Characterization of wildfire regimes in Canadian boreal terrestrial ecosystems

Yueyang Jiang[A,E], *Qianlai Zhuang*[B], *Mike D. Flannigan*[C] *and John M. Little*[D]

[A]Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA.

[B]Department of Earth and Atmospheric Sciences and Department of Agronomy, Purdue University, West Lafayette, IN 47907, USA.

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

[D]Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton, AB, T5H 3S5, Canada.

[E]Corresponding author. Email: jiang5@purdue.edu

Abstract. Wildfire is a major disturbance in boreal terrestrial ecosystems. Characterizing fire regimes and projecting fire recurrence intervals for different biomes are important in managing those ecosystems and quantifying carbon dynamics of those ecosystems. This study used Canadian wildfire datasets, 1980–1999, to characterize relationships between number of fires and burned area for 13 ecozones and to calculate wildfire recurrence intervals in each ecozone. For the study period, wildfires were found to follow power–law relationships between frequency densities (number of fires normalized to unit bins) and burned areas in all ecozones. Power–law frequency–area relationships also held for both anthropogenic fires and natural fires in the 1980s and 1990s. For each Canadian ecozone using the parameters of the power–law frequency–area distributions, fire recurrence intervals were then calculated for wildfires equal to or larger than a given size of burned area. Fire recurrence intervals ranged from 1 to 32 years for burned areas $>2\,km^2$, and from 1 to 100 years for burned areas $>10\,km^2$ in every $10\,000$-km^2 spatial area for each ecozone. The information obtained through characterizing the wildfires and the fire recurrence intervals calculated in this study will provide guidance to wildfire risk managers throughout Canada. The findings of this study will also be a benefit to future efforts in quantifying carbon dynamics in Canadian boreal terrestrial ecosystems.

Additional keywords: carbon dynamics, ecozone, fire management, power–law frequency–area statistics, recurrence interval.

Introduction

Wildfires play a significant role in ecosystem carbon cycling over the boreal region (e.g. Flannigan *et al.* 1998; Amiro *et al.* 2000; Wooster *et al.* 2003; Randerson *et al.* 2006; Zhuang *et al.* 2006; Balshi *et al.* 2007). Fire activities also affect ecosystem structure and permafrost degradation, further affecting carbon cycling in this region (Zhuang *et al.* 2002; Harden *et al.* 2006). To adequately quantify the effects of future fire disturbance on carbon cycling, a characterization of fire recurrence intervals and burned areas is needed. In addition, more information on the relationships between number of fires and burned area will also help fire management in this region. To date, projecting these fire characteristics in the region is still a challenge, although the relationships between fires and their environmental and climatic factors have been extensively explored (e.g. Stocks *et al.* 1989, 2002; Oldford *et al.* 2006; Maingi and Henry 2007; Xiao and Zhuang 2007; Martell and Sun 2008). Some studies focus on analyzing the number of fires and burned area based on existing fire data (e.g. Kasischke and Turetsky 2006), whereas other studies focus on analyzing the effects of individual factors such as human activity (e.g. Mollicone *et al.* 2006; Calef *et al.* 2008).

Recent fire analyses have also strived to characterize wildfire regimes focusing on the relationships between frequency (number of fires) and burned area (Malamud *et al.* 1998, 2005; Cui and Perera 2008). For example, in an effort to examine forest fires in the conterminous USA, Malamud *et al.* (2005) found that despite the complexities concerning their initiation and propagation, wildfires exhibit power–law frequency–area statistics over many orders of magnitude. Their study further calculated fire recurrence intervals based on the established power–law relationships. Similar studies also used the power–law statistical method to characterize wildfire regimes in different countries including McCarthy and Gill (1997) for Australia, Ricotta *et al.* (1999, 2001) for Italy and Spain, Niklasson and Granstrom (2000) for Northern Sweden, Song *et al.* (2001) for China, Zhang *et al.* (2003) for Russia and Fiorucci *et al.* (2008) for Italy. These studies suggest that wildfires exhibit robust power–law relationships between fire frequency and burned area at regional scales. A summary of many of these and other studies, as of 2006, is given in Millington *et al.* (2006).

While much progress has been made to characterize wildfires in Canada in terms of their controls and factors affecting

observed burned areas, more work is needed to examine the large-scale statistical relationships between number of fires and burned area as has been done in many studies for other regions. Some studies have tried to characterize the frequency–area relationships in some regions of Canada (e.g. Turcotte and Malamud 2004); however, more thorough studies based on a complete fire database are needed. Here, we carried out such a study to characterize frequency–area distribution and calculate fire recurrence intervals by analyzing the statistical properties of wildfires within each ecozone in Canada.

Materials and methods

Data description

Our analysis was based on a wildfire dataset from the Canadian Forest Service, consisting of 152 769 fires over the time period from 1980 to 1999. The database contains two inventories of historical fire occurrence records (Flannigan and Little 2002; Stocks *et al.* 2002): (i) the Small and Medium Fire Database (SMFDB, fire burned size $A_F < 2\,\text{km}^2$); (ii) the Large Fire Database (LFDB, fire burned size $A_F \geq 2\,\text{km}^2$). Both datasets include information on fire location, start date, fire size and cause. They cover both anthropogenic and non-anthropogenic fires in forests, grasslands and in non-urban areas.

The main limitation of the SMFDB is that the data are organized by various provinces, territories and parks, all of which have different methods for estimating and reporting burned area. In this study, we discarded fires whose burned area $A_F < 0.001\,\text{km}^2$ because they are not complete or not accurate due to rounding or the method of recording. After discarding, in the SMFDB (1980–1999), the percentages of human-caused, lightning and unknown-reason fires are 51, 48 and 1% respectively.

The limitations of the LFDB have been recognized in previous studies, and include: (i) estimates of burned area are the result of aerial mapping or analysis of satellite imagery, and it is thought that more recent fire size estimates tend to be more accurate (Stocks *et al.* 2002); (ii) some fires in remote northern regions occurred between 1959 and the mid-1970s are missing; (iii) fire reports for the 1970s in Saskatchewan have been lost after digitizing, and the only record available is for the polygons of fires >1000 ha (Stocks *et al.* 2002). To overcome these limitations and also to have an identical temporal scale with the SMFDB, we only used data from the LFDB for the years 1980–1999. In the LFDB (1980–1999), the percentages of human-caused, lightning and unknown-reason fires are 18, 80 and 2% respectively.

The combined database of the SMFDB and the LFDB had 128 600 fire-occurrence records (for fire sizes $A_F \geq 0.001\,\text{km}^2$) (Fig. 1). In this combined database (1980–1999), the percentages of human-caused, lightning and unknown-reason fires are ~49.2, 49.3 and 1.5% respectively. We analyzed the fire data for each Canadian ecozone using the classification system developed by the Ecological Stratification Working Group (1996). The analysis at ecozone level was conducted since each ecozone incorporates distinctive regional ecological factors (e.g. climate and vegetation) to some degree, and is much larger than the area for an individual fire. It transcends provincial boundaries, thus better reflecting the continuity of the landscape (Amiro *et al.* 2001; Stocks *et al.* 2002).
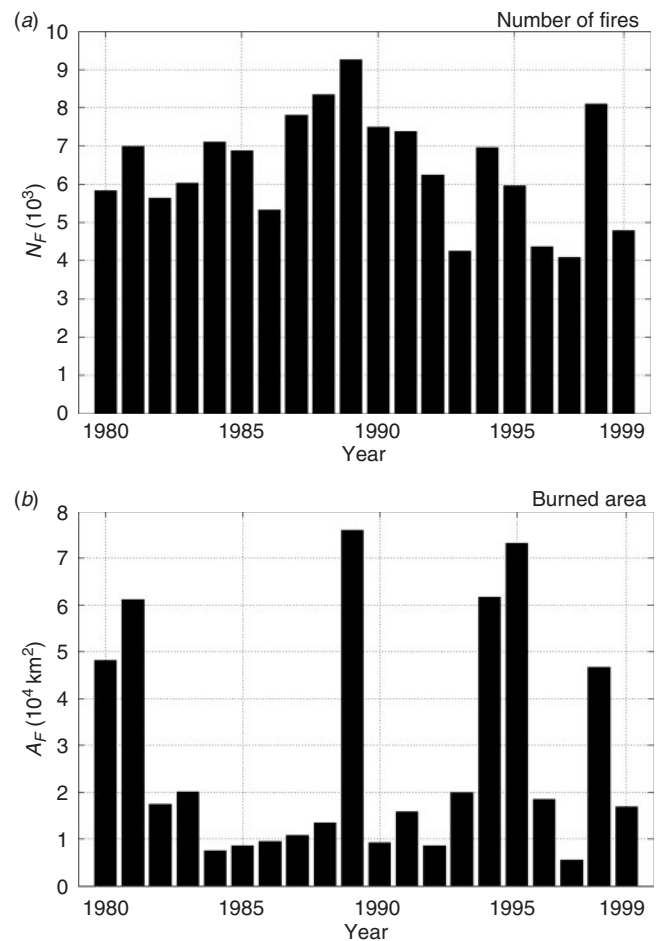

Fig. 1. Annual (*a*) fire numbers and (*b*) burned area in Canada from 1980 to 1999, with burned areas $A_F \geq 0.001\,\text{km}^2$.

Relationships between frequency density and burned area

To characterize the relationship between number of fires and burned area for each ecozone, we first defined the frequency density $f(A_F)$ as below, following Malamud *et al.* (2005):

$$f(A_F) = \frac{\Delta N_F}{\Delta A_F} \qquad (1)$$

where ΔN_F is the number of fires in a 'bin' of width ΔA_F. Here, a 'bin' is a range of burned areas. For instance, if there are five wildfires ($\Delta N_F = 5$) with burned areas that have occurred in a bin that is from 0.2 to 0.3 km^2 ($\Delta A_F = 0.1\,\text{km}^2$), then the frequency density is $f(A_F) = \Delta N_F/\Delta A_F = 5/(0.1\,\text{km}^2) = 50\,\text{km}^{-2}$. In other words, there are 50 fires in an equivalent 'unit' bin of 1 km^2. Since there are many more small fires than large ones, we increased the bin size logarithmically as the fire size increases. We plotted the frequency density as a function of burned area and found that the power–law is a robust fit $f(A_F) = aA_F^{-b}$ with burned area A_F and constants a and b, as presented in Malamud *et al.* (2005). Here, we calculated A_F as the average of lower and upper boundary values of each bin. For instance, if the bin is from 0.02 to 0.1 km^2, the A_F is $[0.02 + 0.1]/2 = 0.06\,\text{km}^2$. We left off
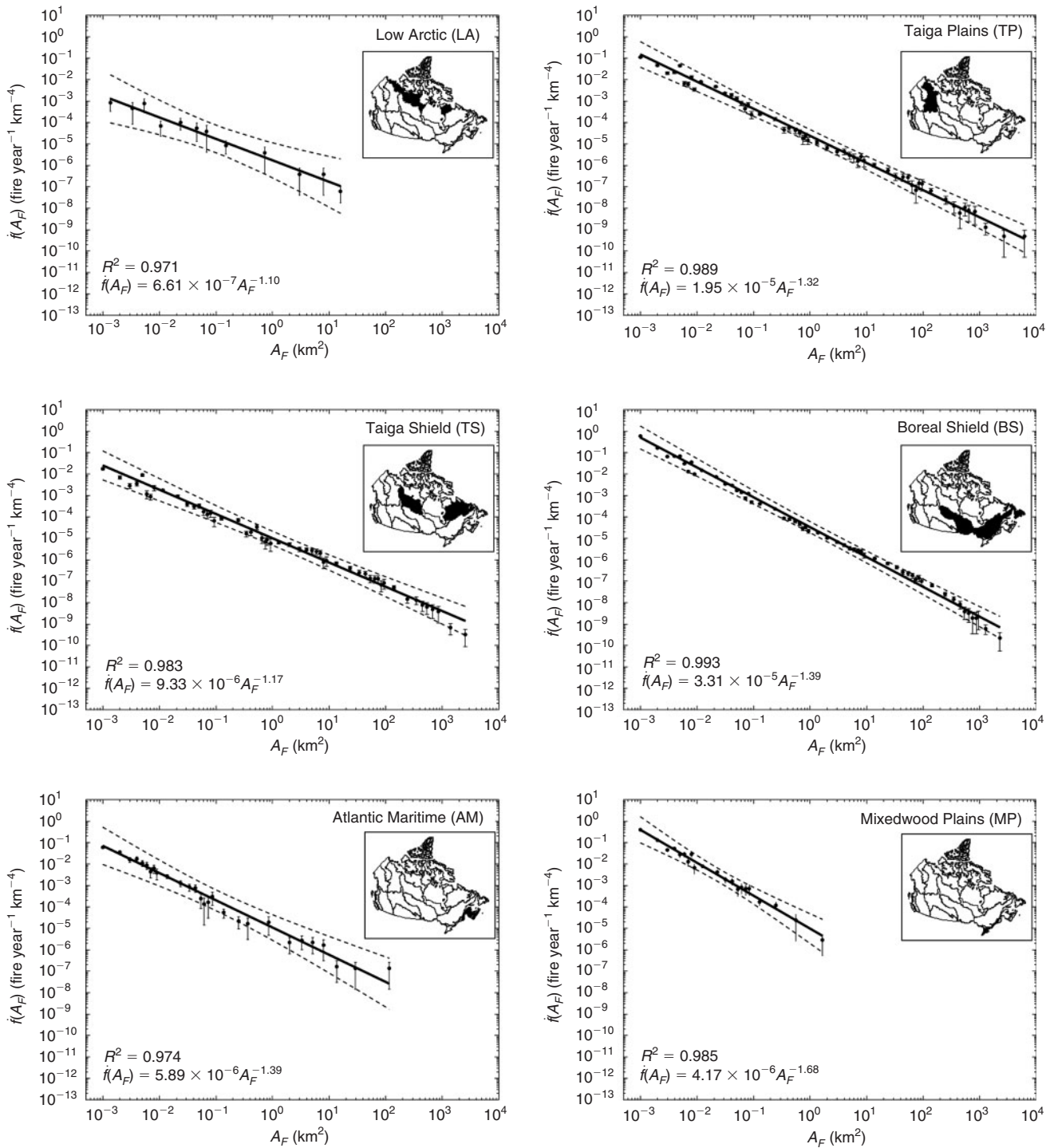
Fig. 2.   Normalized frequency–area wildfire statistics for 13 ecozones and the whole of Canada (1980–1999). Points in the above figures are normalized frequency densities $\dot{f}(A_F)$ (normalized by observation length in years and the vegetated area within each ecozone) as a function of burned area A_F which is determined by the average value of the upper and lower bounds of each bin. Dashed lines represent lower and upper 95% confidence intervals. The solid line shows the best least-square fit of $\log \dot{f}(A_F) = -\beta \log(A_F) + \log \alpha$. The coefficient of determination (R^2) is also shown in each figure. The vertical error bar is calculated with $\pm 2\sqrt{\Delta N_F}$ (normalized by the length of observation in years and the vegetated area in each ecozone). Vertical error bars (± 2 s.d.) are approximately equivalent to lower and upper 95% confidence intervals (± 1.96 s.d.).
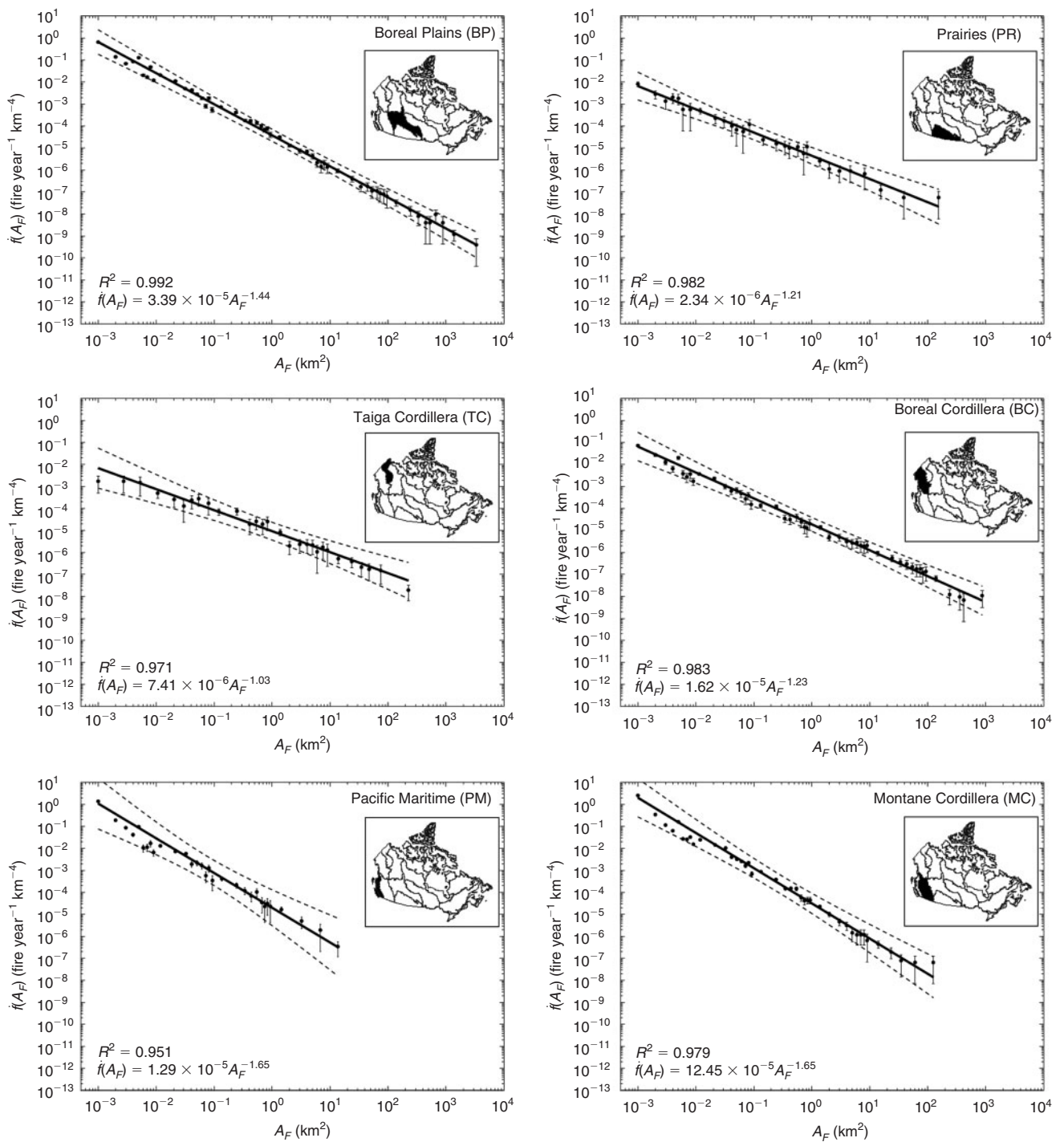
Fig. 2. (*Continued*)

the 'final' bin in the fitting of $f(A_F)$ *v.* A_F. To facilitate the comparison between ecozones following Malamud *et al*. (2005), we normalized $f(A_F)$ using the vegetated area (areas covered by vegetation excluding urban areas) in each ecozone, and the length t of fire records (here, 20 years). We then obtained the normalized fire frequency density $\dot{f}(A_F)$ (fire year^{-1} km^{-4}) and plotted it as

a function of burned area A_F. A robust fit was found in the form:

$$\dot{f}(A_F) = \alpha A_F^{-\beta} \qquad (2)$$

where α and β are constants. When $\beta = 0$, the number of large fires is equal to the number of small fires, per 'unit' bin. Eqn 2
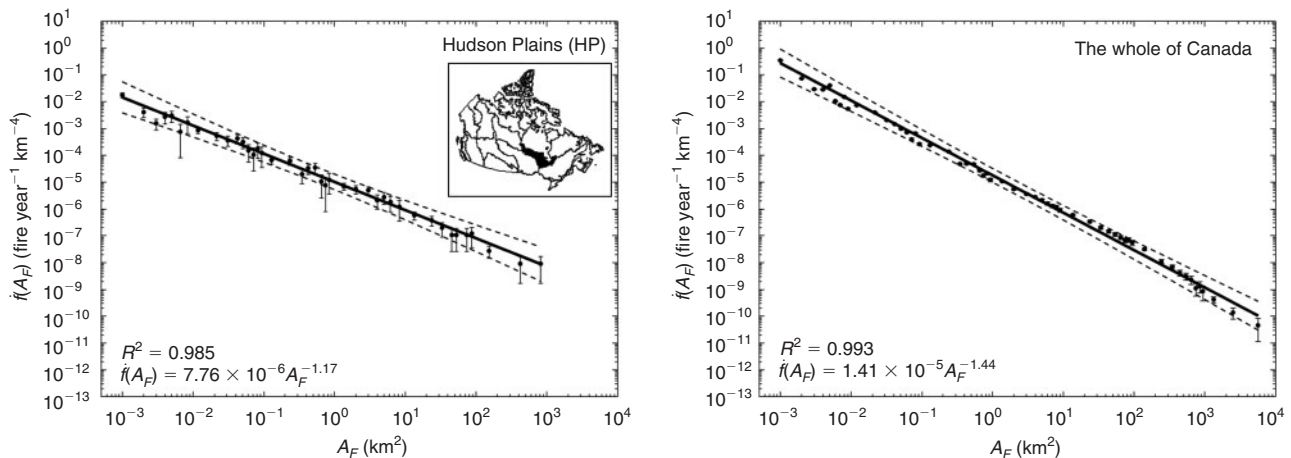
Fig. 2. (*Continued*)

is equivalent to a linear relationship on a log–log space:

$$\log \dot{f}(A_F) = -\beta \log A_F + \log \alpha \qquad (3)$$

Still referring to Malamud *et al.* (2005), the cumulative number of wildfires $N_{CF}(\geq A_F)$ is:

$$N_{CF}(\geq A_F) = \int_{A_F}^{\infty} f(A)dA = \tau A_R \left(\frac{\alpha}{\beta - 1} \right) A_F^{1-\beta}, \quad \beta > 1 \quad (4)$$

where A_R is a spatial area over which the fires are recorded (in our case, 10 000 km²). The number of fires equal to or larger than a given size, $N_{CF}(\geq A_F)$ in that region increases as A_R increases.

Using the least square method, we determined the s.d. of β and $\log \alpha$. The s.d. for β and $\log \alpha$ are given below following Acton (1966):

$$\sigma_\beta = \sqrt{\frac{\sigma_x^2 \sigma_y^2 - \sigma_{xy}^2 \sigma_{xy}^2}{\sigma_x^2 \sigma_x^2 (n - 2)}} \qquad (5)$$

$$\sigma_{\log \alpha} = \sqrt{\left(\frac{\sigma_x^2 \sigma_y^2 - \sigma_{xy}^2 \sigma_{xy}^2}{\sigma_x^2 (n - 2)} \right) \left(1 + \frac{\bar{x}^2}{\sigma_x^2} \right)} \qquad (6)$$

where σ_x^2 and σ_y^2 are variances of x and y and σ_{xy}^2 is the covariance. The subscripts $x = \log A_F$, $y = \log \dot{f}(A_F)$ and $\bar{x}$ is the mean value of x. Finally, n is the number of bins for each ecozone. The error bars ± 2 s.d. of β and $\log \alpha$ are approximately equivalent to upper and lower 95% confidence intervals (± 1.96 s.d.).

Calculation of fire recurrence intervals

To calculate fire recurrence intervals based on the obtained power–law relationships between number of fires and burned area following Malamud *et al.* (2005), the fire recurrence interval $T(\geq A_F)$ in a spatial area A_R was calculated:

$$T(\geq A_F) = \frac{\tau + 1}{N_{CF}(\geq A_F)} = \left(\frac{\tau + 1}{\tau} \right) \left(\frac{\beta - 1}{\alpha} \right) \left(\frac{A_F^{\beta - 1}}{A_R} \right), \quad \beta > 1 \qquad (7)$$

where t is the length of observation in years. For each ecozone and the whole Canadian boreal ecosystems, we calculated $T(\geq A_F)$ when $A_F = 0.01$ km², $A_F = 2$ km² and $A_F = 10$ km² respectively. Using the upper and lower 95% confidence interval values of β and $\log \alpha$, the 95% confidence intervals for fire recurrence intervals $T(\geq A_F)$ were also calculated.

Results

Relationships between frequency density and burned area

Fire frequency–area distributions in each ecozone and the whole of Canada all followed power–law relationships (Fig. 2). The analysis using an ordinary least-square regression between normalized frequency density and burned area resulted in a range of power–law coefficients, with 1.03 (Taiga Cordillera) $\leq \beta \leq 1.68$ (Mixedwood Plains), and $10^{-6.2} \leq \alpha \leq 10^{-4.4}$. The coefficients of determination (R^2) are mostly larger than 0.98 (Table 1). Two s.d., approximately equivalent to lower and upper 95% confidence intervals (± 1.96 s.d.) for both β and $\log \alpha$, are also in Table 1. We found that although 24.9% fires occurred in Montane Cordillera with a relatively large β (1.65), these fires only covered 0.6% of the total burned area in Canada. A larger β implies that the ratio of number of small to large fires is larger than those of other ecozones. In contrast, Taiga Shield, which has a relative small β (1.17), experiences only 2.7% of the total fire occurrences but covers 20.5% of total burned area in Canada.

Spatially, a general north to south gradient of lower to higher values of β exists (Fig. 3) (see *Discussion*). All ecozones with β larger than 1.39 are located south of latitude 50°N. Our analysis indicated that the errors of β range from 1.4 to 8.2% of β values.

To test if ignition source influences the frequency–area relationships, we separately analyzed anthropogenic and lightning fire data for the period 1980–1999 (Table 2). We found that when taking into account ignition sources, similar results exist for β and $\log \alpha$ compared with that using the combined data (Table 3). However, $\beta_{anthropogenic}$ is greater than $\beta_{lightning}$ in most ecozones and the whole of Canada except Pacific Maritime (1.62 *v.* 1.63) and Montane Cordillera (1.59 *v.* 1.71).

To characterize the decadal fire frequency–area relationship for each ecozone, we also analyzed both decades. Each ecozone

Table 1. Results of frequency–area and fire recurrence interval analyses for 13 ecozones in Canada (fire size ≥ 0.001 km²)

Error bars on β and $\log\alpha$ are ±2 s.d. and approximately equivalent to 95% confidence intervals. Error bars are determined by: (i) s.d. calculated with Eqn 5 and Eqn 6; (ii) the degrees of freedom which depends on the number of 'bins' used in the least-square fit. Recurrence intervals $T(\geq A_F)$ are presented for $A_F = 0.01\,\text{km}^2$, $A_F = 2\,\text{km}^2$, $A_F = 10\,\text{km}^2$, which represent the average time between wildfires $\geq0.01\,\text{km}^2$, $\geq2\,\text{km}^2$, $\geq10\,\text{km}^2$ in a spatial area of $10\,000\,\text{km}^2$ in each ecozone respectively. Error bars for recurrence intervals are also calculated by ±2 s.d. approximately representing 95% confidence intervals. Arctic Cordillera and High Arctic are not presented since there are very few fire records or no fire record for these two ecozones. It should be noted that because the lower boundary of β for Taiga Cordillera is smaller than 1 when we calculated its error bars of recurrence interval, we used 1.030 ± 0.028, which is ~52% confidence interval

Ecozone division name (abbreviation)	Ecozone division code	Spatial area (10³ km²)	Vegetated area (10³ km²)	Total burned area (10³ km²)	Number of fires	β	$\mathrm{Log}\,\alpha$	R^2	$T\,(\geq 0.01\,\text{km}^2)$ (year)	$T\,(\geq 2\,\text{km}^2)$ (year)	$T\,(\geq 10\,\text{km}^2)$ (year)
Low Arctic (LA)	3	801	650	0.19	95	1.10 ± 0.09	−6.18 ± 0.17	0.971	9.99 ± 8.54	26.4 ± 24.8	36 ± 34
Taiga Plains (TP)	4	630	503	112.58	6259	1.32 ± 0.03	−4.71 ± 0.09	0.989	0.40 ± 0.10	2.2 ± 0.7	4 ± 1
Taiga Shield (TS)	5	1339	1030	111.86	3498	1.17 ± 0.04	−5.03 ± 0.10	0.983	0.88 ± 0.25	2.4 ± 1.1	3 ± 2
Boreal Shield (BS)	6	1940	1561	186.10	49 303	1.39 ± 0.02	−4.48 ± 0.07	0.993	0.21 ± 0.04	1.7 ± 0.4	3 ± 1
Atlantic Maritime (AM)	7	221	182	0.96	916	1.39 ± 0.04	−5.23 ± 0.11	0.974	1.23 ± 0.39	9.7 ± 3.4	18 ± 7
Mixedwood Plains (MP)	8	164	105	0.04	2001	1.68 ± 0.06	−5.38 ± 0.18	0.985	0.87 ± 0.47	31.6 ± 15.6	100 ± 57
Boreal Plains (BP)	9	732	626	80.35	24 154	1.44 ± 0.02	−4.47 ± 0.08	0.992	0.18 ± 0.04	1.9 ± 0.4	4 ± 1
Prairies (PR)	10	463	444	1.33	421	1.21 ± 0.05	−5.63 ± 0.11	0.982	3.67 ± 1.01	12.4 ± 6.1	18 ± 10
Taiga Cordillera (TC)	11	262	233	4.41	382	1.03 ± 0.08	−5.13 ± 0.13	0.971	0.43 ± 0.41	0.6 ± 0.6	1 ± 1
Boreal Cordillera (BC)	12	471	367	29.75	2682	1.23 ± 0.04	−4.79 ± 0.10	0.983	0.53 ± 0.12	1.8 ± 0.7	3 ± 1
Pacific Maritime (PM)	13	209	130	0.38	6034	1.65 ± 0.05	−4.89 ± 0.18	0.951	0.31 ± 0.16	9.5 ± 4.7	28 ± 16
Montane Cordillera (MC)	14	485	381	3.44	31 982	1.65 ± 0.03	−4.61 ± 0.12	0.979	0.15 ± 0.06	4.6 ± 1.6	13 ± 5
Hudson Plains (HP)	15	372	328	14.19	873	1.17 ± 0.05	−5.11 ± 0.11	0.985	1.07 ± 0.33	3.0 ± 1.6	4 ± 2
Total all ecozones		8089	6540	545.58	128 600	1.44 ± 0.03	−4.85 ± 0.12	0.993	0.45 ± 0.14	4.8 ± 1.6	10 ± 4

exhibits frequency–area power–law behavior and most ecozones have similar values of β and $\log\alpha$ for both decades (Table 3, only β values were shown). There were no statistically significant differences of β values between these two decades. Similar to the entire 1980–1999 period, both decades had larger β values for anthropogenic fires than those for lightning fires in most ecozones, suggesting that the ratio of the number of small to large anthropogenic fires is larger than that of natural (lightning) fires.

Fire recurrence intervals

There are significant spatial variabilities for the fire recurrence intervals $T(\geq A_F)$ between ecozones (Fig. 4). Errors of $T(\geq A_F)$ range between 20 and 60% of the estimated recurrence intervals in most of ecozones (Table 1). Specifically, in the Mixedwood Plains, when $A_F = 10\,\text{km}^2$, the fire recurrence intervals $T(\geq A_F)$ are 100 ± 57 years. This means that we would expect, over a spatial area of $10\,000\,\text{km}^2$ within that ecozone, fires with burned area $A_F \geq 10\,\text{km}^2$ will occur on average every 43–157 years (i.e. 1 : 157 to 1 : 43 probability of having a fire of this size or bigger in any given year). In contrast, for the Boreal Cordillera, when $A_F = 10\,\text{km}^2$, the fire recurrence intervals $T(\geq A_F)$ are ~2–4 years. In other words, the probability of occurring of a fire ($\geq10\,\text{km}^2$) in any given year rises to 1 : 4 to 1 : 2 compared with that of Mixedwood Plains.

Excluding the Low Arctic, the western and central parts of Canada generally exhibit a north-to-south gradient of small to large fire recurrence intervals (Fig. 4). Since the Taiga Shield and Boreal Shield account for a great part of area and both have a relatively small fire recurrence interval, eastern Canada has a higher hazard compared with western and central Canada. However, the two ecozones at the boundary of eastern Canada, Atlantic Maritime and Mixedwood Plains, both exhibit larger recurrence intervals (lower hazard).

Discussion

One requirement for using frequency–area distribution to calculate the recurrence intervals of wildfires is that the occurrences are independently and identically distributed. In other words, the fire events are unclustered in time and wildfires are not changing in time. In our study, we used different lower cutoff bounds for burned areas in each ecozone and then followed Díaz-Delgado *et al.* (2004) to fit Poisson distribution parameters λ by means of the maximum likelihood estimate (MLE). Here, λ represents the average number of fires per year for each ecozone. A Chi-Square test suggested that for all ecozones, the smaller fires are correlated in time, but not the larger ones. This suggests that the results of the frequency–area statistics could be used to calculate the recurrence intervals of the medium and large fires.

The finding of the increasing trend of β values from north to south suggests that the ratio of number of small to large fires increases from north to south. This north–south gradient is potentially due to any or all of a complex set of factors including climate, latitude, fuel type, topography, provincial fire management policy and efficiency, the presence or absence of water bodies and the density of population. Generally, temperature increases from north (higher latitude) to south (lower latitude)
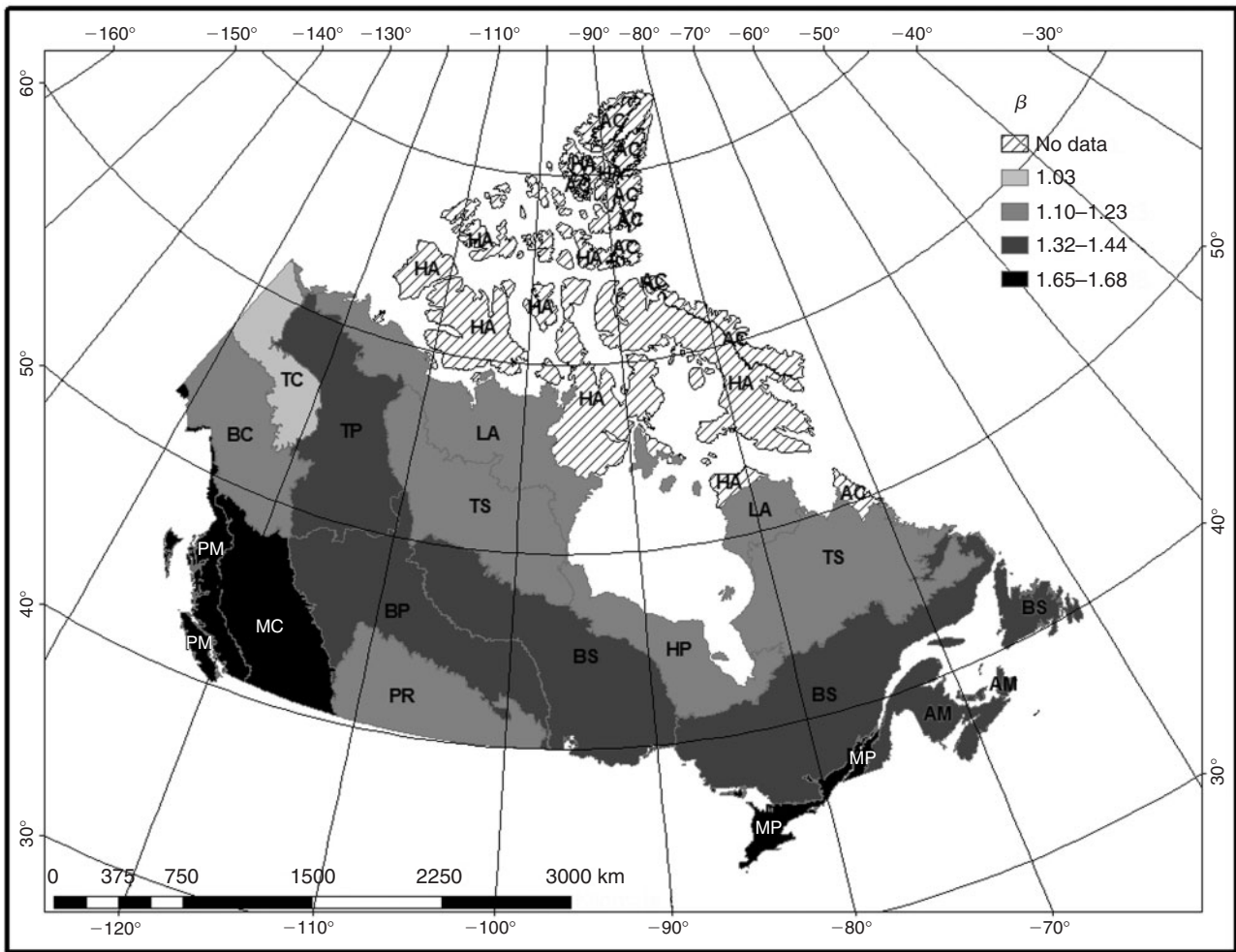
Fig. 3. Spatial distribution of β for 13 ecozones in Canada (for fires $A_F \geq 0.001\,\mathrm{km}^2$, 1980–1999). The β values are obtained based on the best-fit frequency–area distributions (Fig. 2). The projection is equal area projection. For abbreviations of ecozones, see Table 1. AC, Arctic Cordillera; HA, High Arctic.

Table 2.   Number of fires due to different ignition sources within two decades (fire size $\geq 0.001\,\mathrm{km}^2$) in Canada

Ecozone	1980–1999			1980–1989			1990–1999		
	Anthropogenic	Lightning	All	Anthropogenic	Lightning	All	Anthropogenic	Lightning	All
Low Arctic	16	62	95	11	40	51	5	22	44
Taiga Plains	989	4736	6259	578	2721	3306	411	2015	2953
Taiga Shield	542	2648	3498	329	1105	1450	213	1543	2048
Boreal Shield	25 074	23 597	49 303	13 788	11 674	25 841	11 286	11 923	23 462
Atlantic Maritime	833	83	916	397	12	409	436	71	507
Mixedwood Plains	1834	99	2001	984	55	1081	850	44	920
Boreal Plains	12 903	11 043	24 154	7269	4838	12 176	5634	6205	11 978
Prairies	374	45	421	238	22	260	136	23	161
Taiga Cordillera	23	356	382	16	216	232	7	140	150
Boreal Cordillera	1034	1627	2682	562	763	1326	472	864	1356
Pacific Maritime	4069	1964	6034	2561	1128	3689	1508	836	2345
Montane Cordillera	15 417	16 524	31 982	9485	9482	18 967	5932	7042	13 015
Hudson Plains	214	636	873	82	195	298	132	441	575
Total all ecozones	63 322	63 420	128 600	36 300	32 251	69 086	27 022	31 169	59 514

Table 3. Estimated values and coefficients of determination R^2 of β for each ecozone for the whole period (1980–1999) and two separate decades (1980–1989 and 1990–1999) in Canada

Within each period, a statistical analysis is performed by different ignition source (anthropogenic or natural) and for all fires irrespective of ignition source for each ecozone and the whole of Canada. In each cell in the table, the first line is the estimated value of β and its ±2 s.d. error bar which is equivalent to upper and lower 95% confidence intervals. The coefficient of determination R^2 is presented in the second line. In cells marked with asterisks (***), the uncertainty of estimates for β values is large due to very small number of wildfires (<50).

Ecozone	1980–1999			1980–1989			1990–1999		
	Anthropogenic $\beta\pm2$ s.d., R^2	Lightning $\beta\pm2$ s.d., R^2	All $\beta\pm2$ s.d., R^2	Anthropogenic $\beta\pm2$ s.d., R^2	Lightning $\beta\pm2$ s.d., R^2	All $\beta\pm2$ s.d., R^2	Anthropogenic $\beta\pm2$ s.d., R^2	Lightning $\beta\pm2$ s.d., R^2	All $\beta\pm2$ s.d., R^2
Low Arctic	***	0.99±0.09, 0.919	1.10±0.09, 0.971	***	***	1.01±0.07, 0.921	***	***	***
Taiga Plains	1.37±0.05, 0.970	1.29±0.03, 0.988	1.32±0.03, 0.989	1.42±0.05, 0.976	1.27±0.03, 0.990	1.29±0.03, 0.990	1.30±0.06, 0.970	1.27±0.03, 0.985	1.30±0.03, 0.988
Taiga Shield	1.33±0.06, 0.983	1.12±0.05, 0.979	1.17±0.04, 0.983	1.33±0.07, 0.976	1.13±0.06, 0.988	1.17±0.05, 0.982	1.24±0.07, 0.967	1.10±0.05, 0.984	1.14±0.04, 0.982
Boreal Shield	1.52±0.02, 0.993	1.33±0.02, 0.990	1.39±0.02, 0.993	1.52±0.02, 0.983	1.33±0.03, 0.986	1.39±0.02, 0.991	1.52±0.02, 0.995	1.33±0.03, 0.990	1.40±0.02, 0.993
Atlantic Maritime	1.38±0.04, 0.985	1.20±0.07, 0.983	1.39±0.04, 0.974	1.35±0.06, 0.984	***	1.36±0.06, 0.985	1.39±0.05, 0.985	1.18±0.07, 0.980	1.38±0.04, 0.973
Mixedwood Plains	1.68±0.06, 0.969	1.61±0.19, 0.955	1.68±0.06, 0.985	1.62±0.07, 0.962	1.49±0.22, 0.923	1.62±0.07, 0.969	1.61±0.06, 0.986	***	1.63±0.06, 0.962
Boreal Plains	1.48±0.03, 0.984	1.40±0.02, 0.986	1.44±0.02, 0.992	1.46±0.03, 0.978	1.38±0.03, 0.972	1.41±0.02, 0.986	1.45±0.03, 0.984	1.42±0.02, 0.983	1.44±0.02, 0.990
Prairies	1.20±0.05, 0.977	***	1.21±0.05, 0.982	1.15±0.06, 0.973	***	1.16±0.06, 0.976	1.22±0.07, 0.981	***	1.25±0.06, 0.984
Taiga Cordillera	***	1.01±0.08, 0.968	1.03±0.08, 0.971	***	1.02±0.09, 0.956	1.02±0.09, 0.966	***	1.00±0.07, 0.975	1.02±0.06, 0.977
Boreal Cordillera	1.31±0.03, 0.982	1.18±0.04, 0.987	1.23±0.04, 0.983	1.26±0.04, 0.977	1.19±0.05, 0.989	1.23±0.04, 0.987	1.32±0.04, 0.994	1.13±0.04, 0.990	1.18±0.04, 0.991
Pacific Maritime	1.62±0.07, 0.933	1.63±0.07, 0.923	1.65±0.05, 0.951	1.60±0.07, 0.944	1.68±0.09, 0.919	1.64±0.06, 0.922	1.60±0.08, 0.966	1.52±0.07, 0.969	1.58±0.05, 0.966
Montane Cordillera	1.59±0.04, 0.977	1.71±0.04, 0.943	1.65±0.03, 0.979	1.56±0.04, 0.972	1.70±0.06, 0.952	1.62±0.03, 0.970	1.60±0.05, 0.973	1.71±0.05, 0.979	1.63±0.04, 0.976
Hudson Plains	1.28±0.06, 0.972	1.12±0.06, 0.987	1.17±0.05, 0.985	1.18±0.07, 0.974	1.03±0.05, 0.982	1.09±0.05, 0.988	1.25±0.08, 0.974	1.14±0.07, 0.986	1.18±0.06, 0.989
Total all ecozones	1.52±0.02, 0.996	1.39±0.03, 0.988	1.44±0.03, 0.993	1.51±0.02, 0.993	1.38±0.03, 0.983	1.42±0.02, 0.991	1.53±0.02, 0.992	1.37±0.03, 0.989	1.42±0.03, 0.993

in the northern hemisphere. This temperature gradient may contribute more to the number of small fires than that of large fires, resulting in the increasing trend of β. Although several studies suggest that the warmer temperature will increase the number of fires and burned area (e.g. Gillett *et al*. 2004; Flannigan *et al*. 2005), the impact of temperature on burned areas with different sizes has not typically been discussed. In addition, it is difficult to judge if temperature is the major factor to control the burned area because other factors (e.g. population density and fuel connectivity) could also greatly control the burned area.

Here, we further discuss the meaning of β values. In our result, the values of β can be separated into four groups (Table 4). Group A (Taiga Cordillera) has the smallest β (1.03) in Canada; i.e. the lowest ratio of number of small to large fires. This is probably due to lower levels of fire protection and generally more severe fire weather and flammable fuel conditions compared with other ecozones.

For ecozones in group B, similar reason as in group A could lead to low β values in the Low Arctic, Taiga Shield, Hudson Plains and the Boreal Cordillera, but the proximity to large water bodies and different climates may contribute to having smaller fires compared with Taiga Cordillera, increasing the values of β. Two opposite effects resulted in relatively small β values, but larger than that of group A. In the grassland-dominated Prairies, high-speed wind and warmer climate could result in large burned areas, and thus lowering the value of β.

For group C, the explanation is more complex. The Boreal Plains (1.44) and Boreal Shield (1.39) experienced 57.1% of the total fire occurrences of the whole of Canada and these accounted for 48.8% of total burned area. These ecozones cover large remote areas that do not generally warrant aggressive fire suppression and the majority of fires are allowed to burn naturally (Stocks *et al*. 2002). Furthermore, they had more continental climate and thus generally more extreme fire danger conditions. However, they also experienced higher small-fire activities, probably due to the greater population densities in four provinces (Alberta, Saskatchewan, Manitoba and Ontario), which increase the forest fragmentation and enhance the fire detection and suppression. The combination of these opposite mechanisms leads to relatively large β values compared with those in groups A and B. For the Atlantic Maritime ecozone, intensive fire protection and the presence of Atlantic Ocean could be the potential reason leading to a high ratio of small to large number of fires. In the Taiga Plains, fires due to low population density and lightning may contribute to large fire activities. However, the existence of the Great Slave Lake, the Great Bear Lake, the Mackenzie River and its many tributaries increase the forest fragmentation. Permafrost degradation leads to many areas being waterlogged and remnants of glacier activity make the landscape more varied. These conditions, together with rough terrain especially in the western part of this ecozone, could impede the fire spread and lead to a large β value.

The largest β values of group D may be due to intensive fire protection, landscape fragmentation and proximity to large water bodies, leading to a lack of large fires.

Overall, we found that $\beta_{\text{anthropogenic}}$ is generally greater than $\beta_{\text{lightning}}$ in most ecozones. This suggests that within most ecozones, lightning contributes more to a lower ratio of number of small to large fires than human ignition does. This is probably
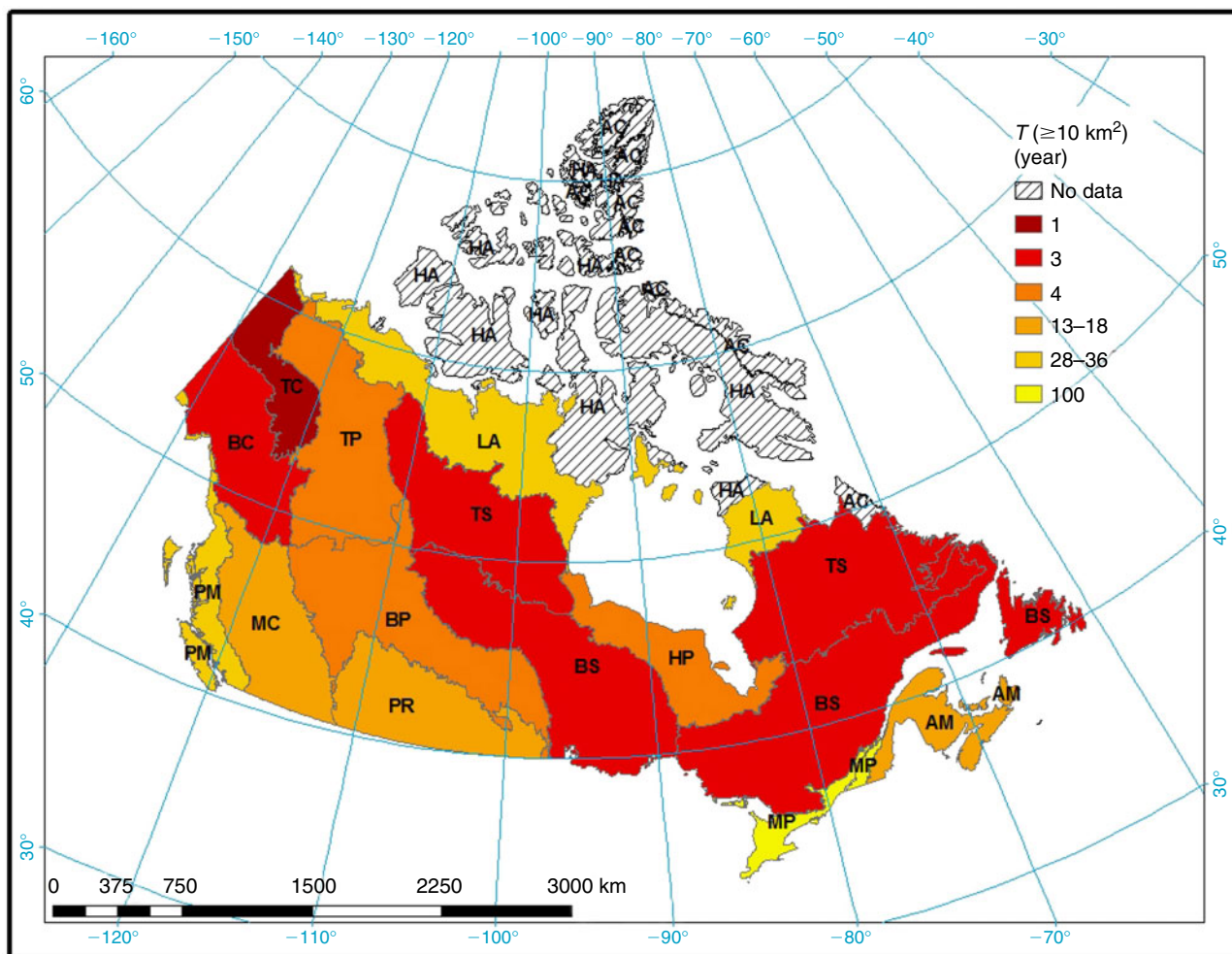
Fig. 4. Spatial distribution of fire recurrence intervals in Canada (1980–1999, $A_F \geq 0.001$ km^2). To obtain this map, the parameters α and β are first obtained based on the best-fit frequency–area distributions (Fig. 2). These parameters are then used in Eqn 7 to calculate recurrence intervals T (≥ 10 km^2); i.e. the average amount of time between fires of a given size (in this case 10 km^2) or larger, that occur in a spatial area A_R (10 000 km^2) within the ecozone. From dark red to solar yellow, the color legend represents 'high' hazard (small recurrence intervals) to 'low' hazard (large recurrence intervals). The projection is equal area projection.

Table 4. The classification of β values and the specific value of β for individual ecozones in Canada

For each group, the lower and upper bounds of range for each group are determined by the lowest and highest β values of that group. For ecozone abbreviations, please refer to Table 1

Group	Range of β	Ecozone (β value)
A	1.03	TC (1.03)
B	1.10–1.23	LA (1.10), HP (1.17), TS (1.17), PR (1.21), BC (1.23)
C	1.32–1.44	TP (1.32), AM (1.39), BS (1.39), BP (1.44)
D	1.65–1.68	MC (1.65), PM (1.65), MP (1.68)

because lightning-ignited fires are more difficult to detect since they occur more often in remote areas and are less likely to be suppressed resulting in relatively large burned areas. In contrast, human-caused fires generally occur near human settlements and therefore are suppressed before leading to large burned areas.

Therefore, anthropogenic fires have a higher ratio of number of small to large fires than natural (lightning) fires. However, the Pacific Maritime had a β value of 1.62 for anthropogenic fires and 1.63 for natural fires, while Montane Cordillera had a β value of 1.59 for anthropogenic fires and 1.71 for natural fires.

For Pacific Maritime, a possible reason could be that greater population densities may lead to an equal probability of fire suppression irrespective of ignition sources, thus similar values of β. A larger β value for lightning fires in the Montane Cordillera may be explained by the complex topography which keeps natural fires smaller in size.

Conclusions

In this analysis, we used a wildfire database (fire size $A_F \geq 0.001\,\mathrm{km}^2$) for the period 1980–1999 compiled by the Canadian Forest Service to characterize the relationships between number of fires and burned area and further calculated the fire recurrence intervals for 13 ecozones in Canada. We found that although wildfires are affected by climate, topography, fuel load and population density, the number of wildfires and burned area in each ecozone and the nation all follow power–law frequency–area relationships with different orders of magnitude. Similar results were found for analyses on anthropogenic and natural fires, and for the 1980s and 1990s. These power–law relationships were further used to calculate the fire recurrence intervals for each ecozone. We believe that the relationships between frequency density and burned area and the fire recurrence interval information obtained from this study will be useful for fire management in this region. The statistical algorithms for calculating fire recurrence intervals will be helpful for fire mangers to quantify the wildfire risk in this region. In addition, the characterization of the past wildfire regimes and projection of fire recurrence intervals are important to study future carbon dynamics of Canadian terrestrial ecosystems.

Acknowledgements

References

Acton FS (1966) 'Analysis of Straight-Line Data.' (Dover: New York)

Amiro BD, Chen JM, Liu J (2000) Net primary productivity following forest fire for Canadian ecoregions. *Canadian Journal of Forest Research* **30**, 939–947. doi:10.1139/CJFR-30-6-939

Amiro BD, Todd JB, Wotton BM, Logan KA, Flannigan MD, Stocks BJ, Mason JA, Martell DL, Hirsch KG (2001) Direct carbon emissions from Canadian forest fires, 1959–1999. *Canadian Journal of Forest Research* **31**, 512–525. doi:10.1139/CJFR-31-3-512

Balshi MS, McGuire AD, Zhuang Q, Melillo J, Kicklighter DW, Kasischke E, Wirth C, Flannigan MD, Harden J, Clein JS, Burnside TJ, McAllister J, Kurz WA, Apps M, Shridenko A (2007) The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: a process-based analysis. *Journal of Geophysical Research* **112**, G02029. doi:10.1029/2006JG000380

Calef MP, McGuire AD, Chapin FS, III (2008) Human influences on wildfire in Alaska from 1988 through 2005: an analysis of the spatial patterns of human impacts. *Earth Interactions* **12**, 1–17. doi:10.1175/2007EI220.1

Cui W, Perera AH (2008) What do we know about forest fire size distribution, and why is this knowledge useful for forest management? *International Journal of Wildland Fire* **17**(2), 234–244. doi:10.1071/WF06145

Díaz-Delgado R, Lloret F, Pons X (2004) Statistical analysis of fire frequency models for Catalonia (NE Spain, 1975–1998) based on fire scar maps from Landsat MSS data. *International Journal of Wildland Fire* **13**(1), 89–99. doi:10.1071/WF02051

Ecological Stratification Working Group (1996) A national ecological framework for Canada, Agriculture and Agric.-Food Canada and Environment Canada. (Ottawa, ON)

Fiorucci P, Gaetani F, Minciardi R (2008) Regional partitioning for wildfire regime characterization. *Journal of Geophysical Research* **113**, F02013. doi:10.1029/2007JF000771

Flannigan MD, Little J (2002) 'Canadian Large Fire Database, 1959–1999 point data set.' (Canadian Forest Service: Edmonton, AB)

Flannigan MD, Bergeron Y, Engelmark O, Wotton BM (1998) Future wildfire in circumboreal forests in relation to global warming. *Journal of Vegetation Science* **9**, 469–476. doi:10.2307/3237261

Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ (2005) Future area burned in Canada. *Climatic Change* **72**, 1–16. doi:10.1007/S10584-005-5935-Y

Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. *Geophysical Research Letters* **31**, L18211. doi:10.1029/2004GL020876

Harden JW, Manies KL, Turetsky MR, Neff JC (2006) Effects of wildfires and permafrost on soil organic matter and soil climate in interior Alaska. *Global Change Biology* **12**, 2391–2403. doi:10.1111/J.1365-2486.2006.01255.X

Kasischke ES, Turetsky MR (2006) Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters* **33**, L09703. doi:10.1029/2006GL025677

Maingi JK, Henry MC (2007) Factors influencing wildfire occurrence and distribution in eastern Kentucky, USA. *International Journal of Wildland Fire* **16**, 23–33. doi:10.1071/WF06007

Malamud BD, Morei G, Turcotte D (1998) Forest fires: an example of self-organized critical behavior. *Science* **281**(5384), 1840–1842. doi:10.1126/SCIENCE.281.5384.1840

Malamud BD, Millington JDA, Perry GLW (2005) Characterizing wildfire regimes in the United States. *Proceedings of the National Academy of Sciences of the United States of America* **102**(13), 4694–4699. doi:10.1073/PNAS.0500880102

Martell DL, Sun H (2008) The impact of fire suppression, vegetation, and weather on the area burned by lightning-caused forest fires in Ontario. *Canadian Journal of Forest Research* **38**, 1547–1563. doi:10.1139/X07-210

McCarthy MA, Gill AM (1997) Fire modeling and biodiversity. In 'Frontiers in Ecology: Building the Links – Proceedings of the 1997 Conference of the Ecological Society of Australia', 1–3 October 1997, Albury, Australia. (Eds N Klomp, I Lunt) pp. 79–88. (Elsevier: Oxford, UK)

Millington JDA, Perry GLW, Malamud BD (2006) Models, data and mechanisms: quantifying wildfire regimes. In 'Fractal Analysis for Natural Hazards'. (Eds G Cello, BD Malamud) Vol. 261, pp. 155–167. (Geological Society: London)

Mollicone D, Eva HD, Achard F (2006) Human role in Russian wild fires. *Nature* **440**, 436–437. doi:10.1038/440436A

Niklasson M, Granstrom A (2000) Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. *Ecology* **81**, 1484–1499.

Oldford S, Leblon B, Maclean D, Flannigan MD (2006) Predicting slow-drying fire weather index fuel moisture codes with NOAA-AVHRR images in Canada's northern boreal forests. *International Journal of Remote Sensing* **27**, 3881–3902. doi:10.1080/01431160600784234

Randerson JT, Liu H, Flanner MG, Chambers SD, Jin Y, Hess PG, Pfister G, Mack MC, Treseder KK, Welp LR, Chapin FS, Harden JW, Goulden ML, Lyons E, Neff JC, Schuur EAG, Zender CS (2006) The

impact of boreal forest fire on climate warming. *Science* **314**, 1130–1132. doi:10.1126/SCIENCE.1132075

Ricotta C, Avena G, Marchetti M (1999) The flaming sandpile: self-organized criticality and wildfires. *Ecological Modelling* **119**, 73–77. doi:10.1016/S0304-3800(99)00057-5

Ricotta C, Arianoutsou M, Díaz-Delgado R, Duguy B, Lloret F, Maroudi E, Mazzoleni S, Moreno JM, Rambal S, Vallejo R, Vázquez A (2001) Self-organized criticality of wildfires ecologically revisited. *Ecological Modelling* **141**, 307–311. doi:10.1016/S0304-3800(01)00272-1

Song WG, Fan WC, Wang BH, Zhou JJ (2001) Self-organized criticality of forest fire in China. *Ecological Modelling* **145**, 61–68. doi:10.1016/S0304-3800(01)00383-0

Stocks BJ, Lawson BD, Alexander ME, Van Wagner CE, McAlpine RS, Lynham TJ, Dube DE (1989) The Canadian forest fire danger rating system: an overview. *Forestry Chronicle* **65**, 450–457.

Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR (2002) Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research* **107**, 8149. doi:10.1029/2001JD000484

Turcotte DL, Malamud BD (2004) Landslides, forest fires, and earthquakes: examples of self-organized critical behavior. *Physica A: Statistical Mechanics and its Applications* **340**, 580–589. doi:10.1016/J.PHYSA.2004.05.009

Wooster MJ, Zhukov B, Oertel D (2003) Fire radiative energy for quantitative study of biomass burning: Derivation from the BIRD experimental satellite and comparison to MODIS fire products. *Remote Sensing of Environment* **86**, 83–107. doi:10.1016/S0034-4257(03)00070-1

Xiao J, Zhuang Q (2007) Drought effects on large fire activity in Canadian and Alaskan forests. *Environmental Research Letters* **2**, 044003. doi:10.1088/1748-9326/2/4/044003

Zhang JH, Wooster MJ, Tutubalina O, Perry GLW (2003) Monthly burned area and forest fire carbon emission estimates for the Russian Federation from SPOT VGT. *Remote Sensing of Environment* **87**, 1–15. doi:10.1016/S0034-4257(03)00141-X

Zhuang Q, McGuire AD, O'Neill KP, Harden JW, Romanovsky VE, Yarie J (2002) Modeling the soil thermal and carbon dynamics of a fire chronosequence in interior Alaska. *Journal of Geophysical Research* **107**, 8147. doi:10.1029/2001JD001244

Zhuang Q, Melillo JM, Sarofim MC, Kicklighter DW, McGuire AD, Felzer BS, Sokolov A, Prinn RG, Steudler PA, Hu S (2006) CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. *Geophysical Research Letters* **33**, L17403. doi:10.1029/2006GL026972