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CHARACTERIZING EXTREME DRY-SPELL AND FOREST FIRE EVENTS IN THE PROVINCE OF ONTARIO, CANADA

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1. INTRODUCTION

In Ontario, forest fires are a common feature of both the boreal and the Great Lakes–St. Lawrence forest regions (Fig. 1), which together represent approximately 66% of the 78.9 x 10^6 ha of provincial forested area (Ont. Minist. Nat. Resour. 1996). Descriptions of fire processes in these regions have been developed from a common set of measures that are traditionally used to characterize fire regimes, such as fire frequency, fire intensity, depth of burn (Van Wagner 1983), severity (Reinhardt et al. 2001), season, and patchiness (Whelan 1995).

In the boreal forest, large but infrequent (i.e., 50-130 yr), high intensity crown fires determine forest structure by destroying and regenerating even-aged stands (Bonan and Shugart 1989, Johnson 1992, Payette 1992, Larsen 1997, Weir et al. 2000). In the Great Lakes–St. Lawrence forest region, regular, non-catastrophic surface fires (Maissurow 1941, 1935, McRae et al. 1994) recur every 10 to 100 yr (Swain 1973, Heinselman 1973, Woods and Day 1977, Burgess and Methven 1977, Dey and Guyette 1996a,b) and regulate forest composition by removing competitive vegetation (Methven 1973).

These standard fire regime descriptions provide landscape-level summaries of fire processes that are useful for comparing average fire characteristics between geographical areas and time periods but they are not indicative of the fire extremes that may be characteristic of an area. As a complement to traditional fire regime attributes, Moritz (1997) introduced the statistics of extreme values described by Gaines and Denny (1993) as a useful tool for characterizing extreme fire and fire weather events in a given area and time period. Meehl et al. (2000) provide a conceptual overview of the impact of changes in the mean, standard deviation, and variance on the frequency of extremes in weather variables.

Weather is a key influence on fire regimes (Whelan 1995) and a primary determinant of fire incidence (Cunningham and Martell 1973, Turner and Romme 1994, Bessie and Johnson 1995). Extreme fire activity in Canada can result from deficient moisture levels sustained for just a few days or weeks (Skinner et al. 1999) and long sequences of days with little or no rain can strongly influence provincial area burned (Flannigan and Harrington 1988). Intensification of these types of weather events are expected to accompany predicted future climate change (Trenberth 1999).

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Fig 1. Boreal and Great Lakes –St. Lawrence forest regions of Ontario.

Given emergent fire management objectives that include supporting the occurrence of fires in some areas of the landscape, and the potential for increased fire activity associated with future climate change (Stocks et al. 1998), there is a need to characterize extreme fire and weather events in an effort to quantify the risks associated with these extreme events and the interactions between them and those factors that may influence them now and in the future. As a fire attribute that complements traditional fire regime measures such as the fire cycle, characterization of fire extremes may also provide valuable insight into how fundamental fire processes operate and vary in the boreal and Great Lakes–St. Lawrence forest regions of Ontario.

We used the statistics of extreme values to characterize dry-spell extremes, or runs of consecutive days with little or no rain, and forest fire extremes in various geographical regions in the province of Ontario. Specifically, we ask (1) do the statistical characteristics of extreme forest fire events in Ontario differ across areas characterized by ecosystem classification and level of fire protection; (2) do the characteristics of extreme dry-spell events differ across Ontario; and (3) do the statistical properties of dry-spell and fire extremes vary in a similar manner across the province?

2. METHODS

2.1 Data

Forest fire data for all reported fires in Ontario between 1976 and 1999 were obtained from the Ontario Ministry of Natural Resources (Ont. Minist. Nat. Resour. 2001). Regional differences in forest fire extremes were investigated by extracting fire data sets for polygons with a unique combination of ecosystem classification (Rowe 1972) and forest fire protection zone (Martell

1994). From a total of 44 polygons, only those areas with at least one recorded fire per year for the 1976-1999 period were included in the analysis. This resulted in 21 potential fire datasets, each 24 years in length. Following the approach outlined by Moritz (1997), we created a time series of extreme fire events for each dataset. The time series was composed of observations of the largest fire (ha) reported for an area in a single fire season. Eleven datasets were excluded from the analysis because the total area burned contained in the time series of extreme fire events was <70% of the total area burned that occurred in that polygon between 1976 and 1998, which suggests that analysis of these data would not provide a valid representation of the fire regime (i.e., Moritz 1997).

Regional differences in dry-spell extremes across Ontario were investigated by extracting precipitation data from daily fire weather recorded by the Ontario Ministry of Natural Resources over the 1963-1998 period for 14 fire weather stations (Ont. Minist. Nat. Resour. 1999). The 36-year weather records were used to investigate regional differences in dry-spell extremes for the time period roughly consistent with the available fire record. Droughts are generally measured as sequences of deficient precipitation below a predefined reference level (Sharma 1998). We defined an extreme dry-spell event as the longest run of consecutive days in a fire season (April-October) with <5 mm of precipitation in a 24-hour period reported for a single weather station. Suitability of the "<5 mm" criterion was determined through an investigation of weather conditions associated with 40 large fires (≥5000 ha) in Ontario. Results confirmed that all of these fires occurred during dry-spell events, as defined by our criterion.

2.2 Statistical Analysis

We used the methods outlined by Gaines and Denny (1993) and Moritz (1997) to characterize the statistical properties of fire and dry-spell observations in Ontario that are extreme relative to the rest of the population. The procedure involves recording the extreme value observed in each interval of a time series and ranking them in ascending order. A continuous probability function is fit to their cumulative distribution, *F(x)*, which defines the probability that the largest fire event or dry-spell event in a year will be less than or equal to a given value of *x* (Eq. 1):

$$F(x) = P(X_{\max} \le x) \qquad [1]$$

The inverse of 1–*F(x)* is the return time, $T_r(x)$, which describes the expected number of years that will elapse between consecutive occurrences of a given extreme value *x* (Eq. 2):

$$T_r(x) = \frac{1}{1 - F(x)} \qquad [2]$$

For large samples (N ≥ 20) of extreme values that are independent and identically distributed, the cumulative probability function approaches an asymptotic form (Eq. 3) (Jacocks and Kneile 1975).

$$F(x) = \exp\left(- \left[\frac{\alpha - \beta x}{\alpha - \beta \varepsilon} \right]^{1/\beta} \right) \qquad [3]$$

Where *x* is the maximum fire size or dry-spell length, ε is the most frequently occurring extreme value (mode), α measures the rate of increase of *F(x)* with the natural logarithm of time, and the ratio α/β estimates the maximum fire or dry-spell event achievable (when α and β are both >0).

For each time-series of extreme values, temporal independence was determined from lagged autocorrelations. Spatial independence was assumed if the largest fires in the time series did not burn the majority of the study area. Linear regression was used to investigate stationarity over time.

Maximum likelihood estimates of ε, α, and β were obtained with the SAS NLIN procedure (SAS Institute 1999) by maximizing the logarithm of the likelihood function (see Appendix of Gaines and Denny [1993]). Regional differences in fire and dry-spell extremes were investigated by comparing cumulative probability distributions with a Kolmogorov-Smirnov test. Detailed comparisons of maximum likelihood parameter estimates with t-tests were used to compare fire extremes in two forest regions and dry-spell extremes in northeastern and northwestern potions of the province. For a subset of 5 polygons that had weather stations at or near their centers, correspondence between extreme fire and dry-spell events was investigated with Spearman rank correlation.

3. RESULTS AND DISCUSSION

Autocorrelation coefficients calculated for each of the time series were not significantly different from zero at the 95% confidence limit. For all 10 fire datasets, each maximum annual fire event burned <20% of the study area in question. Linear regressions over time indicated that all of the time series are stationary. The fitted distribution of extreme values (Eq. 3) using maximum likelihood estimation resulted in excellent fits for all datasets. Coefficients of determination (R^2) for all models were ≥0.97.

3.1 Regional Differences in Fire Extremes

Kolmogorov-Smirnov test statistics indicated significant differences in the cumulative probability distributions of extreme fire events in the boreal forest region as compared to the Great Lakes–St. Lawrence forest region. A detailed comparison of maximum likelihood estimates for polygons located in each forest region resulted in significant differences for two of the three parameters (Table 1). There were differences in parameter β and parameter ε, which indicates a significant shift in the position of the distribution (Fig. 2) and a decline in the modal fire size from 32.1 ha in boreal region of northwestern Ontario to 1.5 ha in the eastern portion of the Great Lakes–St. Lawrence forest region.

Table 1. Maximum likelihood estimates of model parameters: extreme fire events in northwestern boreal and eastern Great Lakes-St. Lawrence forest regions.

	Extreme Fire Events 1976-1999	
Parameter	**Northwestern boreal**	**Great Lakes-St. Lawrence**
α	-0.976	1.162
β	-3.733 [a]	-0.875 [a]
ε	32.092 [a]	1.534 [a]
SE of α	2.599	0.237
SE of β	0.201	0.126
SE of ε	4.199	0.086

[a] parameters significantly different at the 95% confidence level

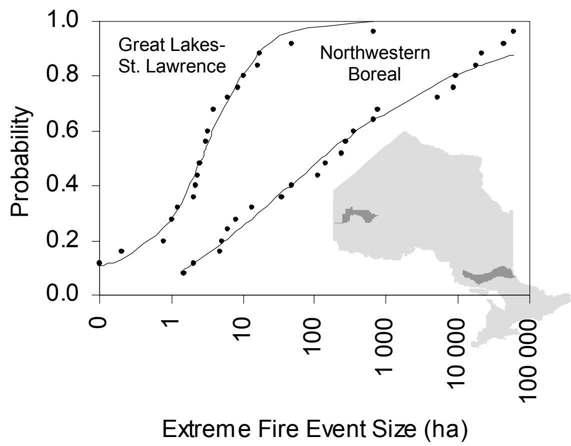

Fig. 2. Cumulative probabilities for maximum fire sizes in polygons in boreal and Great-Lakes St. Lawrence forest regions (describes the chance that the largest fire in a year will be less than or equal to a given value of x). Solid line curves are maximum likelihood fits of continuous probability functions.

3.2 Regional Differences in Dry-Spell Extremes

Kolmogorov-Smirnov test statistics indicated that significant differences in the cumulative probability distributions of extreme dry-spell events followed an east–west division in the northern portion of the province. Detailed comparisons of maximum likelihood estimates for weather stations located in northwestern and northeastern Ontario indicated significant differences for parameter ε, which corresponds to a modal dry-spell event length of ~21 days in northwestern Ontario as compared to ~16 days in northeastern Ontario.

Table 2. Maximum likelihood estimates of model parameters: extreme dry-spell events in northwestern and northeastern Ontario.

	Extreme Dry-Spell Events 1963-1998	
Parameter	**Northwestern Ontario**	**Northeastern Ontario**
α	11.856	10.051
β	0.281	0.244
ε	21.075 [a]	16.122 [a]
SE of α	1.029	1.021
SE of β	0.043	0.054
SE of ε	0.086	0.114

[a] parameters significantly different at the 95% confidence level

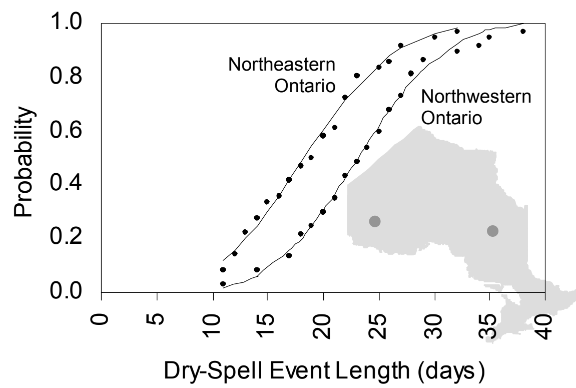

Fig. 3. Cumulative probabilities for maximum dry-spell lengths for weather stations in northeastern and northwestern Ontario over the period 1963-1998 (describes the chance that the longest dry-spell in a year will be less than or equal to a given value of x). Solid line curves are maximum likelihood fits of continuous probability functions.

3.3 Relating fire extremes to weather extremes

Return times of extreme fire or dry-spell events (i.e., Eq. 2) represent the most likely number of years that will elapse between occurrences of an event of a given magnitude (Gaines and Denny 1993). Return times of 100-ha, 1000-ha, and 10 000-ha fires calculated for five polygons that had weather stations at or near their centers, were correlated with the return times of 40-day extreme dry-spell events calculated for the same locations (Table 3).

Table 3. Spearman rank correlations between extreme fire event (1976-1999) and extreme dry-spell event (1963-1998) return times for a subset of 5 polygons that had weather stations at or near their centres.

	20 day dry-spell event		30 day dry-spell event		40 day dry-spell event	
Fire Event Size (ha)	**r**	**p**	**r**	**p**	**r**	**p**
100	-0.60	0.285	-0.40	0.505	0.90	0.037 [a]
1000	-0.30	0.624	0.00	1.0	1.00	<0.001 [a]
10 000	0.00	1.0	0.10	0.873	0.90	0.037 [a]
100 000	0.20	0.747	0.30	0.624	0.70	0.188

[a] significant at the 95% confidence level

Rank correlations between estimated parameters of the model for the same subset of 5 polygons and associated weather stations also indicated a strong correlation for parameter ε, which suggests that the statistical properties of extreme fire and extreme dry-spell events vary in a similar manner across Ontario.

3.4 Fire management implications

This study corroborates existing evidence that fire processes vary across areas that differ in terms of vegetation, weather, and levels of fire protection. Results suggest that the characteristics of fire extremes in an area can be expected to change in response to changes in dry-spell extremes. These statistical properties of extreme fire and dry-spell events may be of practical use for assessments of the risks associated with permitting an individual fire to burn in a given area of the province and for identifying the potential impacts of climate change on fire regimes.

This paper outlines a very preliminary, exploratory assessment of fire and weather extremes in Ontario. Applications of the statistics of extreme values for investigating natural processes such as weather have become increasingly common in recent years in response to concerns over potential climate change impacts and new methodologies and approaches continue to be developed. Future research should focus on emerging methodologies for the analysis of fire and weather extremes in Ontario and elsewhere in Canada.

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