Wildfires in boreal ecoregions: Evaluating the power law assumption and intra-annual and interannual variations

Veiko Lehsten,[1] William J. de Groot,[2] Mike Flannigan,[3] Charles George,[4] Peter Harmand,[5] and Heiko Balzter[6]

[1]   Wildfires are a major driver of ecosystem development and contributor to carbon emissions in boreal forests. We analyzed the contribution of fires of different fire size classes to the total burned area and suggest a novel fire characteristic, the characteristic fire size, i.e., the fire size class with the highest contribution to the burned area, its relation to bioclimatic conditions, and intra-annual and interannual variation. We used the Canadian National Fire Database (using data from 1960 to 2010) and a novel satellite-based burned area data set (2001 to 2011). We found that the fire size distribution is best explained by a normal distribution in log space in contrast to the power law-based linear fire area relationship which has prevailed in the literature so far. We attribute the difference to previous studies in the scale invariance mainly to the large extent of the investigated ecoregion as well as to unequal binning or limiting the range at which the relationship is analyzed; in this way we also question the generality of the scale invariance for ecoregions even outside the boreal domain. The characteristic fire sizes and the burned area show a weak correlation, indicating different mechanisms behind each feature. Fire sizes are found to depend markedly on the ecoregion and have increased over the last five decades for Canada in total, being most pronounced in the early season. In the late season fire size and area decreased, indicating an earlier start of the fire season.

1. Introduction

[2]   Forest fires are an integral part of the boreal ecosystem, and many species have developed adaptations to a certain fire regime [*Rowe*, 1983; *Bourgeau-Chavez et al.*, 2000]. Fire regime is typically described by fire frequency, intensity, severity, seasonality, type of fire, and fire size [*Weber and Flannigan*, 1997; *Gill and Allan*, 2008]. The frequency and size of recurring fires determine the distribution of forest age classes [*Van Wagner*, 1978] and different successional stages. Unburned patches vary in size and number with fire size [*Eberhart and Woodard*, 1987] and are important as regeneration refugia. The size and shape of fires and the number and size of unburned patches define the amount of fire edge and distance to edge within the burned area. These are important fire characteristics that affect seeding distances and the ability to regenerate [*Greene et al.*, 1999]. The distribution of fire sizes (i.e., the relative proportion of each fire size class) is also of economic interest. Fire fighting activity and evacuation activity are based on the assessment of expected number, intensity, and sizes of fires, which affects fire management strategy and decision making [*Ward and Mawdsley*, 2000]. In Canada, the number of people evacuated in response to forest fires ranged from 40 to over 50,000 per year [*Beverly et al.*, 2011] in the period from 1980 to 2007.

[3]   Studying forest fire distribution requires a sufficiently large data set covering forest fire events for a variety of sizes and preferably over a long period of time in order to draw statistically sound conclusions. Forest fire data has commonly been collected by national authorities or national research institutes focusing on the extent of the country, rather than the extent of a certain ecosystem, which hinders analyses at ecosystem scale (like the studies performed by *Malamud et al.* [2005] using compiled data from governmental and nongovernmental organizations in the U.S.). While remotely

[1]Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden.

[2]Canadian Forest Service, Natural Resources Canada, Sault Ste. Marie, Ontario, Canada.

[3]Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada.

[4]Center for Ecology and Hydrology, Wallingford, UK.

[5]Department of Mathematics, University of Oldenburg, Oldenburg, Germany.

[6]Centre for Landscape and Climate Research, Department of Geography, University of Leicester, Leicester, UK.

Corresponding author: V. Lehsten, Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, SE-22362 Lund, Sweden. (veiko.lehsten@nateko.lu.se)
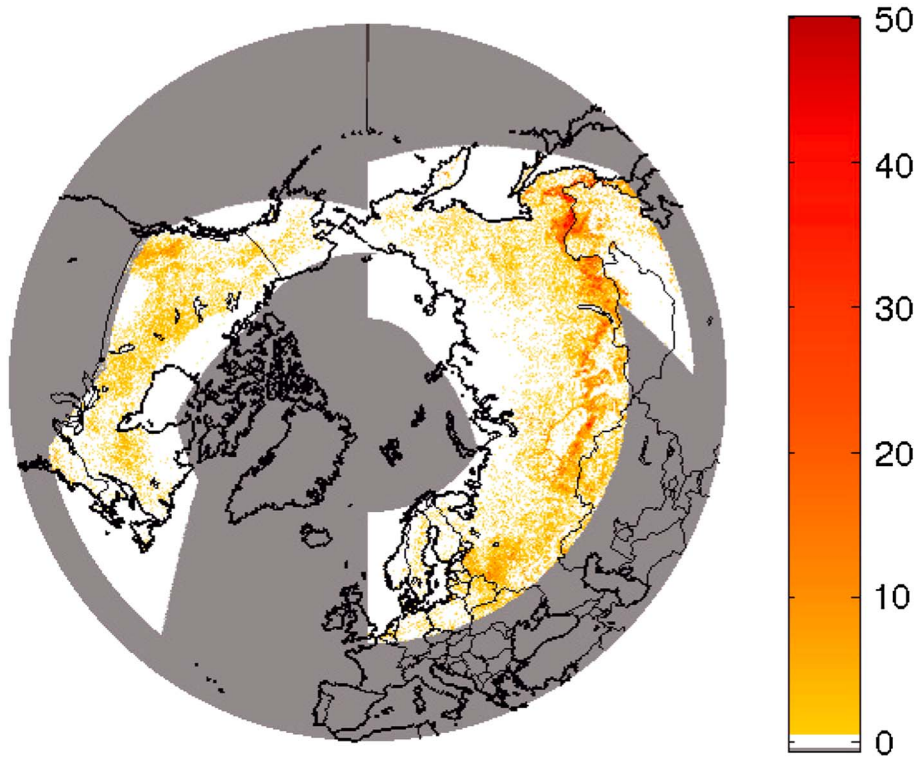
Figure 1. Investigation area of the BBA (white) and number of fires in the combined data set per 0.166°
pixel (mapping unit of the ecoregions map). The CNFBD covers the Canadian forested regions.

sensed forest fire data are potentially independent of administrative borders, their low temporal extent, which for most forest fire-related products is approximately one decade, does not permit the long-term investigation of the fire pattern compared to the long-time range covered by databases at national scale (e.g., *Stocks et al.* [2002] dating back to 1959).

[4] Forest fires size distributions (FSDs) have been increasingly investigated within the last two decades and a comprehensive review by *Cui and Perera* [2008] lists 35 publications estimating FSDs belonging to 11 different types. The areas investigated include not only North America, where the majority of studies have been performed, but also southern Europe and Australia. One of the earliest publications investigating scale invariance was a study by *Malamud et al.* [1998] where the authors interpolated a linear relationship into the noncumulative FSD in log-log space for fire size data from North America and Australia. *Ricotta et al.* [1999] also apply the concept of self-organized criticality to wildfires based on data of about 9000 fires in southern Europe. They parameterize a linear model to the intermediate parts of the size range for a cumulative FSD also in log-log space. Following a similar approach, *Malamud et al.* [2005] stratify fire size data from the conterminous United States according to the ecoregions defined by *Bailey* [1995] and estimate the ecoregion specific parameter of the linear model (in log-log space). While estimated power law coefficients allow the estimation of fire recurrence intervals of fires above a certain area, this method does requires additional calculations to assess the proportion of the total burned area attributed to a certain fire size class.

[5] In this study we develop a novel statistic for the fire size distribution: the characteristic fire size. This statistic indicates which fire size class contributes the highest proportion to the

total burned area in the ecoregion and is therefore typical of the ecoregion. We focus on the boreal biome and investigate the temporal change in this characteristic as well as in the total burned area for the time period from 1960 to 2010.

2. Data and Methods

2.1. Fire Data and Investigation Area

[6] Two data sets covering northern boreal areas were used in this study: the Canadian National Fire Database (CNFDB) [*Canadian Committee on Forest Management*, 2012] and the boreal burned area data (BBA) generated by a further development of algorithm described in *George et al.* [2006]. The CNFDB prior to 2004 is a collection of fire size data from provincial, territorial, and national fire management agencies obtained by various methods including satellite mapping, ground and aerial mapping by observer and/or GPS, and historical agency records. Starting in 2004, Landsat mapping of fire scars and agency-specific data were used.

[7] Since the CNFDB data before 1960 are considered to be less accurate than data for later years [*Stocks et al.*, 2002], we excluded all fires before this time. Though the CNFDB contains very detailed fire records including small (<1 ha) fires, we excluded all fires below 100 ha of area since this data is of poor quality, especially in the first few decades.

[8] The BBA is a new satellite-based fire scar product ranging from 2001 to 2011, which identifies burnt areas in the boreal region on a daily basis with a 500 m resolution; hence, the minimum fire size considered is around 25 ha. It covers most areas in Canada and Alaska as well as northern Europe, Russia, and northern parts of China (Figure 1). The BBA algorithm relies on the synergy of several Moderate

Table 1. Estimated Parameter and Goodness of Fit of the FSD Stratified by Data Set and Ecoregion[a]

Data Set and Ecoregion	Total Area × 10^8 (ha)	Number of Fires	Characteristic Fire Size Log_{10} (ha)			
			μ	σ	a	R^2
CNFDB						
Sub-Arctic	58.54	8636	4.68	0.70	5.20	0.99
Subarctic regime mountains	12.62	1545	4.46	0.60	4.47	0.96
Tundra	41.53	44				
Marine division	0.07	1				
Marine regime mountains	4.34	202	3.85	0.62	3.15	0.71
Prairie	4.33	73				
Warm continental	4.03	238	4.32	0.65	3.54	0.67
Warm cont. regime mount.	6.21	426	4.03	0.48	3.62	0.90
Temperate steppe	2.88	12				
Temp. steppe regime mount.	2.10	402	3.49	0.67	3.12	0.88
BBA Canada						
Sub-Arctic	67.21	6511	4.44	0.73	5.40	0.92
Subarctic regime mountains	17.90	1384	4.67	0.74	5.01	0.82
Tundra	22.35	67				
Hot continental	1.31	120	2.03	0.85	2.74	0.94
Hot cont. regime mount.	1.88	376	2.03	1.37	3.27	0.96
Marine division	0.11	1				
Marine regime mountains	7.55	1180	3.76	0.84	4.32	0.79
Prairie	4.22	378	4.19	0.14	3.87	0.88
Warm continental	4.65	586	3.31	1.15	3.78	0.60
Warm cont. regime mount.	6.18	3819	3.49	0.83	4.60	0.92
Temperate steppe	2.22	42				
Temp. steppe regime mount.	1.62	688	3.75	0.70	3.98	0.90
BBA Siberia						
Sub-Arctic	136.75	45624	3.61	0.82	5.69	0.97
Subarctic regime mountains	76.59	29590	4.00	1.12	5.56	0.90
Tundra	40.33	646	5.19	0.67	4.86	0.66
Hot continental	9.57	9164	3.19	0.83	4.71	0.94
Hot cont. regime mount.	1.44	919	3.18	0.69	3.84	0.91
Marine division	7.53	839	2.82	0.55	3.68	0.95
Marine regime mountains	6.04	257	3.14	0.17	3.55	0.92
Prairie	17.30	10969	3.27	0.92	4.77	0.94
Prairie regime mountains	5.05	3024	3.33	0.86	4.32	0.91
Warm continental	18.64	23315	3.26	0.88	5.22	0.95
Warm cont. regime mount.	8.15	13023	3.45	0.98	4.91	0.81
Temperate desert	4.94	960	2.39	0.55	3.64	0.85
Temperate steppe	23.52	6459	3.15	0.97	4.43	0.88

[a]The parameters of the characteristic fire size distribution are given as $\log_{10}$ values; e.g., the subarctic division has a characteristic fire size of $10^{4.68}$ ha. The parameter *a* is an estimator of the total annual burned area. The bins used for the parameter estimation are (on $\log_{10}$ scale) the following: CNFBD start: 2.0009, bin width: 0.1966; BAA Siberia start: 1.3318, bin width: 0.2439; and Canada start: 1.9338, bin width: 0.1915. These bins together with the distribution parameters can be used to calculate average number and area contribution for any fire size class.

Resolution Imaging Spectroradiometer products. The main data set is the Nadir BRDF Adjusted Reflectance (NBAR, MOD43B4) [*Schaaf et al.*, 2002] product, with the Thermal Anomalies/Fire (MOD14A1) [*Justice et al.*, 2002] and Land Cover Type (MCD12Q1) [*Friedl et al.*, 2002] products also being used. As we were only interested in "woody" areas, we restricted our analysis to International Geosphere-Biosphere Programme classes 1 to 8. New burns are identified by carrying out a change detection on congruent images from 1 year to the next. Any areas less than 4 pixels in area were removed. The burnt areas are then dated using thermal anomalies.

[9] A validation was carried out using Landsat (E)TM (Enhanced Thematic Mapper) images as ground truth at 10 randomly chosen locations throughout our boreal region. At each location, annual time series (2000–2007) of (E)TM images were manually interpreted, with the recent burnt areas delineated. A recent burnt area in our case was taken to be one not present in the previous years (E)TM imagery. After correction for any geolocation errors, reprojection and resampling to match the BBA, a pixel by pixel correspondence check was carried out. The omission and commission errors for the BBA product are 0.48 and 0.43, with a Kappa of 0.54.

2.2. Characteristic Fire Sizes

[10] The sizes of wildfires differ by several orders of magnitude, and their frequencies depend on geographic regions and time. Not only the number of fires of a certain size but also their contribution to the total burned area is of interest. To study this, we first bin the fires according to their size and then multiply the number of fires n_k in bin $[x_{k-1}, x_k]$ by the mean fire size m_k of the bin. It turns out that these new data approximately follow a normal distribution if we work with the logarithms of the fire sizes and bin with equal width on a log scale, i.e., with exponentially growing bins for the real fire sizes. This normal distribution then allows us to introduce the concept of a *characteristic fire size*. This is the value where the maximum of the normal density is attained, and it gives the fire size class that contributes most

Table 2. Estimated Distribution Parameter of the Fire Size in the CNFDB for the Last Five Decades[a]

Decade	μ	μ_{std}	σ	σ_{std}	a	a_{std}	r^2
1960s	4.39	0.12	0.65	0.12	6.4	0.075	0.87
1970s	4.49	0.13	0.68	0.13	6.7	0.078	0.85
1980s	4.78	0.08	0.69	0.08	7.0	0.049	0.94
1990s	4.67	0.04	0.72	0.44	7.1	0.023	0.99
2000s	4.51	0.10	0.64	0.10	6.8	0.063	0.90

[a]The parameters μ (characteristic fire size), σ, and a (see section 2; a is equal to total decadal burned area) as well as their standard deviation are given in $\log_{10}$ ha; r^2 is the goodness of fit of the estimated lognormal distribution. Note that the characteristic fire size in the 1980s was 2.5 times larger than the fire size in the 1960s.

to the burned area. Using this concept also allows us to summarize the distribution with a few parameters and to investigate how these parameters vary for different ecoregions or time periods.

[11] As the binning is crucial to obtain comparable distribution parameters, the number of bins was fixed at 20. A single set of bins was used when comparing the data sets as a whole, while for the estimation of the ecoregion-specific parameter, a specific set of bins was estimated for the CNFDB as well as the Canadian and the Siberian part of the BBA data. The bins are listed in section 3 for each assessment.

[12] For the calculation of the total burned area of a bin, we used as mean fire size of the bin $m_k = \exp(\xi_k)$ with ξ_k being the midpoint of the kth interval in log scale. To the data $(\xi_k, n_k \cdot m_k)$, $k = 1,2,\ldots,20$, we then fitted a scaled density of a normal distribution with parameters μ and σ. We emphasize that μ and σ have a natural meaning for the log-transformed fire sizes and will be used in what follows, but they are not the expectation and the standard deviation of the lognormal distribution. The scaling used for the fit is simply done by adjusting the area of the histogram to the total burned area (parameter "a" in the tables). For all parameters we give the best estimate listed in the tables. We also calculated their uncertainty and added this information by stating also the standard deviation of the estimates in Tables 1 and 2 (the standard deviation of the estimated parameters in Table 1 can be obtained from the authors).

[13] The goodness of fit of the normal distribution is assessed by linearly correlating the product of the mean fire size m_k with the fire count n_k for each bin with the estimate by the parameterized normal distribution. The r-square values are given for each estimate.

[14] To graphically display the uncertainty of the estimated distribution we also plotted uncertainty bands (95%) in Figures 3 and 6.

2.3. Fire Sizes in Relation to Bailey's Ecoregions

[15] To relate the fire characteristics to the large-scale climatic and biophysical conditions, we stratified the data according to the ecoregion divisions developed by *Bailey* [1995]. Figure 2 displays the spatial distribution of the ecoregions within the investigation area; their shape can also be seen in the Figures 4 and 5. The classification system by *Bailey* [1995] uses three different levels of categorization reflecting different criteria used: domains (solely based on climate), divisions (also taking vegetation and soil into account), and provinces (accounting additionally for land-surface form and fauna). Table 1 lists the names and areas of all 15 ecoregions inside the investigation area. Bailey's ecoregion map [*Bailey*, 1995] has a spatial resolution of 0.166° of longitude. Each fire has been assigned to a single ecoregion based on coordinates given in the CNFDB or the middle point of the fire detected in BBA. Ecoregions containing less than 100 fire records (either due to low fire incidence or very low total areas of the ecoregion in the investigation area) were excluded from the further investigation, since the fire incidence in these biomes is too low to detect reliable statistical relationships. For these regions, only the area and the number of recorded fires are stated in Table 1. Fires attributed to the ecoregion "Lake" (caused by the low resolution of the ecoregion map) were discarded as well. We also noticed that for some of the fires, the actual date of the fire seems to be mixed up in the database with the recording date. We therefore excluded all fires that were reported from October to March from the analysis of the intra-annual variability but kept them for the seasonal invariant parts of the analysis. All parameter estimations were made for the CNFDB, as well as the Canadian and the Siberian part of
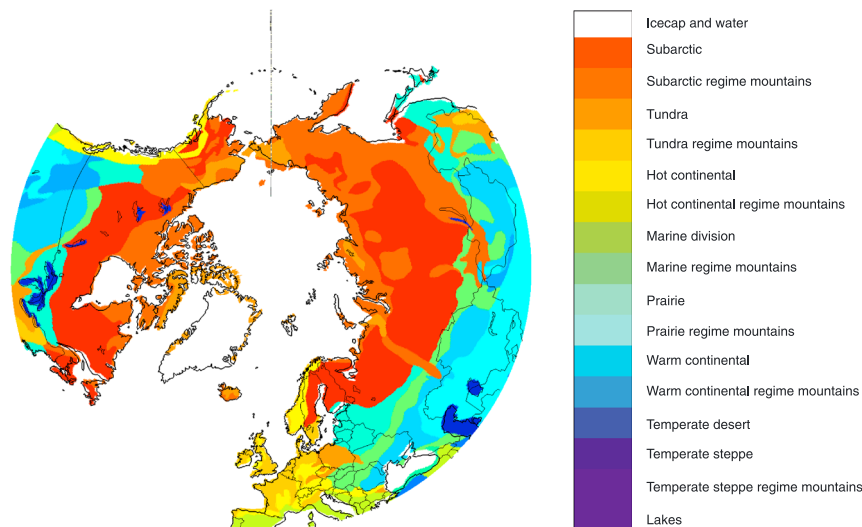

Icecap and water
Subarctic
Subarctic regime mountains
Tundra
Tundra regime mountains
Hot continental
Hot continental regime mountains
Marine division
Marine regime mountains
Prairie
Prairie regime mountains
Warm continental
Warm continental regime mountains
Temperate desert
Temperate steppe
Temperate steppe regime mountains
Lakes

Figure 2. Bailey's ecoregions (divisions) inside the investigation area.
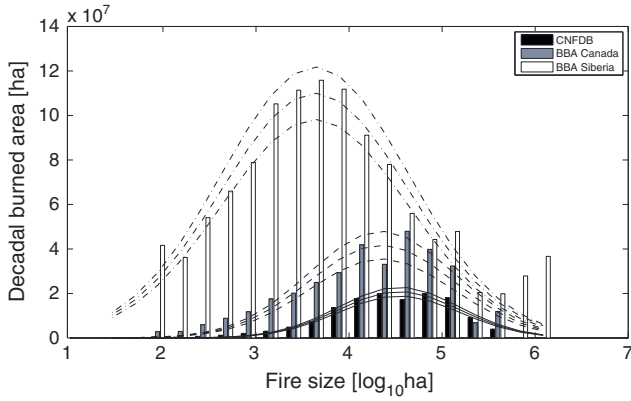
Figure 3. Characteristic fire size distribution for the CNFDB as well as the BBA data set over the decade from 2001 to 2010. The lines indicate the estimated distribution as well as the confidence bands of 95%. The BBA has been separated into Canadian and Siberian fires.

the BBA as a whole. Subsequently, we stratified the data into different ecoregions (given a sufficient number of fires recorded per ecoregion) and estimated the parameters of the FSD. For each sub-data set the characteristic fire size is displayed on a map (Figures 4 and 5). All estimated parameters as well as the goodness of fit (r square values) are listed per ecoregion (Table 1).

2.4. Time Series

[16] The temporal and seasonal changes of the fire size and the burned area were estimated using a time series analysis. Since this required a sufficient temporal extent of the data, only the intraspecific and interspecific variation of the CNFDB was analyzed. We estimated the total burned area and the characteristic fire size for each year (as described above) irrespective of the months and for each month irrespective of the year. Given the constraints of the data, we did not stratify the data into ecoregions for the time series analysis.

[17] A moving average window of 5 years and a linear trend was calculated for the annual burned area and the annual characteristic fire size. The log transformation of the fire size was performed before the moving window and the linear trend were estimated.

[18] The monthly burned area and characteristic fire size were sorted by year and a log-linear trend was estimated for each. To detect decadal trends in the fire size the distribution parameters for the CNFDB were estimated using a mixed model approach in which the data were stratified by decade.

3. Results

3.1. Total Characteristic Fire Sizes

[19] The unimodal distribution of the fire size/fire contribution relationship is displayed in Figure 3 separating the three data sets for the time period from 2001 to 2010. The two Canadian data sets have a considerably higher characteristic fire size of $10^{4.62}$ ha $= 42,370$ ha for the CNFDB and $10^{4.34}$ ha $= 21,976$ ha for the Canadian BBA compared to the Siberian fire size of $10^{3.62}$ ha $= 4153$ ha. The goodness of fit (r^2 value) between the data and the fitted distribution is 0.99 for the CNFDB, 0.95 for the Canadian, and 0.96 for the Siberian BBA data. The total sum of all bars represents the total annual burned area. It is highest for the Siberian data, which also covers the largest investigation area, followed by the Canadian BBA data, which is considerably higher than the CNFBD. We attribute this difference partly to the larger area covered by the Canadian BBA data (it also includes Alaska) as well as a higher probability of picking up small fires. The fire data was binned into 20 bins (at log_{10} scale) starting at $10^{1.628}$ ha with a width of $10^{0.2437}$ ha.

3.2. Ecoregion Typical Characteristic Fire Sizes

[20] Stratifying the data according to Bailey's ecoregions (division) [*Bailey*, 1995] allows climatic and biome influences to be highlighted. The largest ecoregion in all data sets is the sub-Arctic, ranging from 5.9×10^9 ha in the CNFDB to 10.4×10^9 ha in Siberia. The difference between the sub-Arctic in the CNFDB and the Canadian BBA of
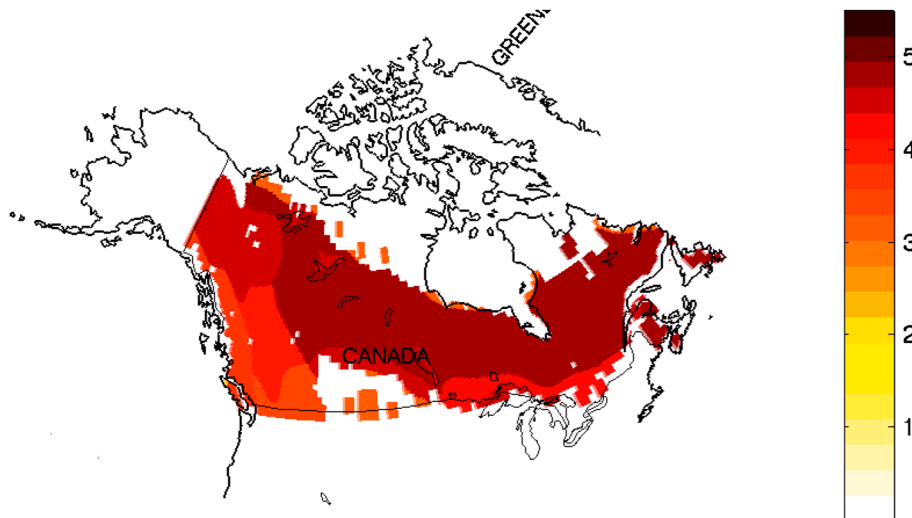

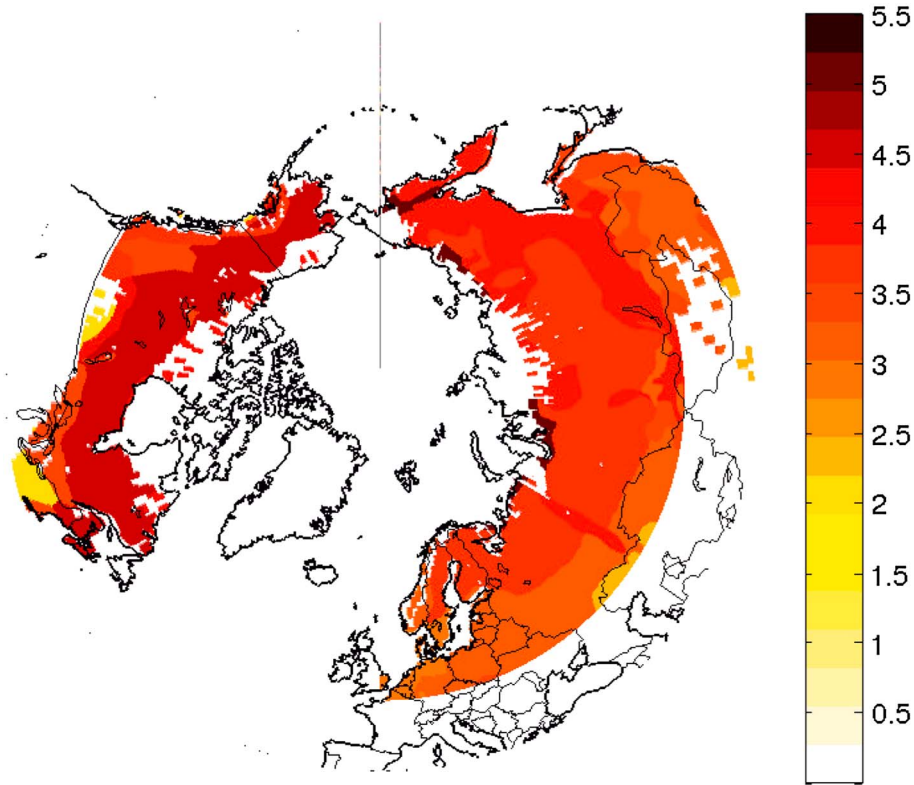**Figure 4.** Characteristic fire size in log_{10} ha in the CNFDB data set.

Figure 5. Characteristic fire size in $\log_{10}$ ha in the BBA data set.

1.2×10^9 ha can be contributed to the inclusion of Alaska in the BBA data set.

[21] The goodness of fit (r^2 values for the estimated normal distribution versus the data) ranges from 0.66 (Siberian Tundra) to 0.99 (subarctic ecoregion in the CNFBD data set). The maximum estimated characteristic fire size of $10^{5.19}$ ha (Siberian Tundra) might be considered as an outlier since this is based on relatively few fires (646) compared to the large coverage of this ecoregion. It is also the ecoregion with the least good fit between the data and the estimated distribution. Low standard deviations (σ) of the estimated distribution are also an indicator that the estimated characteristic fire size is based on very few fires contributing most of the total burned area. The highest characteristic fire sizes are found in the subarctic ecoregion regardless of the data set (with the exception of the Siberian Tundra).

[22] For the prairie ecoregion, which has the third highest characteristic fire size in the Canadian BBA data set, no parameters have been estimated in the CNFBD since less than 100 fires were recorded here, compared to 376 in the BBA. When comparing the characteristic fire sizes between different data sets, one has to bear in mind that they cover different time periods and are based on very different mapping methods.

[23] The complete set of estimated distribution parameters and the goodness of fit as well as the total area and fire frequencies for each ecoregion (with a considerable amount of detected fires) inside the investigation area are listed in Table 1.

[24] The spatial distribution of fire sizes is displayed in Figures 4 and 5. As can be seen from the figures, (similar to Table 1), the Siberian characteristic fire size as well as its variation is, in general, smaller than the Canadian, regardless of the data set.

3.3. Interannual and Intra-Annual Variation

[25] Due to the low temporal extent of the BBA data, only the CNFDB is analyzed for decadal, interannual, and intra-annual trends. The results of the mixed model-based estimation of the decadal fire size are listed in Table 1, and the overlap of the distributions is displayed in Figure 6. While a marked increase in total area can be seen (parameter a in Table 1 and area under the curve in Figure 6) over time, the first decade
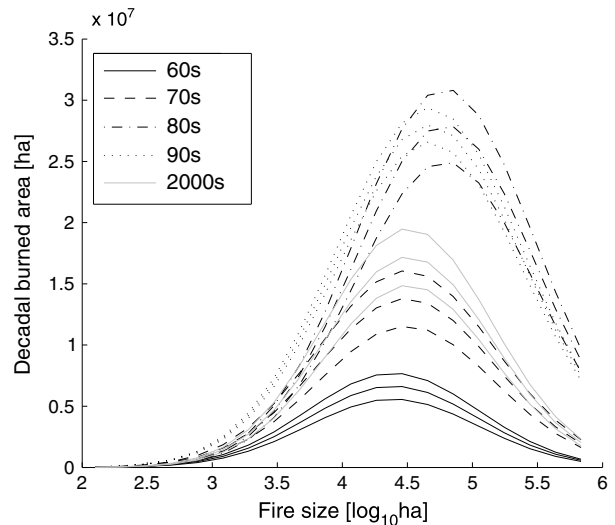

Figure 6. Decadal trends of Canadian fire sizes according to the CNFDB data. The lines indicate the estimated distribution as well as the confidence bands of 95%.
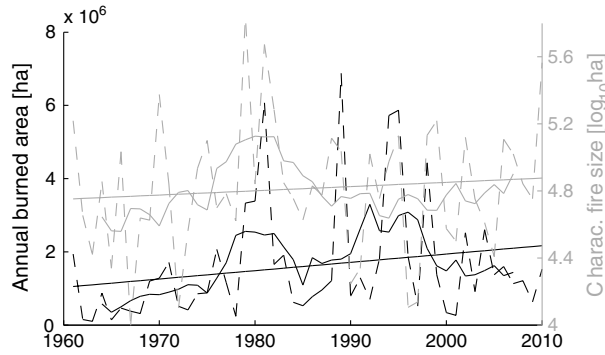
Figure 7. Annual burned area (black) and annual characteristic fire sizes (grey) from 1960 to 2010 for Canada (source CNFDB). Annual data (dashed line), linear trends (solid straight line), and 5 year moving averages (solid line).

of the current millennium showed a decline in average annual burned area. The fire size follows a similar trend.

[26] The annual total burned area as well as the fire size have a significantly ($p < 0.01$) rising trend over the last five decades (Figure 7). The moving average window of 5 years shows a decline in total burned area since the middle 1990s, while the annual characteristic fire size (also with a 5 year moving average window) had its maximum in the early 1980s and has been slowly rising since the early 1990s with a high variability. Though both have a rising trend, the interannual correlation factor (r^2) between total burned area and characteristic fire size is only 0.23. The largest characteristic fire size as well as total monthly burned area is found in the months of June and July. The increase in fire sizes is most marked in the months of May to July, while the months of August and September even show a decreasing trend (Figure 8). This analysis hence points to the fact that the fire season started earlier in the last few decades compared to earlier ones. The trend lines are log-linear estimations of the trend of monthly values over the five decades.

4. Discussion

[27] The fire size distribution of forest fires is of great interest, since the majority of firefighting effort and cost is associated with large fires. Large fires are difficult to control because of the large amount of suppression resources required for fire control and often pose a direct threat to human life and property at the wildland-urban interface. Even remote large fires can create a significant threat to human health at distant population centers as a result of smoke transport [*DeBell*, 2004]. On the other hand, fire is an intrinsic part of boreal ecosystem dynamics with many species relying directly or indirectly on fire for reproduction and survival [*Wein and MacLean*, 1983; *Goldammer and Furyaev*, 1996]. Boreal areas experiencing fire exclusion for more than a century, such as many Scandinavian forests, show a clear decrease in biodiversity, which has been related to the absence of fires in these areas, and sites with a long-term occurrence of fires have been shown to have a higher number of endangered species [*Lindbladh et al.*, 2003]. For the purpose of restoring the fire regime to preserve biodiversity as well as from a scientific point of view, the fire size distribution for a given ecoregion is of great interest [*Johnson et al.*, 1998].

It is also of ecological importance for the recolonization of species and wildlife habitat connectivity [*Bradstock et al.*, 2005]; hence, any temporal change in fire size distribution can potentially affect species occurrence even outside the burned areas.

[28] The notion of wildfires showing a self-organized critical behavior has been suggested by *Malamud et al.* [1998] using data from the United States as well as Australia, interpreting the noncumulative FSD as a scale invariant line in log-log space.

[29] *Ricotta et al.* [1999] contains brief explanation of the self-organized criticality phenomenon and how it can be applied to wildfires. Compared to the investigation area in this study, they used a relatively small data set (9164 fires within an investigation area of 5416 km^2). Their analysis finds a linear relationship of the cumulative FSD (in log-log space in a limited range from 1 ha to 100 ha) and a deviation from the line to lower values of numbers of fires for fires larger or smaller than the indicated range.

[30] In a later publication revisiting the relationship, this deviation has been interpreted as a separate line rather than a deviation due to data limitations such as the low temporal span of the burned area data set. *Ricotta et al.* [1999, 2001] investigate the distribution of the frequency of wildfires above a certain size in a cumulative manner instead of looking at the wildfires in a certain size class; it is done in the same way in this study as well as by *Malamud et al.* [1998]. If however, a linear relationship (in log-log transformed space) can be found in such a cumulative way, the same data would also support a linear relationship when plotted as in our study.

[31] While the universality of the power law relationship over orders of magnitude is mentioned by a number of authors, spatial as well as temporal extent and heterogeneity of the analyzed data is still of considerable importance. Compared to our study, all studies mentioned use investigation areas which are smaller by several orders of magnitude
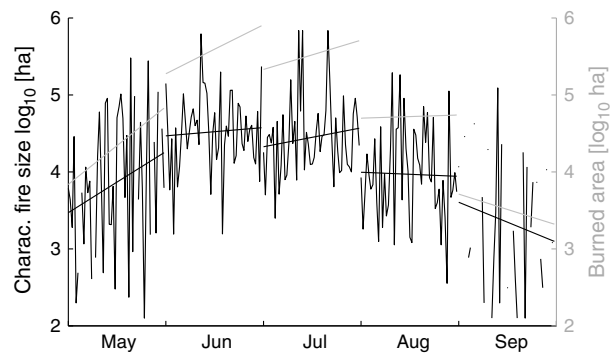

Figure 8. Monthly characteristic fire size and total burned area in Canada for 1960–2010 (source CNFDB). Monthly (black line) and log-linear trends (black straight line) of the characteristic fire size and log-linear trends (grey straight line) of the total burned area. Each month lists the time period from 1960 to 2010 (from left to right). For example, the furthest left value in May the black line lists the characteristic fire size of all fires occurring in May 1960 while the furthest right value reflects the characteristic fire size of all fires in the month of May 2010. The mean values and trends are calculated over the years but are specific to the month.

than the investigation area in this study, thus limiting the occurrence of (more rare) large fires. Of similar or even greater importance might be the heterogeneity of the landscape. The Mediterranean areas investigated in the literature are considered to be highly fragmented, which also severely limits the fire spread in landscapes, compared to the extensive forests covering the boreal region. The fire sizes involved in these studies range to a maximum of about 1000 ha, in some of the data sets only to about 100 ha. This is approximately the size of the characteristic fire for the data sets analyzed in this study. To transform the fire size/fire number relationship found by *Ricotta et al.* [1999, 2001] into a plot of the contribution to burned area by fire size, the numbers have to be multiplied with the fire sizes; hence, the slope of the fitted lines in log-log space would increase but the relationship should still be linear (in log-log space). For the eight examples of Mediterranean landscapes given by *Ricotta et al.* [2001], four would result in continuously increasing curves, while the remaining four would result in unimodal (though mostly very flat) curves. None of them, however, would resemble a Gaussian distribution. Since the size of the sampled landscapes as well as the time covered by the data are relatively low, one might anticipate that the Gaussian distribution is a feature which can only be expressed if a temporally and spatially sufficiently large amount of data is available. Another interpretation might be that such a relationship can only be detected if the landscape is sufficiently undisturbed and large enough for these features to develop since the data set has to be able to potentially contain very rare and very large fires. If the landscape is strongly fragmented (like the Mediterranean landscape) and /or is heavily used with strong fire suppression efforts (like the Scandinavian forest landscape), large fires are effectively prevented. However, given the occurrence of large-scale fires in the Mediterranean in the last decade might change this. The study by *Ricotta et al.* [1999, 2001], however, did not cover this time period.

[32] A systematic study calculating fire distribution parameters for a number of ecoregions within the United States including some of the minor ecoregions used in this study was *Malamud et al.* [2005]. This study used a power law distribution, fitting one straight line in log-log space. This approach allowed the authors to estimate the two parameters for the fitted line for each ecotype and compare them with each other. Though their results show a good fit between the binned data and the estimated line, the deviation between fitted line and data increases with large as well as with small fire sizes.

[33] Similar to the work by *Ricotta et al.* [2001], the fitted lines can be transformed to represent the area contribution by increasing their slope by 2. The slope ($-\beta$ in their notation) of the estimated lines for the ecosystems within the U.S. is between -1.3 and -1.81. An increase of the slope by 2 would result, for all ecosystems, in a continuously increasing line with increasing fire size. On a logarithmic binned axis, the proportion of burned area attributed to the total burned area should therefore be increasing with increasing fire sizes over all investigated magnitudes.

[34] This is contradicting to our findings, which show the highest contribution to the burned area at an intermediate fire size. Whether this unimodal distribution is best approximated by a log-normal distribution might be questioned since we do not develop the decision to choose a log-normal distribution

from theoretical considerations but rather from the facts that it provides a good approximation of the data and is a very common distribution; hence, we aim to aid its application by other researchers. The authors are not aware of a theoretically derived distribution function that would fit the data but would be very interested to see such developments in the future.

[35] For analyzing a distribution, the binning requirements depend on whether a fire count (possibly multiplied with the mean value of the bin) or a fire frequency (i.e., a density) is to be displayed. While in the first case equal binning width (in log space) is of the highest importance, in the latter case a normalization with the bin width is performed and hence the requirement of having equal bin size can be relaxed. To estimate the characteristic fire size like it is done in our study, fire counts are needed and a normalization cannot be performed, which leads to the requirement of equal binning.

[36] While forest fire data from the Unites States have been interpreted to follow a power law distribution by several authors, the article by *Newman* [2005] lists a large number of power law distributions from very diverse fields and uses the fire size fire area data National Fire Occurrence Database of the U.S. Department of Agriculture Forest Service and Department of the Interior as an example of a distribution that does not follow a power law. One of the reasons for the failure to comply to a power law might also be that the fire data used within the mentioned analysis is manually collected. This data tends to have a high probability of round numbers of hectares being reported compared to remotely sensed data for example. This in turn can lead to a failure of the statistical test to correctly identify the power law.

[37] Whether the use of the characteristic fire size to describe the fire regime in ecosystems outside the boreal domain is feasible remains to be tested. If the landscape fragmentation prevents fires from reaching larger sizes, the distribution might resemble a line [*Ricotta et al.*, 2001] instead of a unimodal distribution.

[38] The data sets used in this study clearly show that the assumption of a scale invariance has to be rejected for the boreal domain at a large scale. It might be valid for other domains or scales applied, e.g., if large fires are excluded due to the small investigation area.

[39] The analysis of the decadal trends (within the CNFDB) shows a steady increase for both the characteristic fire size and the fire area from the 1960s to the 1990s. *Gillett et al.* [2004] found a similar increase of decadal burned areas and linked this trend to climatic changes for Canadian forests, while the occurrence of large fires and related evacuations has been related to the Atlantic Multidecadal Oscillation [*Beverly et al.*, 2011].

[40] When evaluating this change, one has to bear in mind that the data, especially for fires before the 1980s, are of a poorer quality compared to the later years. The fact that the total burned area is lower in the 2000s than in the 1980s and 1990s is somewhat counterintuitive given that the last decade contained a high number of globally warm summers. Local processes and climate deviations seem to have acted here to a large degree.

[41] Another factor that may be causing the lower rate of annual area burned in the 2000s is the indirect effect of recent fire history on landscape fuel conditions. Depending on the forest ecosystem, burned areas may take 10–20 years or

more of vegetation regrowth before they are able to provide enough flammable fuel to support a spreading fire, particularly in slow-growing northern ecosystems. For example, *Weir et al.* [2000] found a short fire cycle of 15 years (95% confidence intervals =10-35 years) in the southern boreal region of Western Canada prior to 1890. The northern portion of Bailey's subarctic ecoregion still experiences a primarily "natural" fire regime with many large fires occurring every year. These large fires create large fire-free areas for several decades after burning, limiting the spread of newer fires by breaking up the horizontal continuity of the flammable landscape. Over 54 M ha were burned in Canada during the 1980s and 1990s according to the National Forestry Database, representing almost 20% of the entire Canadian boreal forest (287 M ha) [*Canadian Council of Forest Ministers*, 2012]. The vast majority of the 1980–1999 fires occurred in the western boreal region where there is now very high fragmentation of the flammable forest [*Amiro et al.*, 2001]. Though it is not known how strongly fuel discontinuity affects total annual area burned, it is probably an influential factor.

[42] Though no increase of total burned area within the last decade can be detected on a decadal scale, the intra-annual variation of fire sizes shows a clear increase for the months of May to July and a decrease in the two following months, showing that the fire season starts earlier now compared to earlier decades. A somewhat similar picture can be drawn for the area burned which also increased until July, while for the remainder of the year, the trend is less pronounced. This earlier start of the fire season which we detected fits well with the findings that spring arrives earlier in many temperate and boreal regions which has been documented for a number of regions and indicators by *Sparks and Menzel* [2002].

[43] While we now have the opportunity to perform long-term assessments of fire sizes and areas at large scale for Canadian boreal fires, this is not possible for the majority of the global boreal biome in Eurasia due to the lack of data. Dendrochronological studies have shown that fire activity in Scandinavia has kept the forest open, and fire frequency was much higher before 1750 due to human activity [*Niklasson and Granstrom*, 2000; *Lindbladh et al.*, 2003]. These results are all based on small investigation areas and do not allow a biome-wide analysis. Though fire is a prevalent recurrent disturbance across the boreal forest, generalization across the boreal zone is problematic due to the dichotomy of Eurasia and North America in their distinct fire regimes. Siberia has a predominantly low to moderate intensity surface fire regime and Western Canada a high intensity crown-fire regime, primarily driven by fuels [*de Groot et al.*, 2013]. Fire weather conditions were slightly more severe in Canada during 2001–2007, but forest composition and tree species morphology appear to have an overriding influence on fire regime through fire behavior. Half of the Russian boreal forest is composed of tree species with nonflammable foliage such as *Larix* spp., *Populus* spp., and *Betula* spp. [*Alexeyev and Birdsey*, 1998]. *Picea* spp. has flammable foliage but is generally found in the wetter "dark forest" region where fire is less common. *Pinus sylvestris* also has highly flammable foliage, but it is a tall species (relative to *P. banksiana* in North America) that self prunes, which creates a break in the ladder fuels necessary to initiate crown fire. In Canada, approximately 75% of the boreal forest is dominated by *Pinus* spp., *Picea* spp., and *Abies* spp. according to Canada's

National Forest Inventory (www.nfis.org), which are all crown-fire-promoting conifers with highly flammable foliage. *Picea glauca*, *Picea mariana*, and *Abies balsamea* have a very low branching habit with live branches usually extending to the forest floor, which provides ladder fuels for crown fire, even under moderate fire weather conditions. *Pinus banksiana* self prunes as it ages but not to the extent of *P. sylvestris*, and it is a shorter-growing pine tree, which promotes crown fire.

[44] Type of fire (crown versus surface) is a key defining characteristic of fire regime [*Weber and Flannigan*, 1997; *Gill and Allan*, 2008]. Boreal crown fires are characterized by high to extremely high fire intensity, and most fire suppression actions fail to control this type of fire [*Stocks et al.*, 2004]. Crown fires are fast spreading and result in very large fires, which explains the much larger average fire size distribution in the crown-fire-dominated regime of North America compared to that of Siberia in our study. While the differences of fire sizes between Siberian and Canadian fires for similar ecoregions can be explained by the fire characteristics of the occurring species, the more fundamental differences in fire pattern between different ecoregions still require an ecological interpretation for which we hope the concept of the characteristic fire size can aid in the future.

5. Conclusions

[45] The previously advanced notion of wildfire size-area distributions showing a power law related self similarity is rejected for the largest fire prone biome, the boreal forest.

[46] A novel fire size statistic is advocated, the characteristic fire size, reflecting the fire size which contributes most to the total burned area within a biome.

[47] This statistic allows the characterization of different biomes with respect to their typical fire size and provides a tool for assessing the change of fire sizes. The characteristic fire size as well as the annual burned area has increased over the last five decades in Canada. Both have the strongest increase early in the season, while the late season even shows a decreasing trend.

[48] It is also suggested to use the typical fire size when planning to reinitiate a natural fire regime in areas which have been excluded from naturally occurring fire due to human activity.

[49] The characteristic fire size provides a tool which can foster research on causes of the relationship between fire regimes to both ecoregions as well as climate since it captures important aspects of the fire characteristic in a single value.

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