations. The first highest peak occurred in May, and a smaller second peak occurred in August or September. By contrast, the Russian study area showed a single HFI peak in May or June. There are two fire weather-based factors causing this discrepancy. Fire intensity is the product of rate of fire spread and fuel consumption (Byram, 1959). The ISI is an indicator of potential fire rate of spread and showed highest mean average values (and greatest SD, indicating greater occurrence of higher values) early in the fire season in both study areas. This reflects higher wind speed values, which results in much higher fire intensity in the spring. The Canadian study area showed a secondary peak later in the fire season because the fuel consumption rate steadily increased as the fire season progressed, also causing an increase in fire intensity. The Russian study area showed only minor seasonal change in fuel consumption, so there is no second seasonal peak in fire intensity.

The steadily increasing fuel consumption rate found in the Canadian study area was driven by long-term drying of the forest floor that accumulated during the fire season, as evidenced by increasing DC values (Fig. 2). Forest floor fuel consumption, which is controlled primarily by fuel load and DC (de Groot et al., 2009), accounts for most of the total fuel consumption (Fig. 3). Since the Canadian study area had much higher forest floor fuel loads (average 8.3 kg m^{-2}) than the Russian study area (average 3.0 kg m^{-2}) (de Groot et al., 2013), the seasonal DC trend had a stronger effect on total fuel consumption in the Canadian study area. Average forest floor fuel loads for the Canadian study area were obtained from an extensive national database (Letang and de Groot, 2012), and from a coarse-scale C database from Alexeyev and Birdsey (1998) for the Russian study area. The large difference in forest floor fuel loads is due in great part to the large proportion of *Picea*, *Populus*, and mixedwood forest in the Canadian study area with very high fuel loads, but it is also a reflection of low estimated fuel loads in Russia from the coarse-scale national database. Monthly average total fuel consumption rates in the Canadian study area ranged 1.6–11.0 kg m^{-2}, depending on model, scenario, and month (data not presented). These fuel consumption rates are very similar to estimates calculated (from C emission rates) using multiple models in other boreal fire studies: 2.7–12.2 kg m^{-2} in Alaska, 1.8–13.0 kg m^{-2} in central Saskatchewan, and 1.6–16.0 kg m^{-2} on multiple North American boreal fire studies (French et al., 2011).

The total fuel consumption rate, which is directly related to the C emissions rate, was much higher overall in the Canadian study area due to higher crown and forest floor fuel consumption rates. The crown fuel consumption rate was higher because of the high amount of crown fire that occurs in the North American boreal forest, as compared to the Eurasian boreal forest. Since there was substantial crown fuel consumption in the Canadian study area, the slight decrease in crown fuel consumption found in July was also evident in the total fuel consumption seasonal trend (data not presented). The July decrease in crown fuel consumption was similarly reflected by the mid-summer drop in HFI of the Canadian study area.

The future C emissions rate, which was calculated for the area burned within a fire perimeter, was considerably higher in the Canadian study area because of the higher fuel consumption rate. When this rate is scaled up to the total forest area, the Russian study area will likely have a future total C emissions rate (on a forest area basis) that is exceptionally higher than the Canadian study area because Russia is expected to have a much higher annual area burned rate. This is based on the assumption that the current relative rate of area burned, with a mean fire return interval of about 52 years in central Russia and 167–180 years in western Canada (de Groot et al., 2013), will continue in the future. Other studies indicate that the future annual area burned rate is expected to increase 2–5.5 times in boreal North America (Flannigan et al., 2005; Balshi et al., 2009). Increased fire activity is also predicted for Russia (Dixon and Krankina, 1993; Stocks et al., 1998). Therefore, total future annual C emissions from Russia are expected to be much greater than from Canada because of a higher annual area burned rate, and because Russia has a larger total area of boreal forest. As similarly found by Amiro et al. (2009) for Canada, this study indicates that future increases in total C emissions will be due in part to more severe fire weather conditions (up to 67% in the Canadian study area, and 30% in the Russian study area), but those increases will probably be overshadowed by large increases in annual area burned (e.g., 200–550%).

The results of this study do not account for potential future change in fuel load or fuel type. Fuel consumption and C emissions are dependent on fuel load and fire weather. Any increase or decrease in forest fuel load will result in a corresponding change in consumption and emissions. The sensitivity of fuel consumption and C emissions to changing fuel load can be substantial but it depends on the type of fuel (forest floor, dead woody debris, crown) and the fuel moisture level. As an example, de Groot et al. (2007) found that, under the same fire weather conditions, the total fuel consumption rate for a typical boreal stand approximately doubles as it grows and accumulates fuel from 25 to 100 years old. If increasing annual area burned occurs in the future, it will shift the age-class distribution to a lower average age and fuel load. Increasing boreal fire activity is also expected to favour deciduous tree species (de Groot et al., 2003), which will reduce the amount of crown fire and total fuel consumption. The degree to which future boreal fuel load and fuel type will change is not known.

As already indicated, changes in future fire regimes will also have ecological implications on the boreal forest. de Groot et al. (2003) indicated that the greatest impact of future fire regimes on western Canadian boreal forests was a change in fire frequency. If the mean fire return interval decreases as suggested by other studies, future fire regimes will favour species that quickly resprout from rootstock (*Populus*, *Betula*) and store seeds (*P. mariana* and *P. banksiana*). However, seed storage is only a successful strategy if the fire-free interval is longer than the time required to produce a viable seed crop. For many boreal conifers, this is about 25–30 years. For some species, season of burn is another critical aspect of fire regime. For example, many species produce an annual or regular seed crop (Greene et al., 1999; Greene and Johnson, 2004), but there will be no regeneration if a fire happens early in the growing season before seed maturation occurs. In the case of *P. tremuloides* and other broadleaf species that resprout, burning prior to leaf flush will effectively kill the stand because fire will girdle the stem and prevent transport of photosynthate to restock root reserves (Weber, 1990). Trees will eventually die as the roots are drained of carbohydrates. However, if a fire occurs after leaf flush and the fire is intense enough to scorch the leaves, *P. tremuloides* will resprout as a distress response. Broadleaf forest stands usually only burn during the leafless (spring and autumn) stage because understory vegetation is live and full of moisture during the summer and there is very little solar radiation reaching the forest floor to dry out surface fuels. Thick bark is not a beneficial fire ecology trait in crown fire dominated ecosystems such as boreal North America (de Groot et al., 2003) but it supports a successful survival strategy in surface fire regimes of boreal Eurasia for trees such as *P. sylvestris* and *Larix sibirica* Ledeb. Higher fire intensities will decrease the amount of viable seed that is stored in the tree canopy (de Groot et al., 2004), which will affect post-fire regeneration density of *P. banksiana* and *P. mariana* in North America. Canopy seed storage is not a regeneration strategy in boreal Eurasia, but higher fire intensities will result in a greater amount of crown fire and more regeneration will have to seed-in from outside the fire perimeter or from unburned islands within the fire.

The climate change simulations in this study represent expected changes in future fire weather, and do not account for the effects of a longer fire season, changes in ignition factors, annual area burned rate, or future fire management capacity. The increasing fire weather severity of future fire regimes over the next century will force fire management agencies to re-evaluate and adapt operational programs. The fire management community uses three general suppression tactics: control by direct attack, containment by indirect attack, and confinement using natural boundaries as much as possible to restrict fire spread (Grissom et al., 2000). Fire suppression programs have been based on these tactics for many years, but they operate with a very narrow margin between success and failure (Stocks, 1993). Many agencies are operating near optimal performance with existing suppression resources. Any further increase in suppression capacity will require great expenditure (e.g., McAlpine and Hirsch, 1998) because the cost effectiveness of conventional fire suppression resources is at a point of diminishing returns. Future fire regimes could push fire control capacity beyond a tipping point where a disproportionate number of fires could become large fires (Stocks, 1993). For a significant gain in fire suppression capacity, agencies will need to make changes at a policy and strategic level. For example, greater emphasis will need to be placed on preparedness and inter-agency resource-sharing. This includes an increasing emphasis on prevention, early detection, and fuel management programs (including mechanical and prescribed fire) and closer coordination between government agencies (Grissom et al., 2000).

5. Conclusions

Current global climate models and climate change scenarios suggest that future fire regimes will be characterized by greater severity of fire weather conditions in central Russian and western Canadian boreal forests, although fire weather will be generally more severe in the latter. Daily Severity Rating, as an indicator of fire control difficulty, will peak near the middle of the fire season in both regions at levels much higher than currently experienced. In western Canada, there will be a higher fuel consumption rate overall, with a seasonal increasing trend from spring to autumn. Head fire intensity, an indicator of fire suppression resource requirements and control difficulty, will increase in both boreal regions but will continue to be higher in western Canada. This is mostly due to the crown fire regime of the North American boreal forest and the predominantly surface fire regime of the Eurasian boreal forest. In western Canada, head fire intensity values will peak at extreme levels in the spring due to high fire spread rates, and will peak again at a slightly lower extreme level in late summer due to greater fuel consumption rates. Head fire intensity will seasonally peak at extreme levels in late spring or early summer in central Russia. There will be a higher C emissions rate for fires in western Canada because of greater fuel consumption rates, but total C emissions will be higher in central Russia due to the greater rate of annual area burned (i.e., low mean fire return interval). Future changes in the fire regime will affect forest composition as some species will be favoured over others by fire ecology traits. Fire management will be challenged in the future by increased fire weather severity that could push current suppression capacity beyond a tipping point, resulting in a substantial increase in large fires.

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