Fire weather index system components of large fires in the Canadian boreal forest

Article *in* International Journal of Wildland Fire · January 2004

CSIRO PUBLISHING
www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2004, **13**, 391–400

Fire weather index system components for large fires in the Canadian boreal forest

B. D. Amiro[A,D], *K. A. Logan*[B], *B. M. Wotton*[B,C], *M. D. Flannigan*[B], *J. B. Todd*[A], *B. J. Stocks*[B] *and D. L. Martell*[C]

[A]Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton, AB, T6H 3S5, Canada.
[B]Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, ON, P6A 2E5, Canada.
[C]Faculty of Forestry, University of Toronto, 33 Willcocks Street, Toronto, ON, M5S 3B3, Canada.
[D]Corresponding author. Present address: Department of Soil Science, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada. Telephone: +1 204 474 9155; email: brian_amiro@umanitoba.ca

Abstract. Canadian Fire Weather Index (FWI) System components and head fire intensities were calculated for fires greater than 2 km^2 in size for the boreal and taiga ecozones of Canada from 1959 to 1999. The highest noon-hour values were analysed that occurred during the first 21 days of each of 9333 fires. Depending on ecozone, the means of the FWI System parameters ranged from: fine fuel moisture code (FFMC), 90 to 92 (82 to 96 for individual fires); duff moisture code (DMC), 38 to 78 (10 to 140 for individual fires); drought code (DC), 210 to 372 (50 to 600 for individual fires); and fire weather index, 20 to 33 (5 to 60 for individual fires). Fine fuel moisture code decreased, DMC had a mid-season peak, and DC increased through the fire season. Mean head fire intensities ranged from 10 to 28 MW m^{-1} in the boreal spruce fuel type, showing that most large fires exhibit crown fire behaviour. Intensities of individual fires can exceed 60 MW m^{-1}. Most FWI System parameters did not show trends over the 41-year period because of large inter-annual variability. A changing climate is expected to create future weather conditions more conducive to fire throughout much of Canada but clear changes have not yet occurred.

Additional keywords: drought; duff moisture; fire intensity; forest fire; seasonality; taiga; trends.

Introduction

Assessment of the potential impacts of a changing climate suggest that future fire weather will be more conducive to forest fires in Canada (Flannigan *et al*. 2000, 2001). Most of this change is expected to occur later in this century as a 3 × CO_2 climate is approached. An important question is whether detectable changes have occurred already, given the highly episodic nature of fire. Further complications are changes to the landscape that will affect fuels, changes in the number of fire ignitions, and human-intervention strategies. Fire weather is largely a function of temperature, precipitation, humidity and wind speed. Throughout most of Canada, there has been a general warming both annually and during summer over the 1950–1998 period (Zhang *et al*. 2000). Precipitation trends are more variable through most areas, with no change or even a decrease in others (Zhang *et al*. 2000). Drought codes that relate to fire weather show no trends in the east but periodicities in the central part of Canada through most of the 20th century (Girardin *et al*. 2004).

Area burned has increased in Canada during the 20th century (Podur *et al*. 2002), although it is likely that fire statistics have been under-reported before about 1960. However, the past four decades show an increasing area burned despite the high inter-annual variability (Stocks *et al*. 2002). This area burned is related to synoptic weather patterns (Skinner *et al*. 2002), with these patterns creating conditions favourable to fire ignition and growth.

Canadian forest fire management agencies use the Canadian Fire Weather Index (FWI) System (Van Wagner 1987) to estimate fuel moisture and generate a series of relative fire behaviour indices based on weather observations. This system is also used in some parts of the United States, Mexico, south-east Asia, New Zealand, Portugal, and other parts of the world. These fuel moisture and fire behaviour indices are used by operational personnel to aid in the estimation of expected daily fire occurrence, potential fire behaviour and the difficulty of suppression across a fire management district, region or province. The current day's indices and

 10.1071/WF03066 1049-8001/04/040391

future values generated from forecasted weather can aid in deploying suppression resources to areas of potentially high fire activity.

The FWI System indices are relative indicators of potential fire behaviour, however, and do not by themselves predict differences in expected behaviour between substantially different forest types. While over the years operational personnel have developed experience in understanding the fuel-type specific fire behaviour expected under given values of the FWI System indices, the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada 1992) is often used to predict fire behaviour (fuel consumption, rate of spread and head fire intensity (HFI)) for a range of fuel types found in Canadian forests.

Head fire intensity estimates the amount of energy released per unit time per unit fire front line (Byram 1959; Alexander 1980). It is a good indicator of fire behaviour and HFI forecasts are used to assess potential risks to wildland firefighters (Beck *et al*. 2002). Climatologies of HFI have been developed to estimate fire behaviour potential on the landscape, often using 90 or 95 percentile values (Kafka *et al*. 2000). These are based on historical weather and give the potential for a fire to occur at a given intensity. Flame lengths can also be used to estimate HFI but good observations are rarely documented.

A climatology of FWI System indices and codes has not been reported for Canada for conditions during which fires were burning. This paper reports these calculated for daily weather for the most extreme days when fires with a final size of greater than 2 km^2 in area were burning in the boreal and taiga ecozones of Canada. We use data from the large-fire database (LFDB) (Stocks *et al*. 2002) for the 1959–1999 period. These large fires represent only a very small percentage of the fires but account for almost all (~97%) of the area burned. We look at the seasonal development of these components and also test whether there have been trends over the 41-year period. The distribution of values provides information on the probability of a large fire experiencing certain weather conditions during its growth, and has practical value as a baseline for fire management operations in a given ecozone or region. The trend analysis tests for whether extreme conditions have changed over time, potentially an important issue if a changing climate is involved.

Methods

The LFDB contains information on start location, estimated ignition date, and final size of each fire. Stocks *et al*. (2002) present a map of the location of these fires. The dataset does not indicate the precise dates during which the fire spread. The exact ignition date has some uncertainty although many agencies estimate this using both the date of detection and knowledge of recent weather to account for hold-over fires (especially for lightning-caused fires). In a previous study (Amiro *et al*. 2001), we assumed that most fires had their main period of growth during the first 21 days of the fire. Further analysis showed that the main period of fuel consumption (based on the FWI System) for all fires occurred during the first 4 days. Although we recognise that some fires persist for months and can have several periods of active fire growth, many fires make their greatest runs shortly after ignition when the fire weather is most conducive to both ignition and fire growth.

The FWI System components were calculated using noon-hour (local standard time) values of temperature, relative humidity and wind speed, and daily total precipitation. The data were taken from Environment Canada surface observation stations that operated for a full fire season for at least part of the analysis period. We used noon observations from 415 hourly weather stations distributed across the country. Weather data from the Ontario Ministry of Natural Resources fire weather station archive from 1963 to 1997 were also included to improve the weather station network coverage in northern Ontario. Rainfall data from 90 stations in Environment Canada's daily climatological network were also used to augment the noon records in areas of the country prone to fire but with very sparse hourly weather station coverage. These weather and fire danger data were interpolated to each fire location within the LFDB for the start date and the following 20 days using a thin-plate cubic-spline technique (Flannigan and Wotton 1989).

For each fire, we identified the highest daily reported value of a FWI System index or code within the 21-day period. This gives the most severe day for each fire, which is appropriate as it dictates fire growth. However, it does not represent average conditions experienced over the whole period during which the fire burns. We then used these values to derive statistics for each ecozone and for each year. The fire weather parameters (Van Wagner 1987) were:

- FFMC (fine fuel moisture code) represents the moisture content of litter and other fine fuels in a forest stand, in a layer of dry weight ~0.25 kg m^{-2} (time constant about 2/3 days). It is an indicator of sustained flaming ignition and fire spread.
- DMC (duff moisture code) represents the moisture content of loosely compacted, decomposing organic matter weighing about 5 kg m^{-2} when dry (time constant about 12 days). It relates to the probability of lightning ignition and fuel consumption.
- DC (drought code) represents a deep layer of compact organic matter weighing about 25 kg m^{-2} when dry (time constant about 52 days). It relates to the consumption of heavier fuels and the effort required to extinguish a fire.
- ISI (initial spread index) is a combination of wind and FFMC representing rate of spread without the variable influence of fuel.

Fig. 1. Map of Canadian ecozones.

- BUI (build-up index) is a combination of DMC and DC representing total fuel available to the spreading fire. It is correlated with fuel consumption.
- FWI (fire weather index) is a combination of ISI and BUI representing intensity of the spreading fire as energy rate per unit length of fire front. It is often used as a single integration of fire weather.
- DSR (daily severity rating) is a power function of FWI representing a measure of control difficulty for a fire.

All of these are unit-less. We have included all of these because each index or code is used in a different way, some being more important indicators than others for specific purposes. In addition, we calculated the HFI as the amount of energy released per unit time per unit fire front line as part of the FBP System. Unlike the previous FWI parameters, HFI is dependent on the fuel type, and has units of MW m^{-1}. It is a function of fuel consumption and rate of spread, assuming the heat of combustion is a constant 18 MJ kg^{-1}. The FBP system includes several fuel types that occur throughout the boreal forest. For this analysis, we based the HFI calculations on the boreal spruce (C2) fuel type only. This fuel type occurs throughout the boreal and taiga regions and is used for comparison purposes, but it does exhibit extreme fire behaviour. Analyses for additional fuel types would give different HFI values. Head fire intensity values are often used to depict the aggressiveness of fire behaviour. Typical classifications used by operational agencies are 0.5 (surface fire), 2 (surface fire with torching), 4 (intermittent crown fire) and 10 (full crown fire) MW m^{-1} (Alexander and deGroot 1989). We used these divisions as cut points to evaluate the number of fires above a certain level in a given year. This is a simple approximation of a 'fireload', but differs from that used by Boychuk and Martell (1988; extension of earlier work by P. H. Kourtz, Canadian Forest Service, unpublished data) who estimated total flame area reported in a region during a 24-h interval.

Analyses were done by ecozones (Fig. 1) following the Canadian ecoregion classification of the Ecological Stratification Working Group (1996). However, the boreal shield and taiga shield ecozones transcend the east–west moisture gradient across the country, and there are some obvious differences in fire occurrence across this area (Harrington 1982; Harrington *et al*. 1983). Therefore, we split the taiga shield

Table 1. Parameters for fires >2 km^2 in area for 1959–1999

Weather indices are the maximum noon-hour value for the first 21 days of each fire, with mean values compiled for each ecozone. HFI values are based on a boreal spruce fuel type

Parameter	Ecozone							
	Canada	Taiga Plains	Boreal Plains	Boreal Cordillera	Boreal Shield West	Boreal Shield East	Taiga Shield West	Taiga Shield East
No. fires	9333	1209	1635	755	2998	1057	1209	470
Maximum no. fires in any year	437	69	110	56	334	95	163	43
Minimum no. fires in any year	61	3	2	1	4	2	1	1
Mean fire size (± s.e.) (km^2)	77 (13)	1280 (16)	64 (6)	63 (5)	69 (3)	52 (6)	88 (7)	98 (13)
Median fire size (km^2)	12	18	7	17	13	8	18	15
Maximum fire size (km^2)	10 500	10 500	4497	1825	2898	3783	4770	3778
FFMC	91.4	91.2[a]	92.3[b]	92.2[b]	91.5	91.0[a]	90.6[c]	90.4[c]
DMC	60	72[a]	70[a]	78	55	44	60	38
DC	298	372[a]	266	366[a,b]	288	210[c]	354[b]	227[c]
ISI	13	10[a]	16	12[b]	14	12[b]	10[a]	10[a]
BUI	75	92	80[a]	96	70	54[b]	80[a]	50[b]
FWI	28	27	33[a]	32[a]	28	22	25	20
DSR	10	10[b]	14[a]	14[a]	10[b]	7[c]	9	7[c]
HFI (MW m^{-1})	15	18	24[a]	28[a]	20	14	16	10

[a–c] Similar superscript letters denote no significant difference for a parameter among ecozones at the 0.05 level (ANOVA; SYSTAT 1997). BUI, build-up index; DC, drought code; DMC, duff moisture code; DSR, daily severity rating; FFMC, fine fuel moisture code; FWI, fire weather index; HFI, head fire intensity; ISI, initial spread index.

ecozone into Taiga Shield West and Taiga Shield East using Hudson Bay as the divider. We also split the boreal shield ecozone at the northern tip of Lake Superior where the Boreal Shield West ecozone includes ecoregion numbers less than or equal to 95 and Boreal Shield East includes those with ecoregion numbers greater than 95 (numbers based on Ecological Stratification Working Group 1996).

Annual trends in fire parameters were investigated using linear regression analyses (i.e. parameter $= a * year + b$). This technique is appropriate when there is no temporal autocorrelation, but needs to be used with caution for time series analyses (e.g. Woodward *et al.* 1997). When autocorrelation occurs, false positives can result, but if no significant (i.e. $P > 0.05$) regression is detected, then it is unlikely that a trend exists. We used SAS (SAS 2000) to calculate linear regressions and temporal autocorrelations for each parameter for each ecozone.

Results

Fire statistics

Several of Canada's ecozones have not experienced sufficient fire in recent years to allow analyses. Hence we concentrated on the seven ecozones in the taiga and boreal regions: Taiga Plains, Boreal Plains, Boreal Cordillera, Boreal Shield West, Boreal Shield East, Taiga Shield West and Taiga Shield East (Fig. 1). This included 9333 large fires, and accounts for 94% of the area burned in Canada during the 1959–1999 period. The number of fires and area burned is highly variable among years but, at the ecozone level, a large sample is available for statistical analyses (Table 1). The values for area burned and number of fires are consistent with those reported by Stocks *et al.* (2002), with the addition of data for 1998 and 1999.

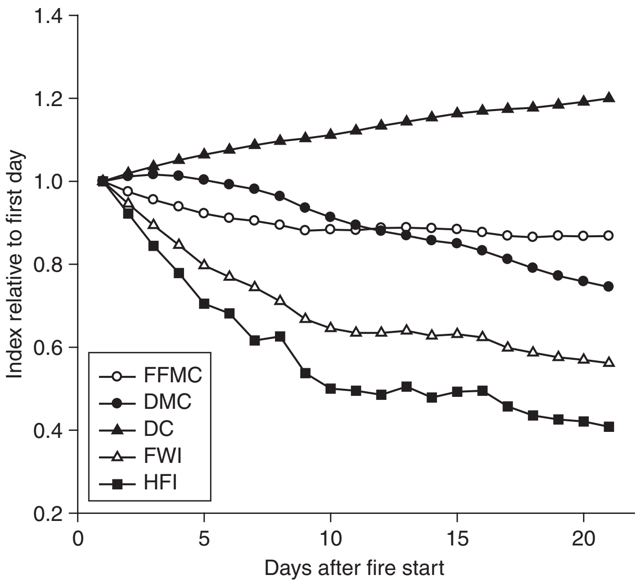

Fig. 2. Values of fire weather indices (FFMC, DMC, DC, FWI) and head fire intensity (HFI) for the first 21 days following the fire start. Data are means for all Canada, calculated by normalising each consecutive day to the initial start day for each fire. Standard error values are $< \pm 0.01$. DC, drought code; DMC, duff moisture code; FFMC, fine fuel moisture code; FWI, fire weather index.

Fire weather indices

The FFMC and FWI are greatest (i.e. more conducive to fire) in the first few days following ignition (Fig. 2). This pattern

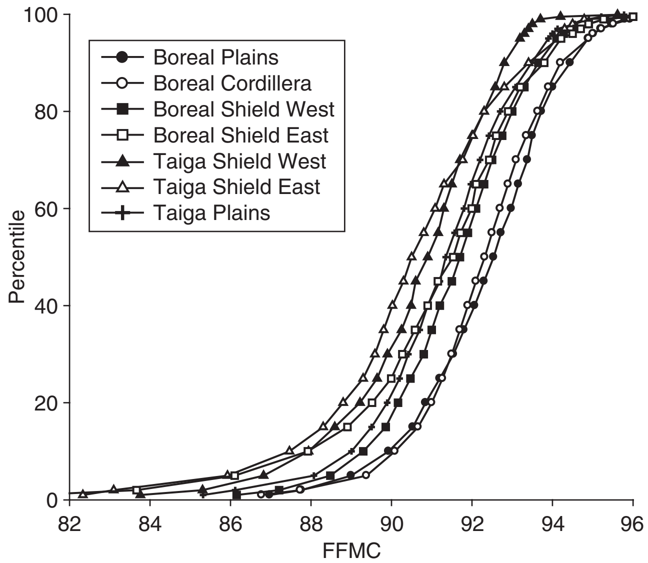

Fig. 3. Cumulative distribution of fine fuel moisture code (FFMC) for each ecozone.

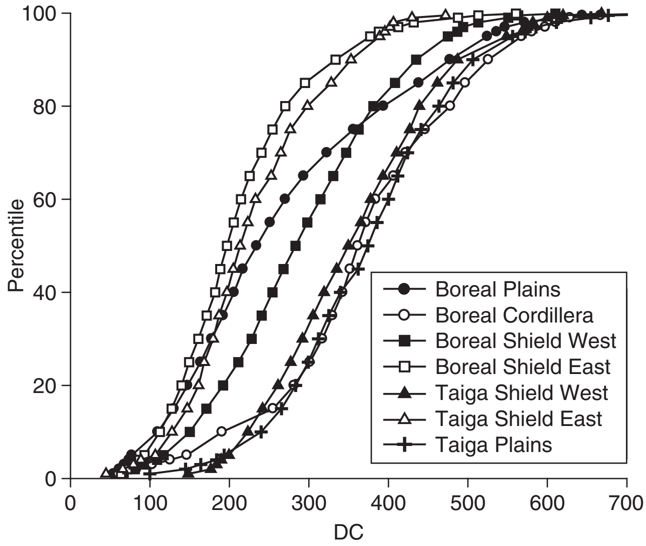

Fig. 5. Cumulative distribution of drought code (DC) for each ecozone.

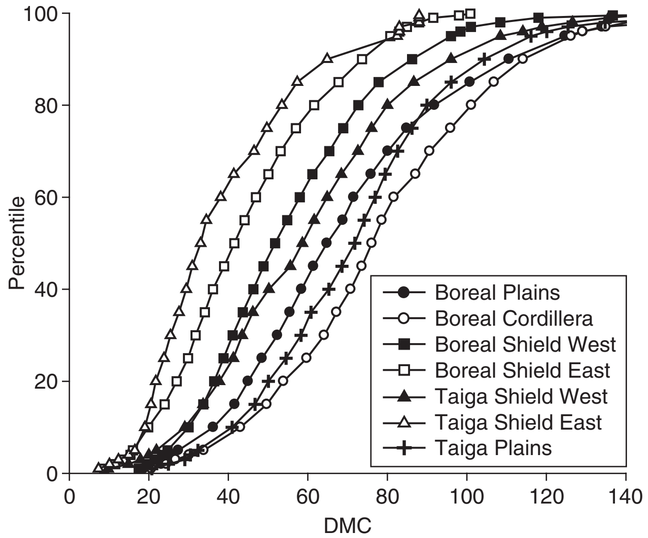

Fig. 4. Cumulative distribution of duff moisture code (DMC) for each ecozone.

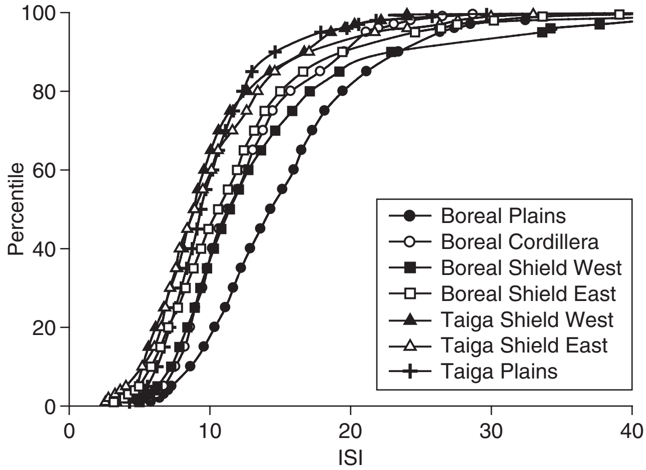

Fig. 6. Cumulative distribution of initial spread index (ISI) for each ecozone.

is consistent among all ecozones. The values in Fig. 2 are expressed relative to day 1 for each fire to allow for plotting on a single axis. However, the indices are not inter-comparable since the dynamic range of their scales is not consistent. The DMC values tend to be relatively flat over the first few days, whereas the DC values increase over time. In the following analyses, we selected the maximum index value within this 21-day period, a value that should correspond to severe fire behaviour. Statistics for these extreme values are given in Table 1 with the cumulative distributions for all indices shown in Figs 3–9.

Most FFMC values are between 82 and 96 with means for an ecozone in the range of 90–92 (the FFMC is a non-linear scale). The highest values are found in the Boreal Plains and Boreal Cordillera ecozones and the lowest in the Taiga Shield ecozones (Fig. 3). Several pairs of ecozones have similar values (Table 1). Duff moisture code values range from about 10 to 140 with the median values between 30 and 70 (Fig. 4) and the ecozone means between 38 and 78. The cumulative distributions show a large spread among ecozones, with eastern and northern ecozones being lower. The Taiga Plains and Boreal Plains have similar DMC values, whereas the other ecozones are significantly different (Table 1). Drought code values range from about 50 to 600 with lower values in the east (Fig. 5). No significant difference in mean DC values

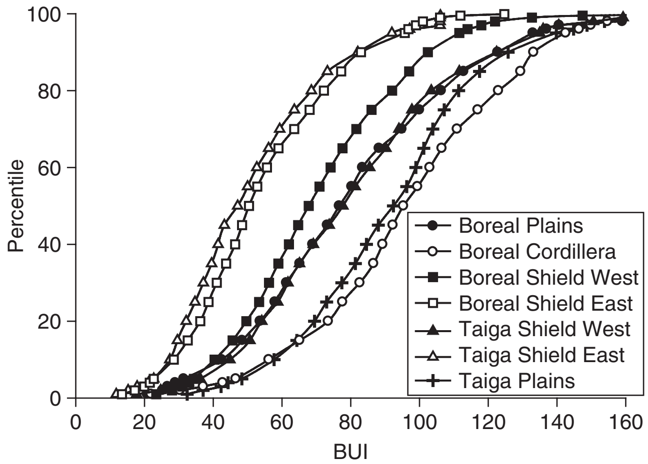

Fig. 7. Cumulative distribution of build-up index (BUI) for each ecozone.

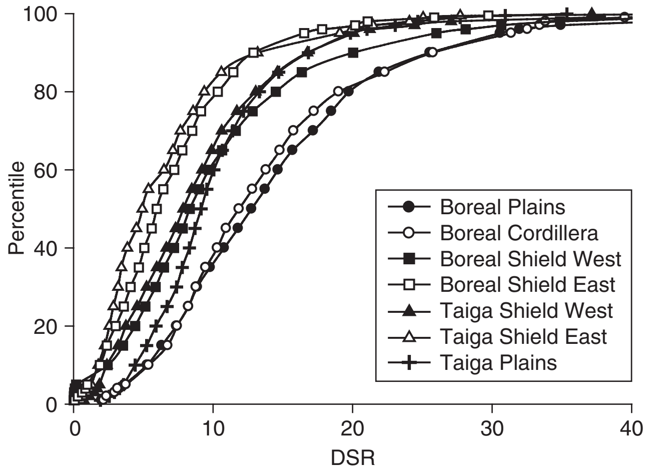

Fig. 9. Cumulative distribution of daily severity rating (DSR) for each ecozone.

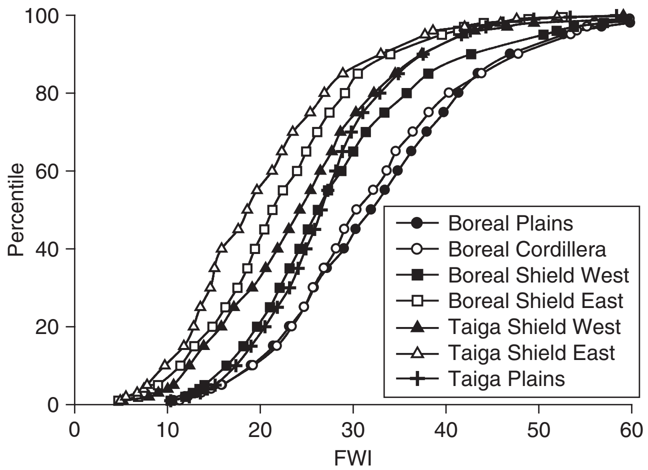

Fig. 8. Cumulative distribution of fire weather index (FWI) for each ecozone.

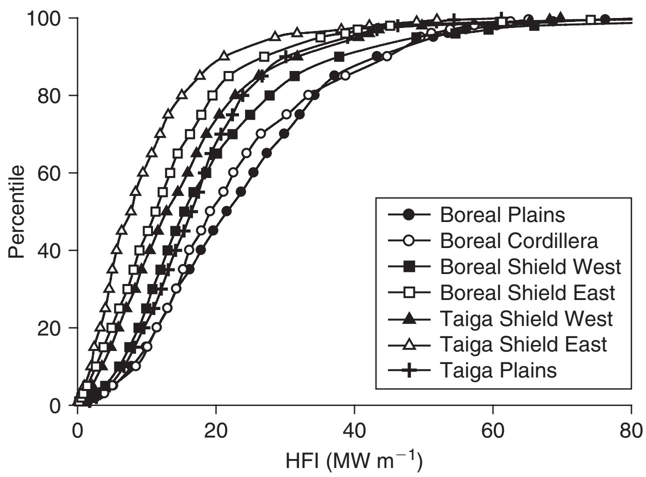

Fig. 10. Cumulative distribution of head fire intensity (HFI) for each ecozone for the boreal spruce fuel type.

was found between the Taiga Plains and Boreal Cordillera, the Boreal Cordillera and Taiga Shield West, and the Boreal Shield East and Taiga Shield East (Table 1). Mean ISI values are close to 10 with the Taiga ecozones having similar values. Extreme values can exceed 30 (Fig. 6). Ecozone mean BUI values range from 50 to 96, with some exceeding 140 (Fig. 7). The ISI values are lowest in the taiga ecozones whereas the BUI values are lowest in the east. These correspond to similar patterns in the other indices, upon which they are based. Values for FWI are typically between 5 and 60 with median values between about 20 and 30 (Fig. 8). The Boreal Plains and Boreal Cordillera are not significantly different (Table 1). Again, the eastern ecozones show lower values. Values for DSR are similar in the Boreal Plains and Boreal Cordillera ecozones, typically being close to 10, but exceeding 30 in extreme cases (Fig. 9). Daily severity rating is lowest in the east and highest in the western boreal ecozones.

Fire intensity

Maximum HFI values were typically about 10–30 MW m^{-1} for the boreal spruce fuel type (Table 1; Fig. 10). The distributions show that all ecozones can experience extreme values, with about 10% of the fires exceeding 30 MW m^{-1}. However, higher HFI values are more common in the western boreal ecoregions. It is important to note that continuous crown fire occurs at HFI values above about 10 MW m^{-1}. This happens in about 80% of the fires in the south and west ecozones, and about 30% of the fires in the extreme north-east. Intermittent crown fires would occur in the majority of the fires in all ecozones (>4 MW m^{-1}).

Seasonality

The seasonal pattern in FFMC is that higher values are experienced in spring and early summer, with values decreasing

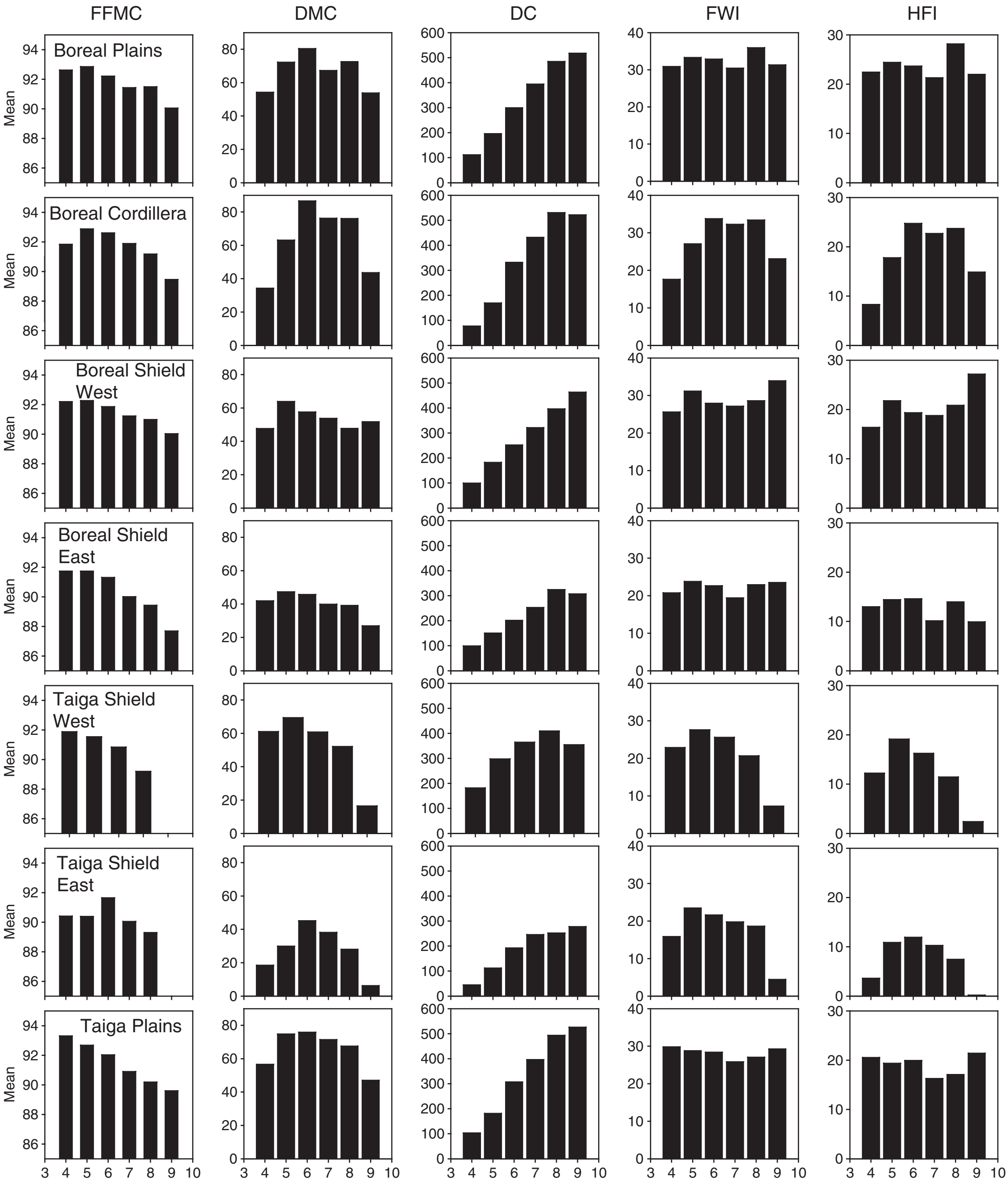

Fig. 11. Monthly mean values of fire weather indices and head fire intensity (HFI) (MW m^{-1}) for each ecozone. DC, drought code; DMC, duff moisture code; FFMC, fine fuel moisture code; FWI, fire weather index.

throughout the summer (Fig. 11). Much lower values occur in September in the Taiga Shield ecozones than elsewhere. For most ecozones, DMC has a seasonal peak in mid-summer, although it does not vary as much in the Boreal Plains and Taiga Shield West. Seasonal trends show an increase in DC through the season at all sites, with the Taiga Shield East and Boreal Shield East showing lower overall values. For most ecozones, this tends to create little seasonal variation in FWI. Similarly, HFI tends to be relatively evenly distributed in most ecozones, although there are lower values in spring and autumn in the Boreal Cordillera and Taiga Shield ecozones. Temperatures are usually lower at these times.

Trends

Regression analyses were performed on the FWI System codes and indices using individual fires as a case and as annual means. The individual fires showed some statistically significant relationships, but r^2 values were always less than 0.01 (n varied from 469 to 9331), yielding no predictive power. A more robust test using the annual mean values showed positive trends for FFMC for the Taiga Shield West ($r^2 = 0.16$, $P = 0.01$), for ISI for the Boreal Plains ($r^2 = 0.18$, $P = 0.005$), and for DSR for the Taiga Shield East ecozones ($r^2 = 0.14$, $P = 0.03$). Although ISI in the Taiga Shield West ecozone was significant, it showed a significant autocorrelation (0.4) at a single year lag. Trends for a given month were not tested since there were many months with no fires, despite the relatively large dataset. There was no evidence in trends in HFI over time, except for in the Taiga Shield West ecozone ($r^2 = 0.21$, $P = 0.003$). Trends in the number of days above a threshold were significant for all Canada for several parameters (e.g. fire days with DMC > 40; ISI > 5; and HFI > 0.5, 2 and 4 MW m^{-1}). This was largely caused by trends in the two taiga shield ecozones, and r^2 values were less than 0.2. There were also trends in the standard deviation of some variables for some ecozones, such as ISI in the Taiga Shield West. However, these trends were caused by the larger number of fires over time because the counts of fires above a threshold depend on the number of fires. Therefore, we suspect that these trends could be an artifact of missing fires in the early part of the record.

Discussion

Our distributions of FFMC, DMC and DC differ from the climatological distributions published by Simard and Valenzuela (1972) because they examined fire weather data for all days during the fire season. Their climatological data are more right-skewed for FFMC, and left skewed for both DMC and DC. Harrington *et al.* (1983) looked at a fire weather climatology including monthly extremes, irrespective of whether a fire was burning. Their monthly extreme values for FFMC, DMC, DC, BUI and FWI are similar to ours but their extreme ISI values are much higher, probably caused by their selection of periods with very high winds even if a fire was not burning. Hence our distributions and statistics really reflect conditions after ignition when large fires are growing. These distributions give baseline data for fire management agencies. For example, if current conditions exceed the 95 percentile for historical large-fire conditions, a fire manager would know that a very extreme situation has developed. The differences in values among ecozones demonstrate that large fires can burn under a range of conditions. Hence, we expect that other countries using the FWI System will observe different frequency distributions than observed in Canada.

In general, FFMC and DMC values are slightly greater in the southern and western ecozones, and DC values are greater in the three northern ecozones west of Hudson Bay. These differences are caused by climate, but may also reflect fire management policies. Many northerly regions have a modified suppression policy, which does not call for all fires to be actively suppressed unless they threaten areas of value, such as a community. This means that fires with lower FFMC and DMC values may be suppressed effectively in the more southern regions, and may not reach a size of 2 km^2 (i.e. only the extreme conditions allow for escaped fires). Values for FWI and DSR are lowest in the two eastern ecozones. All indices are significantly different between the Boreal Shield West and East ecozones, supporting the split of the boreal ecozone into two regions. Similarly, there are differences in many indices between the Taiga Shield East and West ecozones.

Clear seasonal patterns are evident for FFMC, DMC and DC for all ecozones. These patterns were expected, and illustrate the increased probability of deep burning fires because of increases in DC as the fire season progresses. However, there is little seasonal trend in FWI and, as an integrator of the other codes, suggests that periods of extreme fire weather can occur throughout the fire season. Similarly there is not a strong seasonal pattern for HFI for most ecozones, indicating that a range of fire intensities can be experienced.

There were very few trends in the FWI System indices and codes with FFMC, ISI and DSR each showing significant trends in only one ecozone. This is caused by the large interannual variability in fire weather. However, counts of number of fire days with an index above a certain threshold showed trends for the two taiga shield ecozones and for all Canada. This is possibly confounded by missing fire data over the early part of the period, since the number of fires influences the count of fire days. For example, there is an increase in the number of fires for the Taiga Shield West ecozone from 1959 to 1999 ($P = 0.019$), but no trend from 1973 to 1999 (post-LANDSAT era) ($P = 0.33$). Although this could be real, we are concerned that an unknown number of earlier fires were not detected in the north.

Head fire intensity values ranged up to 123 MW m^{-1}, although the mean value for an ecozone using the boreal spruce fuel type was closer to 20 MW m^{-1}. Values between 13 and 93 MW m^{-1} have been observed during recent experimental crown fires where more exact measurements have been made (B.J. Stocks, personal communication 2003), so we believe that our estimates are in a reasonable range of observed fire behaviour. The trend in HFI greater than 0.5, 2, 4 and 10 MW m^{-1} in the two taiga shield ecozones is likely confounded by fires missed in the early years. However, if the number of fires is estimated correctly, this result implies an increased level of fire control difficulty. The probability of containment of fire decreases with an increase in fire size and fire area, with fires greater than 5 ha in size having less than a 50% probability of containment during initial attack at intensities greater than 2 MW m^{-1} (Hirsch *et al.* 1998). Although our large fires have escaped initial attack, or were allowed to burn freely, the greater number of fire days at these higher HFI values still reflects a lower probability of containment. It is important to recognise that our HFI values are for a constant fuel type and reflect changes in fire weather only. Fuel is very important in determining HFI, and fuel changes have also occurred on the landscape over time. Therefore, there could be trends in HFI caused by fuel that we would not identify in our analysis.

Much of the uncertainty relating fire weather to the location of the fire is random. Temperature tends to reflect a large area governed by air masses and the generated temperature fields forming an input into several of the FWI parameters should not be biased (Flannigan and Wotton 1989). Precipitation is a greater problem since it is spatially more patchy. Although it is unlikely that the interpolated data are biased, fires may preferentially occur in drier locations that may have less moisture than estimated from weather station interpolation. Many of the large fires cover vast areas and we have a large dataset, so we do not expect substantial bias. Wind speed is also very site-specific, and it is difficult to evaluate bias, since this is often caused by the details of a weather station location.

Harrington *et al*. (1983) found relationships between area burned and fire weather indices (especially DMC) that could explain as much as 38% of the variance in a given province, although much weaker relationships were found in eastern Canada. Fine fuel moisture code and the monthly severity rating also showed significant relationships for specific weather stations. Estimates of monthly area burned and fire weather indices by Flannigan *et al*. (2002, 2004) showed significant regressions explaining 36–64% of the variance, depending on ecozone. The significant variables included mean and maximum air temperature, total precipitation, maximum FFMC, mean DMC, mean FWI, mean DC, mean ISI, mean DSR and minimum relative humidity. These data included all fire season days, and were not linked to specific fires. Using these relationships with global circulation models they suggested that area burned in Canada could increase by 74–118% by the end of the 21st century in a $3 \times CO_2$ scenario. The present analysis of the recent 41-year period indicates that we cannot detect changes in fire weather yet.

Conclusions

The LFDB describes the characteristics for Canadian fires greater than $2\,km^2$ in size. The present paper builds on this database by analysing the fire weather associated with each of the large fires. The statistics of the fire weather indices form a benchmark for fire management agencies based on a large sample of fires, recognising that we present the extreme days for each fire. Analyses of trends in fire weather indices yield few consistent relationships with only a small amount of variance explained. The northern ecozones are especially of interest since they may show a climate change effect earlier than more southern regions as climate change is expected to be stronger at northern latitudes. In addition, fire suppression is normally a lesser factor in these regions. It is difficult to evaluate trends on short datasets with high inter-annual variability. This means that the continuation of a good dataset will be critical for continued evaluation of whether the fire characteristics and fire weather are changing over time. This is especially important if estimates of increased future fire caused by climate change are realised.

Acknowledgements

The authors thank the large number of individuals who contributed to data compilation for the Canadian large-fire database in the provincial and territorial agencies, Parks Canada, and the Canadian Forest Service. The weather data were kindly provided by W. Skinner of the Canadian Meteorological Service, and we also thank him for advice on these data. We also thank E. Bosch for contributing some of the fire data and S. Lavoie for drafting some of the figures. This study was partly funded by Canadian government programs of the Climate Change Action Fund, Action Plan 2000 and the Program on Energy Research and Development (PERD).

References

Alexander ME (1980) Calculating and interpreting forest fire intensities. *Canadian Journal of Botany* **60**, 349–357.

Alexander ME, deGroot WJ (1989) 'A decision aid for characterizing fire behavior and determining fire suppression needs.' Technical Transfer Note A-008. (Canadian Forest Service: Edmonton)

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

Beck JA, Alexander ME, Harvey SD, Beaver AK (2002) Forecasting diurnal variations in fire intensity to enhance wildland firefighter safety. *International Journal of Wildland Fire* **11**, 173–182. doi:10.1071/WF02002

Boychuk D, Martell DL (1988) A Markov chain model for evaluating seasonal forest fire fighter requirements. *Forest Science* **34**, 647–661.

Byram GM (1959) Combustion of forest fuels. In 'Forest fire: control and use'. (Ed. KP Davis) pp. 61–89. (McGraw-Hill: New York)

Ecological Stratification Working Group (1996) 'A national ecological framework for Canada.' (Agriculture and Agri-Food Canada and Environment Canada: Ottawa)

Flannigan MD, Wotton BM (1989) A study of interpolation methods for forest fire danger rating in Canada. *Canadian Journal of Forest Research* **19**, 1059–1066.

Flannigan MD, Stocks BJ, Wotton BM (2000) Climate change and forest fires. *Science of the Total Environment* **262**, 221–229. doi:10.1016/S0048-9697(00)00524-6

Flannigan M, Campbell I, Wotton M, Carcaillet C, Richard P, Bergeron Y (2001) Future fire in Canada's boreal forest: paleoecology results and general circulation model–regional climate model simulations. *Canadian Journal of Forest Research* **31**, 854–864. doi:10.1139/CJFR-31-5-854

Flannigan MD, Logan K, Stocks BJ, Wotton BM, Amiro BD, Todd JB (2002) Projections of future fire activity and area burned in Canada. In 'Forest fire research and wildland fire safety'. (Ed. DX Viegas) p. 14. (Millpress: Rotterdam)

Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ (2004) Future area burned in Canada. *Climatic Change* In press.

Forestry Canada (1992) 'Development and structure of the Canadian forest fire behavior prediction system.' ST-X-3. (Science and Sustainable Development Directorate: Ottawa)

Girardin M-P, Tardif J, Flannigan MD, Wotton BM, Bergeron Y (2004) Trends and periodicities in the Canadian drought code and their relationships with atmospheric circulation for the southern Canadian boreal forest. *Canadian Journal of Forest Research* **34**, 103–119. doi:10.1139/X03-195

Harrington JB (1982) 'A statistical study of area burned by wildfire in Canada 1953–1980.' PI-X-16. (Petawawa National Forestry Institute, Canadian Forestry Service: Petawawa)

Harrington JB, Flannigan MD, Van Wagner CE (1983) 'A study of the relation of components of the fire weather index to monthly provincial area burned by wildfire in Canada 1953–80.' PI-X-25. (Petawawa National Forestry Institute, Canadian Forestry Service: Petawawa)

Hirsch KG, Corey PN, Martell DL (1998) Using expert judgement to model initial attack fire crew effectiveness. *Forest Science* **44**, 539–549.

Kafka V, Tymstra C, Hirsch K, Flannigan M (2000) Assessing fire behavior potential: a comparative analysis of two spatial techniques. In 'Crossing the millenium: integrating spatial technologies and ecological principles for a new age in fire management'. Vol. 1. (Eds LF Neuenschwander, KC Ryan) pp. 113–122. (University of Idaho: Moscow, ID)

Podur J, Martell DL, Knight K (2002) Statistical quality control analysis of forest fire activity in Canada. *Canadian Journal of Forest Research* **32**, 195–205. doi:10.1139/X01-183

SAS (2000) 'OnlineDoc®, Version 8. SAS Institute Inc.' (SAS Institute Inc.: Cary, NC)

Simard AJ, Valenzuela J (1972) 'A climatological summary of the Canadian Forest Fire Weather Index.' FF-X-34. (Canadian Forestry Service: Ottawa)

Skinner WR, Flannigan MD, Stocks BJ, Martell DL, Wotton BM, Todd JB, Mason JA, Logan KA, Bosch EM (2002) A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959–1996. *Theoretical and Applied Climatology* **71**, 157–169. doi:10.1007/S007040200002

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* **108**, 8149. doi:10.1029/2001JD000484

SYSTAT (1997) 'SYSTAT software.' (SPSS Inc.: Chicago)

Van Wagner CE (1987) 'Development and structure of the Canadian forest fire weather index system.' Forest Technology Report 35. (Canadian Forestry Service: Ottawa)

Woodward WA, Bottone S, Gray HL (1997) Improved tests for trend in time series data. *Journal of Agricultural Biological & Environmental Statistics* **2**, 403–416.

Zhang XB, Vincent LA, Hogg WD, Niitsoo A (2000) Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean* **38**, 395–429.