Reprinted from the preprint volume of the ***Ninth Symposium on Global Change Studies and Namias Symposium on the Status and Prospects for Climate Prediction****, 11-16 January 1998, Phoenix, AZ, by the American Meteorological Society, Boston, MA.*

10.12

FIRE WEATHER: PAST, PRESENT AND FUTURE

Mike Flannigan *
Canadian Forest Service, Edmonton, Alberta

Mike Wotton
Canadian Forest Service, Sault Ste. Marie, Ontario

Pierre Richard and Christopher Carcaillet
Université de Montréal, Montréal, Quebec

Yves Bergeron
Université du Quebec a Montréal, Montréal, Quebec

1. INTRODUCTION

Fire and climate are closely linked (Swetnam 1993). According to simulations of various general circulation models (GCMs), the earth's climate will be 1-3.5° C warmer by the end of the next century due to increasing atmospheric concentrations of radiatively active gases such as carbon dioxide, methane, nitrous oxides and the chloroflourocarbons. These changes in the climate will result in changes in the day to day weather that influences forest fires. Fire is an important factor in the vegetation dynamics of Canadian forests, in particular, the boreal forest. On average, over 2.5 million ha of forest are burned every year in Canada. Typically, a few large fires are responsible for most of the area burned (3% of the fires are responsible for 97% of the area burned). Most of the fire activity occurs during a few days with severe fire weather.

How will the fire weather respond to the so-called greenhouse warming? Many believe that increases in temperature will lead to increased fire weather severity and to increased area burned (Overpeck et al. 1990). However, fire is strongly dependent on other weather variables as well, such as precipitation, wind speed and relative humidity . In this study we will use the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) to forest fire danger. This system uses temperature, precipitation, wind speed and relative humidity as inputs.

The objective of this study is to examine the fire weather in the past, present and future. Three approaches are used in this study on fire weather. First, we modelled the fire weather 6 000 years ago (6 kyr, hereafter 6k) as well as the present day using a specially modified version of the Canadian GCM. The output from these simulations were used to calculate the FWI System indexes. The present day FWI was compared to the actual FWI observations. Second, a charcoal core from Lake Francis in northwestern Quebec was examined to give an indication of the fire activity in this region during most of the Holocene. Finally, the Canadian GCM was used to model the present and future fire weather by calculating the FWI System indexes for the $1xCO_2$ and $2xCO_2$ simulations. These approaches will allow us to comment on the future fire weather relative to the present day and to conditions 6 000 years ago. We are using the 6k simulation and the charcoal record because there were periods in the Holocene that were warmer than present day and these warm periods might be an an analog for future warming. The charcoal record gives us an indication of the fire frequency during the holocene and is an independent means to validate the 6k simulation.

2. METHOD AND DATA

To model the fire weather we used the Canadian Fire Weather Index (FWI) System and in particular we used the Fire Weather Index (FWI) which represents the intensity of a spreading fire. In this study, we used a specially modified version of the Canadian GCM II to model the present and the 6k FWI. The Canadian GCM was modified by changing the orbital parameters and the carbon dioxide levels to be appropriate for 6k and present day. The Canadian GCM has a transform grid spacing of 3.75° by 3.75° with full diurnal and annual cycles (Boer et al. 1992; McFarlane et al. 1992). Daily data, rather than monthly data, were used because the fire weather can change dramatically over time periods much shorter than a month. Temperature, specific humidity, precipitation and wind speed were obtained every 12h (0000 and 1200 GMT) for 10 years for both the present day and 6k simulations. We used the maximum daily temperature, relative humidity derived from the specific humidity, 24 h precipitation and the 12 h (00 GMT) mean wind speed to calculate components of the Canadian FWI System during fire season. We defined the fire season as May 1 to August 31. The FWI was calculated for both simulations and then compared by taking the ratio of 6k to present day. Extreme FWI maximums, in addition to the mean values for the 10 years were used in this analysis. Extremes were used because most of the area burned is a result of a few days with extreme fire weather conditions (Flannigan and Harrington 1988).

The procedure outlined above was also used to generate the mean and extreme maximum FWI for the $1xCO_2$ and $2xCO_2$ simulations.

---

* Corresponding author address: Mike Flannigan, Canadian Forest Service, 5320 - 122nd St, Edmonton, AB T6H 3S5 Canada; e-mail mflannigan@nofc.forestry.ca

Lacustrine sediments have been recovered by a modified Livingstone sampler from the frozen surface of a kettle hole lake named Lake Francis (Abitibi, Quebec; 48°31'35"-78°28'20"). Six radiocarbon dates on terrestrial plant macrofossils were measured to secure chronology. Radiocarbon ages were calibrated in dendrochronological years before present (BP = 1950 AD) (Stuiver and Reimer 1993). Sediments span the last 7400 years and show varved sections covering approximately 5730 years.

Charcoal abundance ($mm^2 \cdot cm^{-2} \cdot an^{-1}$) was microscopically measured on 1cm-thick contiguous samples over the entire length of the 3 m-long sediment core (figure 5a). Fire events were identified by charcoal values exceeding one standard deviation over a 8 data running mean, in order to account for varying charcoal background values (figure 5b). The background is composed of the extra-local charcoal occurrence (Clark 1988; Clark et al. 1996). The age of each event was derived from the chronology of sediment accumulation, according to its position along the core.

3. RESULTS AND DISCUSSION

Figure 1 displays the difference in mean daily maximum temperature in degrees C for 6k to present day for the May 1 to August 31 period. The model results indicate that the forested regions of Canada 6 000 years ago were about 1°C warmer than present. Figure 2 shows the difference in mean daily maximum temperature in degrees C for $2xCO_2$ to $1xCO_2$ for the May 1 to August 31 period. The forested regions of Canada are expected to be 3 to 4° warmer in a doubled CO_2 world. The patterns of temperature differences are similar in both figures though the temperature change is larger for Figure 2 ($2xCO_2$ minus $1xCO_2$). Caution should be used when using the results from mountainous regions like western North America as the resolution of the models is so coarse that the topography is not realistically incorporated. Regional Climate Models (RCMs) could be employed for mountainous regions as they have a much improved spatial resolution.

Figure 3 shows the ratio of the mean FWI for 6k over present day. Ratios greater than 1.0 indicate increased FWI with greenhouse warming while ratios less than 1.0 indicate decreased FWI. The increase in FWI is most pronounced over the center of the continent. However, decreases in FWI occur over eastern Canada. Figure 4 depicts the ratio of the mean FWI for $2xCO_2$ over $1xCO_2$. The results are similar to those shown in Figure 3 with increases in FWIs over the center of the continent with values significantly greater than the $1xCO_2$ simulation. However, there are regions in eastern and western Canada where the ratio drops below 1.00, which means the FWI is expected to decrease despite the warmer temperatures (Figure 2). Differences between the figures include regions of northwestern Canada where the $2xCO_2$ over $1xCO_2$ ratios show decreased FWI as opposed to increased FWI in Figure 3. Also, the increases in FWI were much larger with future warming simulations as opposed to the 6k over present day FWI ratios.

Noteworthy is the spatial variability in the response of fire weather to increasing temperatures. Despite increasing temperatures the corresponding FWI does not necessarily increase. The reason is due to changes in the other elements in the FWI System calculations, namely, precipitation and relative humidity. In particular, increases in precipitation amount and frequency more than offset the increased temperatures in regions where the FWI has decreased. There is historical evidence that fire frequency has decreased despite warmer temperatures. Bergeron and Archambault (1993) found that fire frequency decreased in northwestern Quebec since the end of the Little Ice Age (~1850) despite increasing temperatures. Figure 4 suggests that northwestern Quebec will continue to have decreasing FWI with increasing temperature (Bergeron and Flannigan 1995).

Preliminary analysis of this charcoal data yields 25 local fire events with widely varying fire intervals during the last 7400 years (figure 5b), over an equally varying, but generally increasing background of charcoal abundance through time (figure 5a). Average fire intervals were longer (474 yr ± 337; n=12) during the mid-Holocene than during the last 1500 years (111 yr ± 76; n=13). Fire frequency was much lower under the 6 k BP climate around the lake studied (figure 5c).

Additional sites are needed to assess the regional validity of those results, but they support previous low-resolution studies from nearby lake sediments that show lower charcoal influxes during the mid Holocene.

The 6k climate simulation is similar to projections from the Cooperative Holocene Mapping Project (COHMAP) (1988) though the warmer and drier summer conditions modelled by COHMAP should have lead to higher FWI values for 6k and therefore increased FWI ratios (Figure 3).

What are the implications from these results in terms of fire activity? Forest fire activity is related to the FWI, as FWI increases we would expect increases in area burned. Harrington et al. (1983) found that the FWI System was correlated to area burned. From Figure 4 we would expect large increases in area burned by wildfire in the forests of Manitoba, eastern Saskatchewan and northwestern Ontario. At the southern edge of the forest the increased fire activity might lead to a more rapid transition from forest to grassland than expected from warming alone. Other areas like Quebec and northeastern Ontario might experience a reduction in area burned due to lower fire weather severity. There are other factors in addition to the weather that are affecting area burned such as landscape fragmentation, ignition agents, fire management activities, fire season length and the composition and structure of the vegetation. Most of the area burned by wildfire is the result of lightning-ignited wildfires. Indications are that lightning and lightning ignitions will increase in a $2xCO_2$ climate (Price and Rind 1994). Also, Wotton and Flannigan (1993) have shown that the fire season length in Canada on average will increase by 22% or 30 days in a $2xCO_2$ climate

These results suggest that the mid-Holocene may be analogous to future warming in terms of fire weather though conditions may be warmer and the magnitude of the changes larger in the future. However, there are other factors that could be playing a role in any comparison of this nature. The orbital characteristics of eccentricity, obliquity and date of perihelion are different. Human activities will have a larger impact on fire activity in the future as compared to the 6k simulation either directly through fire suppression or indirectly through landscape fragmentation.

In summary, if the climate changes as suggested by the Canadian GCM we would anticipate large spatial variations in the fire weather and consequently, fire activity. Changes, increases and decreases in fire activity will impact the vegetation in a complicated fashion, accelerating vegetational

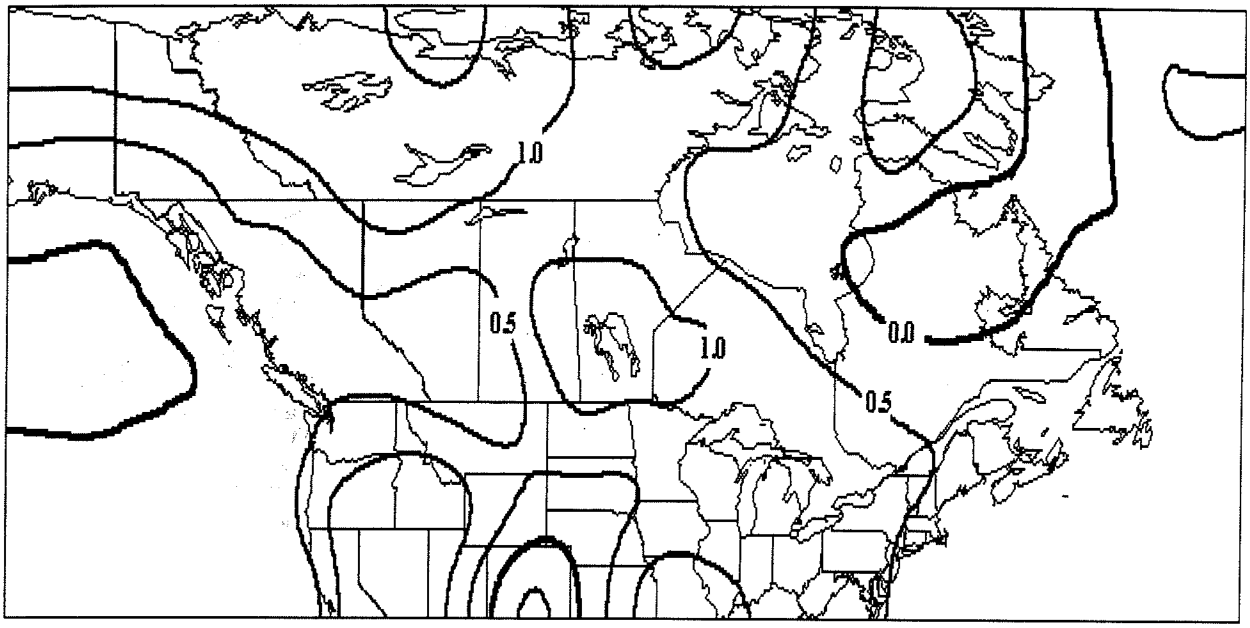

Figure 1 Mean Temperature change 6k - present (°C). The thick line is the 0°C isoline.

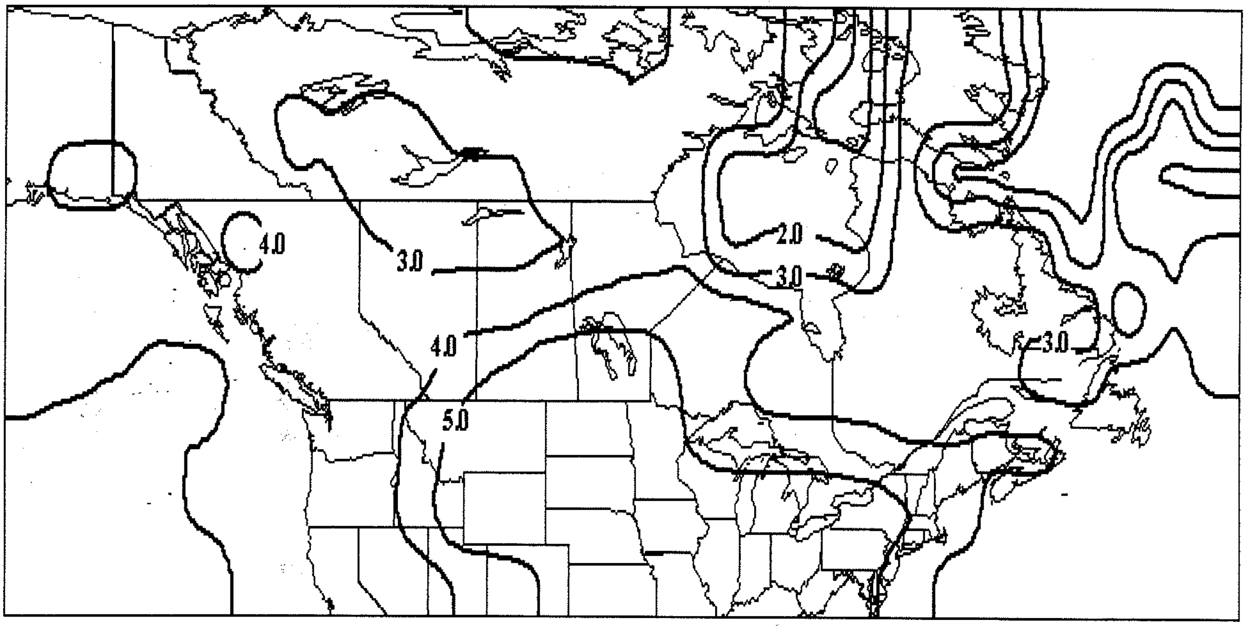

Figure 2. Mean Temperature change $2xCO_2$ - $1xCO_2$.

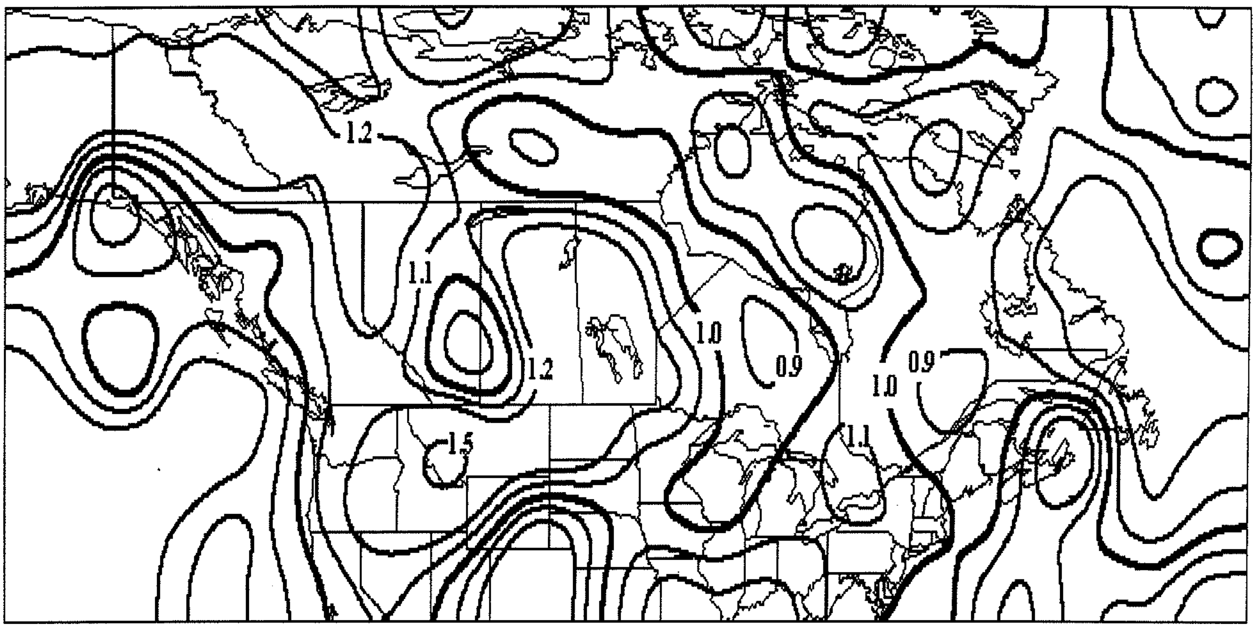

Figure 3. Mean FWI ratio (6k/present). Thick line is the 1.00 isoline.

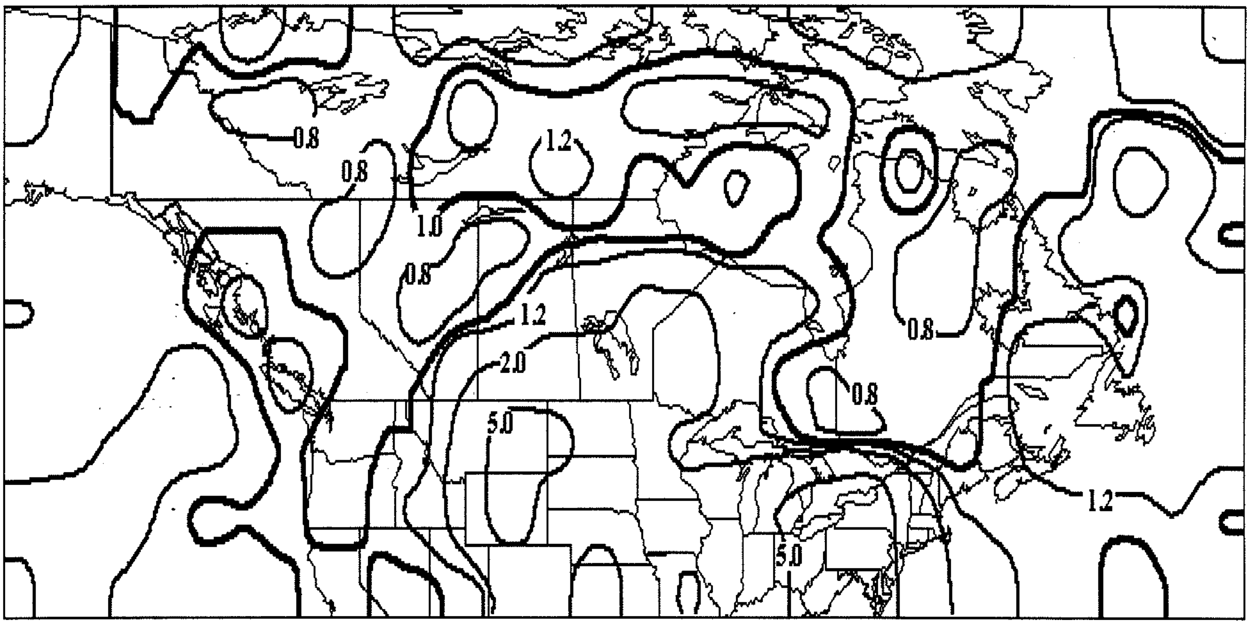

Figure 4. Mean FWI ratio ($2xCO_2$ - $1xCO_2$).

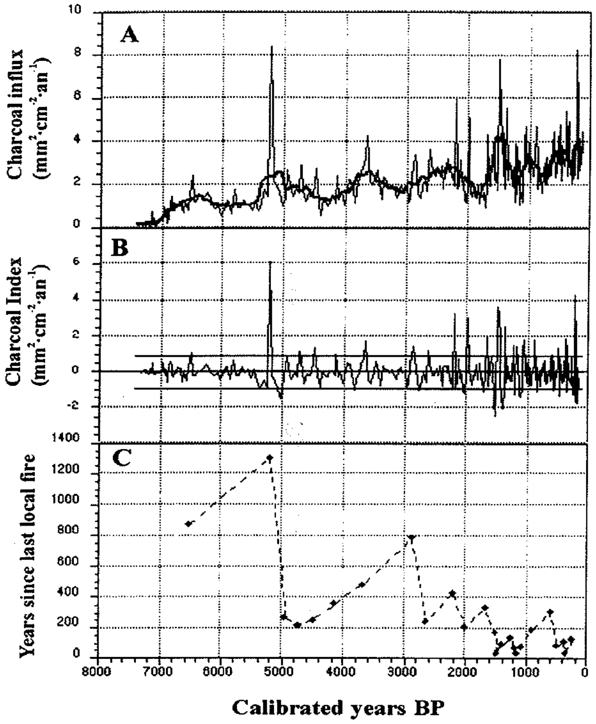

Figure 5. (a) Distribution of charcoal influx (thin line) and its 8-data running mean (thick line). (b) Charcoal index represents difference between charcoal influx and the value of the running mean. Positive values higher than one standard deviation represent high probability that a local fire occurred. (C) Local fire chronology.

change where fire increases and retarding vegetational change where fire decreases. The 6k fire weather may be a reasonable analog of a warmer climate to come, however, these results suggest even a more pronounced change in fire weather with greenhouse warming.

4. REFERENCES

Bergeron, Y., and S. Archambault. 1993. Decreasing frequency of forest fires in the southern boreal zone of Québec and its relation to global warming since the end of the 'Little Ice Age'. *The Holocene*. **3**:255-259.

Bergeron, Y. and M.D. Flannigan. 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian Boreal Forest. *Water, Air and Soil Pollution*. **82**:437-444.

Boer, G.J., N.A. McFarlane, and M. Lazare. 1992. Geenhouse gas-induced climate change simulated with the CCC second generation General Circulation Model. *J. Clim.*, **5**:1045-1077.

Clark, J.S. 1988. Particle motion and the theory of charcoal analysis: Source area, transport, deposition, and sampling. *Quat. Res.*,**30**:67-80.

Clark, J.S., P.D. Royall, and C. Chumbley. 1996. The role of fire during climate change in an eastern deciduous forest at Devil's Bathtub, New York. *Ecology*, 77:2148-2166.

Cooperative Holocene Mapping Project (COHMAP), 1988. Climatic changes of the last 18,000 years: Observations and model simulations. *Science*, **241**:1043-1052.

Flannigan, M.D., and J.B. Harrington. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada 1953-80. *J. Appl. Meteorol.*, **27**:441-452.

Harrington, J.B., M.D. Flannigan, and C.E. Van Wagner. 1983. A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wildfire in Canada 1953-80. *Inf. Rep. PI-X-25*, Can. For. Serv., Chalk River, Ontario.

McFarlane, N.A., G.J. Boer, J.-P. Blanchet, and M. Lazare. 1992. The Canadian Climate Centre second-generation General Circulation Model and its equilibrium climate: *J. Clim.*, **5**:1013-1044.

Overpeck, J.T., D. Rind, and R. Goldberg.1990. Climate-induced changes in forest disturbance and vegetation. *Nature*. **343**:51-53.

Price, C., and D. Rind. 1994. The impact of a 2xCO_2 climate on lightning-caused fires. *J. Clim.*, **7**:1484-1494.

Stuiver, M., and P.J. Reimer. 1993. Extended 14C data base and revised CALIB 3.0 14C age calibration program. Radiocarbon. **35**:215-230.

Swetnam, T.W. 1993. Fire history and climate change in giant Sequoia groves. *Science*, **262**:885-889.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. *For. Tech. Rep.* 35. Can. For. Serv., Ottawa, Ontario.

Wotton, B.M., and M.D. Flannigan. 1993. Length of the fire season in a changing climate. *For. Chron.*, **69**:187-192.