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The potential and realized spread of wildfires across Canada

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Abstract

Given that they can burn for weeks or months, wildfires in temperate and boreal forests may become immense (eg., 10^0 – 10^4 km^2). However, during the period within which a large fire is 'active', not all days experience weather that is conducive to fire spread; indeed most of the spread occurs on a small proportion (e.g., 1 – 15 days) of not necessarily consecutive days during the active period. This study examines and compares the Canada-wide patterns in fire-conducive weather ('potential' spread) and the spread that occurs on the ground ('realized' spread). Results show substantial variability in distributions of potential and realized spread days across Canada. Both potential and realized spread are higher in western than in eastern Canada; however, whereas potential spread generally decreases from south to north, there is no such pattern with realized spread. The realized-to-potential fire-spread ratio is considerably higher in northern Canada than in the south, indicating that proportionally more fire-conducive days translate into fire progression. An exploration of environmental correlates to spread show that there may be a few factors compensating for the lower potential spread in northern Canada: a greater proportion of coniferous (i.e., more flammable) vegetation, lesser human impacts (i.e., less fragmented landscapes), sufficient fire ignitions, and intense droughts. Because a linear relationship exists between the frequency distributions of potential spread days and realized spread days in a fire zone, it is possible to obtain one from the other using a simple conversion factor. Our methodology thus provides a means to estimate realized fire spread from weather-based data in regions where fire databases are poor, which may improve our ability to predict future fire activity.

Keywords: boreal forests, Canada, fire spread, MODIS fire detections, temperate forests, weather

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Introduction

Wildland fire is an important natural process in the boreal and temperate biomes of Canada, both as an ecological process influencing forest composition and dynamics, and as a natural hazard to human values and communities. Understanding and predicting fire activity, especially how fire spreads across heterogeneous landscape, is crucial in fire risk assessment, fuel treatment planning, and fire suppression operations (Finney *et al.*, 2007). Although wildland fire is controlled by a number of factors (flammable biomass, weather, topography, and ignition sources), the impact of weather is of scientific interest because of its high temporal variability (Abatzoglou & Kolden, 2011) and dominant influence during extreme years (Moritz, 2003; Gedalof *et al.*, 2005). As such, a number of studies have evaluated how monthly or annual variability in fire activity is related to monthly or annual variability in weather (e.g., Flannigan *et al.*, 2005; Balshi *et al.*, 2009). Although fire–weather relationships at these coarse temporal resolutions have been shown to be good predictors of fire activity (e.g., Littell *et al.*, 2009), the variability in day-to-day conditions controlling fire activity (Parisien *et al.*, 2011a) is not well understood.

In most boreal and temperate forests, large fires (e.g., 10^0 – 10^4 km^2) occur relatively infrequently but are responsible for most of the area burned (Stocks *et al.*, 2003; Stephens, 2005). These large fires may burn for weeks or months until they are extinguished by a substantial rain event (Latham & Rothermel, 1993). Rain-free periods within the fire season largely govern the potential for fires to become large (Wiitala & Carlton, 1993; Beverly & Martell, 2005), but this is contingent upon the number of days with weather conducive to substantial fire spread (hereafter, 'potential' spread

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days) occurring during these periods. Typically, a potential spread day corresponds to hot, dry, and windy conditions and is more likely to result in non-negligible fire spread compared to days with less extreme weather conditions (Podur & Wotton, 2011). In other words, a potential spread day is a day where a fire will grow if an ignition occurs and there are sufficient landscape-level fuels to burn. This is particularly the case in coniferous forests, where surface fire intensity must exceed a critical threshold to induce and sustain crowning (van Wagner, 1977; Alexander & Cruz, 2011).

Regardless of how long a fire burns, a large proportion of its growth occurs during relatively few (but sometimes many) days (e.g., Rothermel *et al.*, 1994) (hereafter 'spread days'). Although spread days are generally constrained by 'potential' spread days, there is a discrepancy — sometimes important — between the potential for spread and the realized on-the-ground spread (Parisien *et al.*, 2005; Podur & Wotton, 2011). There are many reasons why a potential spread day may not result in a spread day: lack of flammable biomass, a geographic impediment to spread, successful fire suppression, or simply that a fire has not been ignited (Finney *et al.*, 2009). We hypothesize that a large difference between potential and realized fire spread may be due to a greater influence of bottom-up controls of fire regimes; that is, the usually nonclimatic environmental and human factors that vary substantially across the landscape (Gavin *et al.*, 2006; Parks *et al.*, 2012).

The forested landmass of Canada is an ideal study area to examine the correspondence between potential fire spread and on-the-ground fire progression because large-scale (~5000 km East-West and ~ 2000 km North-South) environmental gradients (Skinner *et al.*, 1999; Macias Fauria & Johnson, 2008) translate into different fire regimes (Burton *et al.*, 2008; Boulanger *et al.*, 2012). Although patterns in fire climatology have been assessed across Canada (Flannigan & Harrington, 1988), there has been no large-scale evaluation of the number of days of fire-conducive weather. In addition, little is known about spatial patterns in realized spread and whether or not the relationship between potential and realized spread days varies spatially. The central goal of this study is to evaluate the extent to which potential fire spread is realized. Specifically, we aim to (i) characterize potential spread using three decades of daily weather observations, (ii) characterize realized spread days using fire progression maps generated from remotely sensed data, (iii) examine how the relationship between potential and realized fire-spread days varies across Canada, (iv) identify environmental factors associated with the spatial variation in potential and realized spread days, and (v) develop a method to estimate the frequency of realized spread days from that of potential spread days.

Materials and methods

Study area

The study area encompasses the predominantly forested landmass of Canada (6.37×10^6 km^2), as defined by the Ecological Stratification Working Group (1995) (Fig. 1). Forests are bounded in the north by shrub tundra and in the south by extensive areas of cultivated land and urban development. The study area spans three major biomes: the temperate coniferous forests (west coast), the temperate broadleaf and mixed forests (east coast and Great Lakes area), and the boreal forests (central Canada and north of the two other biomes). We used the homogeneous fire zones (hereafter, 'fire zones'; Fig. 1) developed by Boulanger *et al.* (2012) as analysis units. The fire zones were derived from clustering of fire regime attributes such as the number of fires, the fire sizes, and the seasonality of fires within 40 × 40 km cell grids. An area north of 54°N in Ontario was excluded from this zonation because of missing fire data. The fire zones are a suitable sample unit for our analysis because they are small enough to encapsulate distinctive fire regimes yet they are large enough to contain enough fire observations for a robust analysis.

The major environmental gradients of the study area are summarized using a suite of variables similar to those found in Parisien *et al.* (2006) (Table 1). The climates of the study area are broadly characterized by long, cold winters and short, warm summers, although areas adjacent to the Pacific and Atlantic coasts and the Great Lakes have milder climates. Mean annual temperature generally decreases northward, whereas annual precipitation is lower in the center of the continent than in the coastal areas. The areas experiencing the most fire-conducive weather (i.e., fire danger) lie in the continental central and western parts of the country (Simard, 1973). Although the fire danger of southern Canada is high (Flannigan & Harrington, 1988), it is an area where many fires are suppressed by fire management agencies (Parisien *et al.*, 2011b). In spite of its relatively low fire danger, northern Canada experiences substantial fire activity. This is presumably due to the high proportion of coniferous trees, which are more flammable than deciduous trees, and comparatively longer periods of daylight during the fire season (Amiro *et al.*, 2004; Parisien *et al.*, 2011b). At the northern fringe of the study area, the flammable vegetation (i.e. fuels) becomes highly discontinuous; similarly, the mountainous areas of western Canada have a high proportion of alpine tundra, exposed rock, and glaciers that limit fire spread (Parisien *et al.*, 2006).

Potential fire spread

Potential spread days (PSD) consist of observed daily weather conditions for which substantial fire spread is possible. Data were obtained from a database of 593 stations (Environment

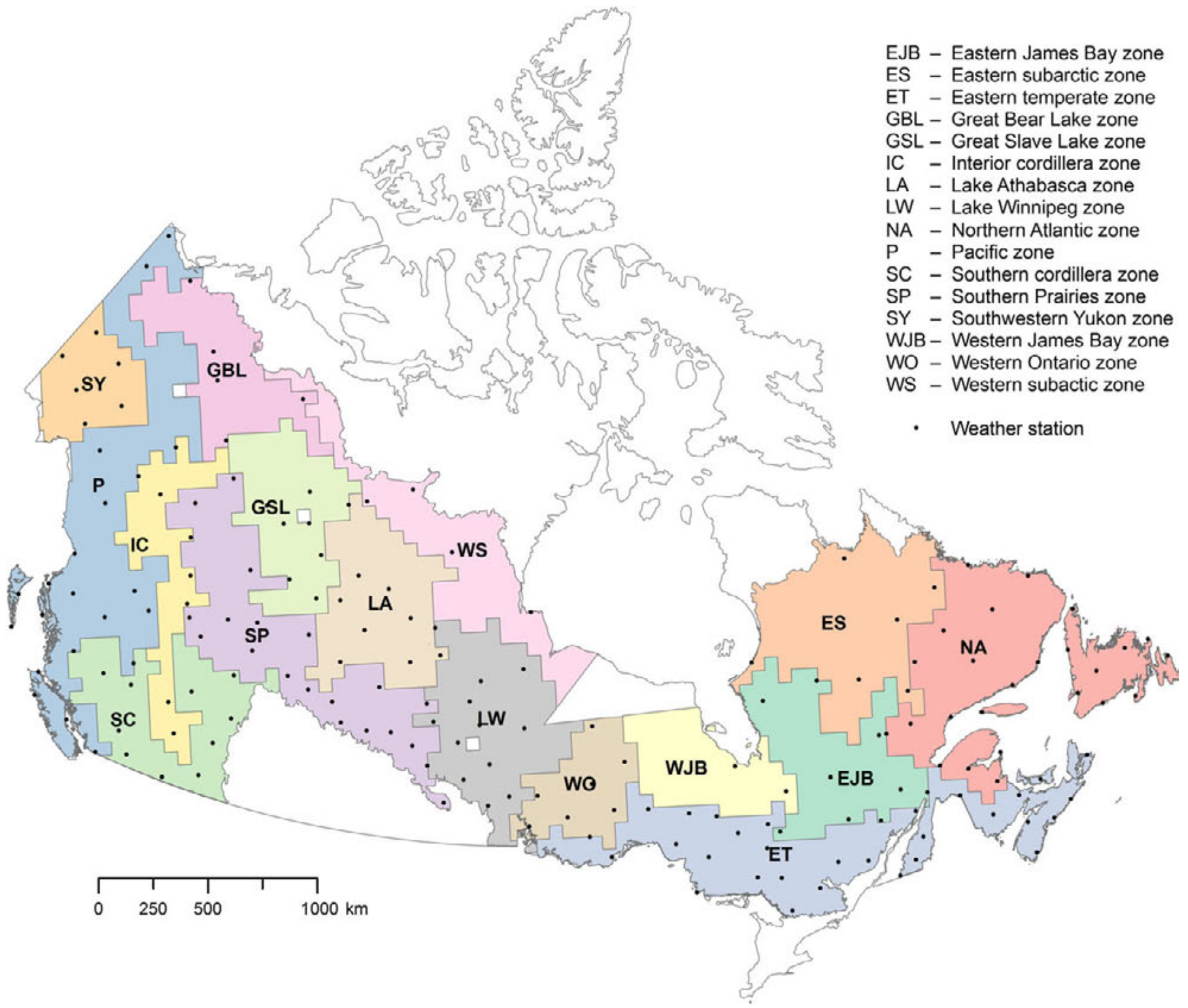

Fig. 1 The fire zones and Environment Canada weather stations (black dots) used in this study. Medians from distributions of potential spread days and spread days were computed on the basis of each zone.

Canada, 2013) with daily weather observations made at noon (local standard time) from March to December, the time of year during which ~100% of the fires occur, between 1953 and 2007. Because stations are unevenly distributed throughout the study area, with a decreasing density from south to north, the following filter was applied to obtain a more equal number of weather stations among fire zones. Stations with less than 10 consecutive years of records were removed unless they were operational during the time period of overlap with the fire data (2001–2007, see below). To limit the duplication in weather conditions, only one station within a 100 km radius was selected according to the longest operational history; if stations had the same operational longevity, the selection was made from a random draw. This was more likely to occur in the southern portion of the study area due to the higher density of weather stations. A resulting 181 stations were retained for analysis (Fig. 1).

The next step consisted of calculating the components of the Fire Weather Index (FWI) System (van Wagner, 1987) for each daily weather observation. The FWI System combines the values of temperature, relative humidity, wind speed, and 24 h precipitation to calculate three fuel moistures codes and three fire–weather indexes. The principal index of the FWI System, also named FWI, is an index of potential fire intensity whereby higher values indicate greater fire danger. For this study, PSD were defined as days when FWI ≥ 19, as recommended by Podur & Wotton (2011). Although this may vary somewhat from one vegetation type to the next, values above this FWI threshold have long been associated with high-to-extreme fire behavior in coniferous stands (Simard, 1973).

The number of PSD was constrained by the rain-free period, which is the period between two significant rain events. We defined the rain-free period as days when the duff moisture code (DMC) component of the FWI System was ≥20. The DMC

Table 1 Environmental descriptors of the study area by fire zone. See footnotes for data sources. The seasonal severity rating (SSR) is a weather-based index of potential fire danger. Conifer : other refers is the ratio of coniferous land cover to nonconiferous land cover (excluding nonfuels). Nonfuels consist of all areas without natural vegetation, such as open water, exposed rock, urban areas, and irrigated agricultural fields

Fire zone	Mean temperature* (°C)	Mean total precipitation* (mm)	Mean SSR†	Conifer: other‡	Percent nonfuel‡ (%)	Mean surface-area ratio§	Mean human footprint index**	Mean annual area burned†† (%)
Eastern James Bay zone (EJB)	−1.0	868	4.6	1.0	14.5	1.000	6.4	0.70
Eastern subarctic zone (ES)	−5.1	711	2.0	2.8	49.6	1.001	2.4	0.15
Eastern temperate zone (ET)	2.9	972	6.4	0.2	10.6	1.000	14.8	0.04
Great Bear Lake zone (GBL)	−7.3	309	5.5	1.5	38.0	1.002	1.5	0.57
Great Slave Lake zone (GSL)	−3.8	345	12.7	2.1	19.0	1.000	1.3	0.95
Interior cordillera zone (IC)	−1.1	690	6.7	2.0	15.4	1.019	5.7	0.22
Lake Athabasca zone (LA)	−3.2	424	9.4	2.2	20.9	1.000	0.8	1.66
Lake Winnipeg zone (LW)	−1.2	505	10.4	1.2	21.5	1.000	2.9	0.80
Northern Atlantic zone (NA)	−0.5	1067	2.3	1.3	13.8	1.001	6.8	0.10
Pacific zone (P)	−1.6	894	3.3	2.1	31.2	1.020	5.5	0.06
Southern cordillera zone (SC)	2.0	700	11.3	2.3	17.9	1.018	10.7	0.10
Southern Prairies zone (SP)	0.1	456	16.9	0.7	18.6	1.000	8.2	0.24
Southwestern Yukon zone (SY)	−4.4	426	6.7	1.0	23.3	1.013	4.2	0.47
Western James Bay zone (WJB)	−1.1	661	6.3	1.7	3.4	1.000	3.4	0.13
Western Ontario zone (WO)	−0.1	670	7.9	1.5	15.5	1.000	2.8	0.43
Western subarctic zone (WS)	−7.8	346	5.3	4.1	62.3	1.000	0.4	0.23

*Normals from Environment Canada weather stations, 1971–2000 (McKenney *et al*., 2011).
†Calculated for the fire season from Environment Canada weather stations, 1981–2010.
‡MODIS North American land cover 2000 (Pouliot *et al*., 2011).
§Canada 3-D digital elevation model (Natural Resources Canada, 2001).
**Last of the Wild project of the Wildlife Conservation Society (Sanderson *et al*., 2002).
††Canadian Forest Serivce National Fire Database (Parisien *et al*., 2006).

is a numerical rating of the moisture content of forest floor organic matter approximately 0–6 cm in depth. It is sensitive to substantial rain and has been found to be a good predictor of fire-spread potential in large boreal fires (Anderson, 2010). The rain-free period, as define here, starts when days become sufficiently warm and dry enough to result in a DMC >20 and ends with a fire-stopping event, which is usually associated with a substantial rain (e.g., 10–20 + mm), thus driving DMC below 20. This DMC threshold effectively distinguished fire-stopping events from days of light rain following extended dry periods when the DMC is high and fires can survive and rekindle during a subsequent dry period.

Because fires do not always ignite at the beginning of the rain-free period, a simple Monte Carlo simulation was performed to 'ignite' hypothetical fires at any given time in the rain-free period and 'extinguish' them when they reach a fire-stopping event (i.e., DMC < 20). This was achieved by simulating one fire per year, but for a very large number of years. As such, the effect of the number of ignitions on the PDS is the same for each zone. For each simulation, a weather station and an ignition date were randomly selected in a given fire zone. To determine an ignition date, the first step consisted of randomly selecting a year from the weather station's record. A month within the selected year was then chosen; however, because the number of ignitions varies by month, this selection was weighted based on the proportional representation from fire records in the Canadian National Fire Database (Canadian Forest Service, 2013) (Table S1). Finally, a day that was not a fire-stopping event within the month was randomly selected. Once an ignition date and station was determined, the number of days meeting the PSD criterion (FWI ≥ 19) was tallied from the ignition date until a fire-stopping event (DMC ≤ 20) was reached. For each fire zone, 10 000 iterations (i.e., simulated fires) were conducted to obtain robust estimates of the variability in the PSD. These simulations resulted in 10 000 data points representing the number of PSD for the 1953–2007 time period for each fire zone. Ultimately, the median of the frequency distribution ('distribution' hereafter, unless specified otherwise) of the PSD was used to represent the annual fire-spread potential in each fire zone.

Realized fire spread

Spread days (SD) are defined as days in which the spread distance exceed 240 meters, according to a set of simplifying assumptions. This value corresponds to daily fire progressions calculated for a nominal rate of spread of at least 1 m min^{-1} assuming a 4 h burning period each day and circular growth (c.f., Hirsch, 1996). This threshold was chosen based on simulation studies in the Boreal and northern Rocky Mountain regions (Parks *et al.*, 2012; Parisien *et al.*, 2013). In light of the simplifying assumptions, the selected threshold is synthetic and should not be expected to be indicative of the actual fire progression – it is simply a means to differentiate probable spread and nonspread days. As such, it does represent an effective and scalable (i.e., one that is not dependent of the final fire size) means of identifying days where substantial spread occur. To calculate rate of spread, we first generated fire progression maps for each fire using the methods described by Parks (2014), which maps day of burning for each 30 × 30 m pixel within a fire perimeter by spatially interpolating Moderate Resolution Imaging Spectroradiometer (MODIS) fire detection data (NASA MCD14ML product, Collection 5, Version 1). These fire detection data depict the date and location of actively burning MODIS pixels (Available at: http://activefiremaps.fs.fed.us/gisdata.php). Although these data are coarse resolution (pixel size = 1 km^2), their fine temporal resolution (two MODIS sensors, each passing twice/day) allows day-of-burning to be estimated at fairly fine spatial resolution via interpolation techniques. We used this approach to map fire progression because agency-generated fire progression maps are not available for the vast majority of the fires we analyzed and interpolated MODIS data provide reasonable estimates (Parks, 2014).

The dates of the MODIS fire detection data were interpolated using the ‘weighted by mean and distance’ (WMD) method (Parks, 2014), resulting in a spatially continuous representation of day of burning for each fire (e.g., Fig. 2) at a 30 – meter resolution. The WMD interpolation method is a weighted average of the five nearest MODIS fire detections; the weight of each fire detection is defined by the following equation:

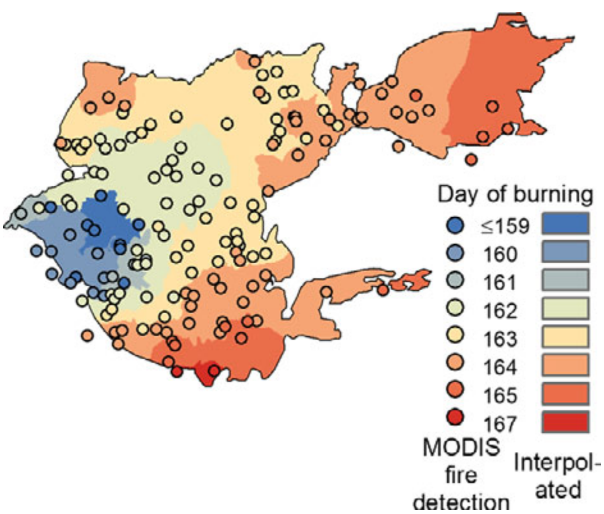

Fig. 2 Example of daily fire progression used to compile spread days. The daily MODIS fire detections (Julian day) (dots) are interpolated (Parks, 2014) for each active day of spread within the perimeter of fires from the Canadian National Fire Database (see Methods).

$$w_i = \left(\frac{1}{\left(\left| \left(\mathrm{jday}_i - \frac{\left(\sum_{i=1}^{5} \mathrm{jday}_i\right)}{5} \right) \right| + 1 \right) \times d_i} \right) \qquad (1)$$

where w_i is the weight of each fire detection, jday_i is the date of the fire detection, and d_i is the distance of the fire detection from the pixel being interpolated. Interpolated day of burning is based on the mean date of the five nearest fire detections and the distance of each fire detection to the subject pixel. This interpolation method was found to better correspond to agency-generated fire progression maps than other interpolation methods (e.g., nearest neighbor) (Parks, 2014). Barrett & Kasischke (2013) noted that there are two types of MODIS fire detections, one corresponding to an actively burning fire front and the other to ‘residual burning’ associated with, for example, smoldering combustion after the flaming front passed through. The methods developed and described by Parks (2014) for the most part eliminate areas of residual burning using a two-step process. First, in cases where there were two or more spatially coincident fire detections (i.e., fire was detected in the same pixel but on a different day), the one with the earliest date was retained and others were removed. Second, all interpolated day-of-burning regions that were ≤ 25 ha were removed and reassigned to day-of-burning values of the nearest region > 25 ha; Parks (2014) suggested that these small regions were often associated with residual burning. Daily rate of spread was then calculated from these fire progression maps assuming circular fire growth (Parisien *et al.*, 2013) and the previously described threshold (240 m day^{-1}) was applied to identify SD. This process identified the number of SD per fire zone per year; we used the median value per zone to represent annual realized spread days.

We limited our fire progression analyses to fires ≥200 ha as defined by the Canadian National Fire Database (Canadian Forest Service, 2013) (Table 2) to avoid the data quality issues associated with small size fires, notably incomplete reporting. Furthermore, small fires account for a small fraction of the area burned, as fires ≥200 ha are responsible for approximately 97% of the total burned area in Canada (Stocks *et al.*, 2003). Consequently, daily spread (i.e., fire progression) was estimated for 2246 fires from 2001–2011 with sizes ranging from 200 ha to 576 648 ha. About 15% of the fires in the Canadian Forest Service (2013) fire history dataset were not detected by the MODIS; these undetected fires were generally small (median size = 485 ha) and made up less than 2.0% of the total burned area.

Comparison of potential and realized fire spread

Potential to realized fire spread was compared by zone by calculating the ratio of the median SD and PSD (hereafter, SD : PSD). A high SD : PSD (i.e., closer to 1) indicates relative similarity between the values of SD and PSD for a given zone and thus describes a greater chance of the spread potential being realized. As was the PSD and SD, SD : PSD were mapped by zone to show the spatial variation across the study area. Because the frequency distributions for both SD

Table 2 Summary statistics by fire zone of the MODIS-derived fires (2001–2011) used in the analysis

Fire zone	Number of fires	Mean fire size ± SD (ha)	Median fire size (ha)	Minimum fire size (ha)	Maximum fire size (ha)	Total area burned (ha)
Eastern James Bay zone (EJB)	257	9 811 ± 19 844	3 122	206	136 259	2 560 591
Eastern subarctic zone (ES)	57	12 511 ± 22 384	4 317	201	99 622	825 745
Eastern temperate zone (ET)	44	3 063 ± 5 441	762	214	26 460	134 778
Great Bear Lake zone (GBL)	144	7 924 ± 22 407	1 891	211	175 985	1141 059
Great Slave Lake zone (GSL)	198	13 144 ± 45 652	1 999	220	576 649	2 602 542
Interior cordillera zone (IC)	133	2,938 ± 4,941	766	201	26 895	390 731
Lake Athabasca zone (LA)	561	11 736 ± 29 631	3 076	203	453 492	6 583 903
Lake Winnipeg zone (LW)	282	7 085 ± 12 100	2 041	209	77 489	1 997 928
Northern Atlantic zone (NA)	58	5 286 ± 8 186	2 258	229	41 904	311 881
Pacific zone (P)	142	4 005 ± 7 018	1 142	201	39 073	568 757
Southern cordillera zone (SC)	194	4 008 ± 7 347	1 352	206	67 743	777 626
Southern Prairies zone (SP)	200	6 600 ± 20 993	1 594	202	2 42 303	1 320 082
Southwestern Yukon zone (SY)	144	9 402 ± 13 489	4 352	216	97 665	1 353 879
Western James Bay zone (WJB)	27	2 768 ± 6 724	608	220	27 141	74 728
Western Ontario zone (WO)	82	9 207 ± 22 284	1 505	230	1 47 611	754 992
Western subarctic zone (WS)	110	3 503 ± 5 439	1 349	214	38 999	385 281

and PSD were nonnormal, but of similar shape, it was more meaningful to compare their medians than their means. This interzone comparison was also made among the slopes of the distributions for exploratory purposes, but the results were virtually identical in terms of spatial variation to those of the medians for both PSD and SD; therefore, these results were not shown.

Environmental correlates of potential and realized spread

The association between the median of PSD, SD, and SD : PSD and the environmental descriptors of Table 1 were examined using Pearson's correlation coefficients. These analyses were considered as exploratory and were not intended to provide an in-depth assessment of the environmental of drivers of potential and realized fire spread.

Conversion of the distribution of spread days from the distribution of potential spread days

In concept, a SD can only occur on a PSD; therefore, realized and potential fire spread are related. Because their respective distributions have similar shapes, it is feasible to estimate one to the other using a simple analytical solution. Given the challenge of obtaining SD estimates – rarely are wildfires routinely mapped on a daily basis as part of fire operations – it is useful to devise a way to obtain distributions of realized fire spread from simple daily weather observations. To quantify the relationship between the frequency distributions of PSD and SD, we first standardized the log-transformed frequency distributions as

$$f' = (f - \mu_f)/\sigma_f \quad (2)$$

where f 'is the standardized log-transformed frequency, f is the logarithm of the frequency, μ_f is the mean of f, and σ_f is its standard deviation. The resulting transformed values have a mean of zero (μ_f = 0) and a SD of one (σ_f = 1).

The fitted regressions are then written as follows

$$f_1' = a_1 + b_1\text{PSD} \quad (3)$$

$$f_2' = a_2 + b_2\text{SD} \quad (4)$$

where, PSD = Potential spread day, SD = realized spread day, and $f_1{}'$ and $f_2{}'$ are the standardized log-transformed potential and realized spread day frequencies.

By Eqns (3) and (4),

$$\text{SD} = \frac{a_1 - a_2}{b_2} + \frac{b_1}{b_2}\text{PSD} \quad (5)$$

Equation (5) is thus the transformation function used between potential and realized spread. Following this procedure, linear regression models were fitted for PSD and SD distributions using the standardized log-transformed frequencies as predictor variable for each fire zone (Fig. 3). Transformation models of SD were then formulated following Eqn (5) for each fire zone. The resulting R-squared values served as an indicator of goodness of fit, providing a means of comparison between the linear regression model within each fire zones.

Results

Potential fire spread, realized fire spread, and the comparison between potential and realized fire spread

Potential fire spread, expressed as the medians of the values of PSD, vary substantially among fire zones (Fig. 4a; Table S2), ranging from 6 days in the eastern subarctic zone to 63 days in the southern cordillera zone. In general, potential fire spread is higher in the southern and western fire zones, compared to the

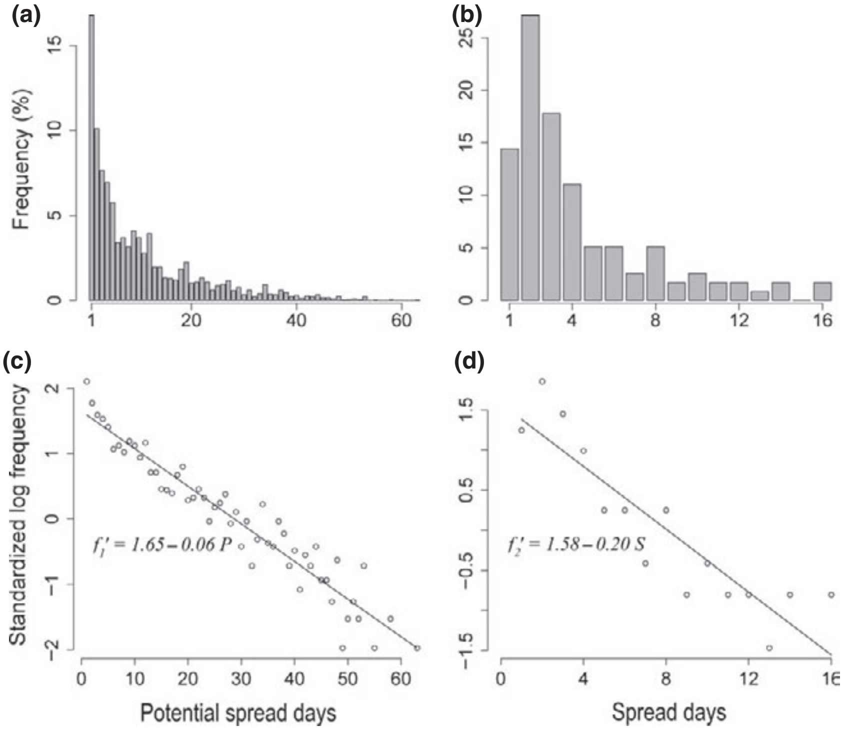

Fig. 3 An example of the frequency distribution of potential spread days (PSD) (a) and spread days (b), as well as the linear regression fit between the log-transformed frequency and PSD (c) and SD (d) for the Pacific zone.

northern and eastern ones, respectively. Realized fire spread, obtained from the distributions of SD, is also highly variable across Canada (Fig. 4b), ranging from 3 to 13.5 days (see also Flannigan & Wotton, 2001) in the western James Bay and Lake Athabasca zones, respectively. The realized spread also generally increases from east to west, but unlike PSD there is no strong latitudinal gradient in SD.

Likewise, the ratio of realized fire spread to potential fire spread (SD : PSD), calculated by dividing SD by PSD, is highly variable among fire zones (Fig. 4c), ranging from 0.14 in the southern cordillera zone to 0.83 in the eastern subarctic zone. There is a generally increasing gradient from south to north. The SD : PSD was >0.5 in the eastern subarctic, the Lake Athabasca, and the western subarctic zone (Table S2), indicating that over 50% of the PSD materialized as realized fire spread.

Environmental correlates of potential and realized spread

The main correlates to potential fire spread are seasonal severity rating (SSR) (r = 0.60), which is a weather-based index of fire danger, and surface-area ratio (SAR) (r = 0.61), a measure of the topographic roughness (Table 3). Realized spread correlates most strongly with mean total precipitation (r = −0.70) and mean annual area burned (r = 0.72). The SD : PSD correlates with several environmental descriptors. The strongest correlations are with mean temperature (r = −0.75) and the mean human footprint index (r = −0.75); however, these two variables covary, as the human impact over the Canadian forest landmass is concentrated at lower latitudes. The degree at which potential fire spread is realized also correlates positively with the proportion of coniferous cover (r = 0.60). Surprisingly, SD : PSD also correlates positively with the percent nonfuel (r = 0.68), as the northern fire zones have a higher proportion (up to 62.3%) of open water and exposed rock than the southern ones (Table 1).

Conversion of the distribution of spread days from the distribution of potential spread days

The linear regression models between PSD and its standardized log frequency were statistically significant ($P \le 0.05$) for all fire zones, with an average of $R^2 = 0.80$, ranging between 0.38 (Northern Atlantic zone) and 0.93 (Great Slave Lake zone) (Table 4). The linear regression models between SD and its standardized log frequency were slightly weaker, with an averaged $R^2 = 0.74$, ranging between 0.56 (Northern Atlantic zone) and 0.89 (Lake Athabasca zone). The simple conversion factor for the regression parameters

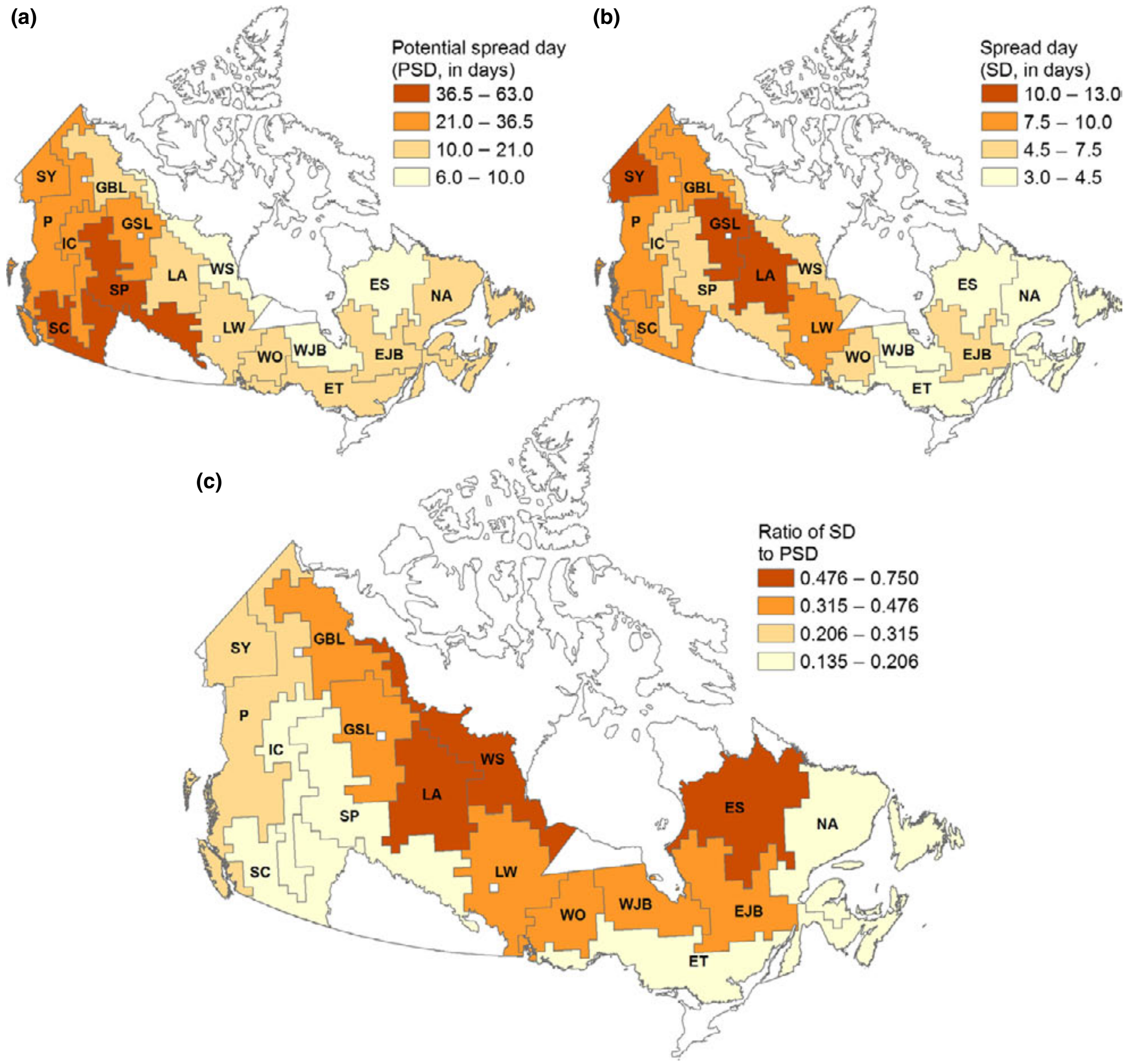

Fig. 4 Potential and realized fire spread across Canada. The median values of the frequency distributions of the potential spread days (PSD) (a) and spread days (SD) (b), as well as the ratio of medians of the distributions of SD and PSD by fire zone. A high ratio (i.e., closer to 1) indicates high realized fire spread relative to the potential fire spread.

was, as expected, variable among fire zones, depending on the discrepancies between the median and shape of the PSD and SD distributions.

Discussion

This study provides the first direct comparison of the weather-based fire-spread potential and observed fire spread (i.e., the realized fire spread). Its results highlight the substantial variability in fire spread – whether potential or realized – among fire zones, as well as within each zone. Despite high variability in the number of days of potential and realized spread observed within each zone, this variability had some fairly well-defined bounds. In fact, the linear shape of the log-transformed frequency distribution is akin to power-law distribution reported in fire size distributions (Malamud *et al.,* 1998; Moritz *et al.*, 2011; but see Lehsten *et al.*, 2014), suggesting some degree of self-regulation in fire regimes. Among fire zones, the Canada-wide variability in potential and realized fire spread provides a critical step in understanding how and why

Table 3 Correlation coefficients between the spread variables (potential spread days [PSD], spread days [SD], and SD : PSD ratio) and the environmental variables found in Table 1

Environmental Variables	PSD	SD	SD : PSD Ratio
Mean temperature* (°C)	0.37	−0.39	−0.75
Mean total precipitation* (mm)	−0.10	−0.70	−0.43
Mean SSR†	0.60	0.43	−0.32
Conifer : other‡	−0.16	0.12	0.60
Percent nonfuel‡ (%)	−0.25	0.16	0.68
Mean surface-area ratio§	0.61	0.21	−0.45
Mean human footprint index**	0.43	−0.42	−0.75
Mean annual area burned†† (%)	−0.10	0.72	0.41

*Normals from Environment Canada weather stations, 1971–2000 (McKenney *et al.*, 2011).
†Calculated for the fire season from Environment Canada weather stations, 1981–2010.
‡MODIS North American land cover 2000 (Pouliot *et al.*, 2011).
§Canada 3-D digital elevation model (Natural Resources Canada, 2001).
**Last of the Wild project of the Wildlife Conservation Society (Sanderson *et al.*, 2002).
††Canadian Forest Service National Fire Database (Parisien *et al.*, 2006).

fires become large. The interzone variability in potential fire spread captures climate and weather patterns across Canada, whereas the discrepancy between potential and realized fire spread is chiefly due to bottom-up constraints on fire progression. Our results thus provide further insights into the relative role of climate (i.e., top down) and nonclimatic (i.e., bottom-up) controls on fire regimes in temperate and boreal forests.

The spatial variability in potential fire spread across Canada is, as expected, highly coherent with well-documented patterns in fire-conducive weather (Simard, 1973; Flannigan & Harrington, 1988; Skinner *et al.*, 1999). Even though the metrics we used for our analysis differs substantially from those of previous studies, our results support previous findings that southern fire zones have generally higher potential fire spread than the northern ones and that the potential for prolonged droughts is a major control on fire spread in Canada (Girardin *et al.*, 2006). Even though some fire zones have an overall substantially lower potential for fire spread than others, high values of PSD have been observed in all of the fire zones. Indeed, each zone can have – and has at some time in the past – experienced fires that have burned for several weeks. For example, the north Atlantic zone, which has a cold moist climate that subdues fire activity, has historically experienced some very large fires (Foster, 1983). Similarly, the Western James Bay zone, which has the second lowest potential for fire spread, experienced one of the largest fires in modern Canadian history in 2013 (the Eastmain fire; approximately 700 000 ha).

Table 4 Linear regression model of potential spread days (PSD) and spread days (SD) as a function of their respective log-frequency distribution. Parameter a represents the intercept, parameter b is the regression slope, and the standard error of these estimates are shown in the parentheses. Note that all linear regression are significant ($p \leq 0.05$)The linear transformation indicates the changes that need to be made to the spread days (SD) regression equation to be equal to that of the potential spread days (PSD) regression.

	Potential spread days			Spread days			Linear transformation PSD → SD	
Fire zone	a	b	R^2	a	b	R^2	a	b
Eastern James Bay zone (EJB)	1.61 (0.16)	−0.11 (0.01)	0.84	1.72 (0.21)	−0.29 (0.03)	0.89	0.38	0.39
Eastern subarctic zone (ES)	1.62 (0.30)	−0.27 (0.04)	0.78	1.18 (0.59)	−0.25 (0.11)	0.37	−1.75	1.06
Eastern temperate zone (ET)	1.57 (0.14)	−0.09 (0.01)	0.83	1.47 (0.48)	−0.40 (0.12)	0.69	−0.25	0.22
Great Bear Lake zone (GBL)	1.63 (0.10)	−0.08 (0.00)	0.89	1.06 (0.24)	−0.08 (0.02)	0.63	−6.78	0.92
Great Slave Lake zone (GSL)	1.66 (0.07)	−0.05 (0.00)	0.93	1.16 (0.20)	−0.09 (0.01)	0.72	−5.73	0.63
Interior cordillera zone (IC)	1.61 (0.09)	−0.05 (0.00)	0.88	1.61 (0.24)	−0.23 (0.03)	0.82	−0.03	0.21
Lake Athabasca zone (LA)	1.54 (0.15)	−0.08 (0.01)	0.77	1.48 (0.17)	−0.11 (0.01)	0.81	−0.55	0.68
Lake Winnipeg zone (LW)	1.50 (0.17)	−0.08 (0.01)	0.74	1.43 (0.19)	−0.15 (0.02)	0.83	−0.52	0.51
Northern Atlantic zone (NA)	0.86 (0.22)	−0.03 (0.01)	0.38	1.42 (0.49)	−0.34 (0.11)	0.62	1.63	0.10
Pacific zone (P)	1.65 (0.08)	−0.06 (0.00)	0.92	1.58 (0.24)	−0.20 (0.03)	0.79	−0.37	0.29
Southern cordillera zone (SC)	1.66 (0.05)	−0.03 (0.00)	0.91	1.47 (0.15)	−0.16 (0.01)	0.90	−1.15	0.16
Southern Prairies zone (SP)	1.61 (0.08)	−0.03 (0.00)	0.86	1.31 (0.27)	−0.16 (0.03)	0.71	−1.86	0.21
Southwestern Yukon zone (SY)	1.61 (0.08)	−0.04 (0.00)	0.89	1.47 (0.20)	−0.12 (0.01)	0.76	−1.21	0.36
Western James Bay zone (WJB)	1.70 (0.19)	−0.23 (0.02)	0.89	0.97 (0.53)	−0.26 (0.11)	0.52	−2.82	0.88
Western Ontario zone (WO)	1.50 (0.11)	−0.09 (0.01)	0.90	1.49 (0.31)	−0.24 (0.04)	0.75	−0.05	0.36
Western subarctic zone (WS)	1.21 (0.36)	−0.12 (0.03)	0.43	1.42 (0.26)	−0.19 (0.03)	0.77	1.11	0.63

Despite some similarities, patterns of realized spread differ substantially from those of potential spread in all fire zones. The fairly strong negative correlation between mean annual precipitation and median SD among zones suggests that, as is the case with potential fire spread, realized spread is limited in eastern Canada by more frequent precipitation. Our results also strongly support the claims that, even though Canadian fire regimes are strongly regulated by weather and climate, bottom-up factors such as vegetation and topography do constrain fire spread (Gralewicz *et al*., 2011; Parisien *et al*., 2011b; Boulanger *et al*., 2013). The spatial patterns of realized spread across Canada are strongly coherent with those of area burned in Canada (Stocks *et al*., 2003), which leads us to believe that it is mainly fire spread, not variability in fire ignitions, that accounts for fire activity (i.e., area burned) in Canada. One reason why the southern fire zones exhibit both low realized spread and total area burned relative to other fire zones is that these warmer areas generally support less flammable vegetation, such as deciduous and mixedwood forests in the boreal biome and tall closed-canopied conifer forests in the western temperate forests (Nitschke & Innes, 2008; Parisien *et al*., 2011b).

In Canada, the degree to which the potential for spread is realized varies substantially across the country. Factors such as a lack of ignition, the quantity and arrangement of flammable vegetation, and topography may hamper potential fires from being realized (Hirsch, 1996). In the mountainous areas (e.g., the Southern cordillera and the Southern prairie zones), even though potential fire spread is high due to hot and dry climates, realized spread is limited by the natural fragmentation caused by topographic complexity (Kellogg *et al*., 2008; Parks *et al*., 2012). In the boreal forest, the strong south-to-north gradient in increasing realized-to-potential ratio supports the intuition of some (Flannigan & Harrington, 1988; Parisien *et al*., 2011b) that some environmental factors largely compensate for the relatively low potential spread in the North: longer day lengths at the time of peak fire activity, a high proportion of the highly flammable vegetation (i.e., relatively short and more open-canopied conifer forests), and a quasi-absence of fire suppression. It is highly plausible that in some parts of Canada, realized spread could be constrained either directly through fire suppression (Martell & Sun, 2008; Finney *et al*., 2009) or indirectly through land-cover changes (Krawchuk & Cumming, 2011). However, even though the ratio between realized and potential spread is generally lower in the most populated zones, many other factors could be contributing to this phenomenon. There is thus a need for more detailed studies of fire spread to better understand how fire suppression and land management alter fire regimes in Canada.

One methodological advance of this study is that we have devised a way in which daily fire-spread distributions can be estimated from distributions of daily weather observations. Assuming that we have fairly high-quality daily projections of climate in hand, it would be possible to evaluate how changes in the distributions of PSD would be reflected in terms of realized spread. We posit that the degree to which these distributions may change in the future may be crucial to understanding and predicting future fire regimes. Given that fires grow as power functions (nonlinear), area burned is highly sensitive to change in fire duration. As a result, seemingly minor changes in the frequency distribution of potential and realized fire spread may yield disproportionally large changes in total area burned (Anderson, 2010; Parisien *et al*., 2011a). Because a conversion from PSD to SD incorporates information pertaining to the frequency and timing of spread, it could provide insights into future of fire regimes in Canada that may not be captured in studies that use climatic averages to predict future fire activity (Balshi *et al*., 2009; Moritz *et al*., 2012).

Data and modeling considerations

Although the weather-based metrics used to identify potential spread days and fire-stopping days were based on those used in fire operations across Canada, they are somewhat arbitrary. Under certain conditions, fires may burn during nonpotential spread days and, conversely, can become extinguished during days with little or no rain. In order to assess the sensitivity of our results to the potential spread days and fire-stopping days, we considered plausible alternative thresholds (e.g., Initial Spread Index = 8.7 for PSD; DMC = 12, 15, 25, and 30 for fire-stopping events). These alternative metrics yielded very similar results to those that were reported in this study and were thus not pursued. We also explored whether the scheme used to separate spread vs. nonspread days (based on rate of spread) was robust by using values that were half (0.5 m min^{-1}) and double (2 m min^{-1}) of the one we selected. Encouragingly, the frequency distributions of days of PSD and SD of each fire zone normally follow an exponential distribution (e.g., Fig. 3) regardless of the thresholds that were used in the simulations and produced very similar spatial patterns across Canada.

The results are subject to inaccuracies in the source data, especially with respect to the data distributions of SD. The MODIS-based fire detection data is subject to noise, given that some active fire areas may not be detected because of obscuring smoke and cloud cover. Also, depending on the time of the satellite capture, vegetation whose combustion has a short residence time (e.g., grasses, shrubs) may not register. However, even if this is the case the interpolation among days of burning may still be correct (Parks, 2014). Because small progressions are more likely to be undetected, the uncertainty in the SD estimates is more pronounced in smaller fires (<500 ha) than in larger ones (Henderson *et al.*, 2010). Although this leads to an underestimate in the number of fires with one or a few spread days, this is likely to result in only minor distortions in slope estimates.

We also examined whether the mismatch in observation period between the PSD and SD datasets created a bias in our results. By splitting the PSD observation period in half, we determined that the former half (no overlap with SD period) and latter half (large overlap with SD period) yielded virtually identical results. Whereas the PSD distributions were not undermined by lack of data, it is difficult to assess to what degree this may be the case with the SD distributions. In some fire zones, 12 years of fire data may not be sufficient to records all of the extremes (i.e., very large fires) necessary to establish a stable distribution, but the number of fires in most zones appears adequate (e.g., >100 fires). Although a longer observation period for the MODIS-based data would have been preferable, the coherence of median SD among fire zones and the generally good linear fits of their log-transformed distributions suggest that our results are robust.

Applications and future work

Several decades of fire–climate studies in Canada have convincingly demonstrated that longer potential burning periods (i.e., droughts) during the fire season are likely to produce larger and more severe fires (e.g., Wotton & Flannigan, 1993; Girardin & Sauchyn, 2008; Groisman & Knight, 2008; Meyn *et al.*, 2010). However, the mechanisms by which fires grow and become large have rarely, if ever, been quantified at the biome level. This is because, until recently, a lack of available data has impeded our ability to obtain quantitative estimates of the daily fire progression for large areas. This study consists of a first step in providing a joint characterization of the potential for spread and the on-the-ground realization of this potential. By the same token, the results of this study underline the fact that, even though there has been a fair amount of laboratory and field research to understand the factors affecting ignition (Beverly & Wotton, 2007; Magnussen & Taylor, 2012), extinguishment of fire in temperate and boreal areas is poorly understood.

The methodology described in this study could be applied to almost any fire-prone part of the world: daily weather observations are collected virtually everywhere (Hijmans *et al.*, 2005) and, since 2001, MODIS fire detection data have been collected globally (Giglio *et al.*, 2009). The possible applications of assessments of potential and realized spread are numerous. For example, understanding and quantifying the relationship between PSD–SD is a necessary step in landscape simulation models that explicitly model the ignition and spread of fires in order to map fire probability (Finney *et al.*, 2011; Parisien *et al.*, 2011a). A more in-depth knowledge of fire spread not only broadens our understanding of fire regimes, but may also improve our ability to predict their changes (Abatzoglou & Kolden, 2013; Boulanger *et al.*, 2013). Although mean annual or monthly fire-weather conditions may be correlated with fire activity, these coarse temporal metrics invariably obscure some of the day-to-day information characterizing fire spread (Flannigan *et al.*, 2005; Balshi *et al.*, 2009; Moritz *et al.*, 2012). More refined predictions, whether at the scale of landscapes of continents, will help up better anticipate changes in future fire activity and the ecological and social change that may ensue.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Monthly proportional number of fires ≥200 ha for each fire zone based on the Canadian National Fire Database (Canadian Forest Service, 2013), which includes fires from 1946 to 2010. These monthly proportions were used to model the seasonal variability in fire occurrences in each fire zones in the fire simulations (see Methods).
Table S2. The medians of the distributions of potential spread days (PSD), spread days (SD), and SD : PSD for each fire zone, as mapped in Fig. 4.