FUTURE AREA BURNED IN CANADA

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Abstract. Historical relationships between weather, the Canadian fire weather index (FWI) system components and area burned in Canadian ecozones were analysed on a monthly basis in tandem with output from the Canadian and the Hadley Centre GCMs to project future area burned. Temperature and fuel moisture were the variables best related to historical monthly area burned with 36–64% of the variance explained depending on ecozone. Our results suggest significant increases in future area burned although there are large regional variations in fire activity. This was especially true for the Canadian GCM where some ecozones show little change in area burned, however area burned was not projected to decrease in any of the ecozones modelled. On average, area burned in Canada is projected to increase by 74–118% by the end of this century in a 3 × CO_2 scenario. These estimates do not explicitly take into account any changes in vegetation, ignitions, fire season length, and human activity (fire management and land use activities) that may influence area burned. However, the estimated increases in area burned would have significant ecological, economic and social impacts for Canada.

1. Introduction

Forest fire is the dominant disturbance that shapes and maintains many of Canada's forests. During the 1990s an annual average of close to 8,000 forest fires burned about 2.8 million ha in Canada. These fires were typically crown fires that were responsible for renewal of stands (Weber and Stocks, 1998; Stocks et al., 2002). Fire activity is strongly influenced by four factors; weather/climate, fuels, ignition agents and humans (Johnson, 1992; Swetnam, 1993; Flannigan and Wotton, 2001). Climate and the associated weather are dynamic and are always changing due to changes in the earth's orbital parameters, solar output and atmospheric composition. Recently, our climate has been warming due to increases of radiatively active gases (carbon dioxide, methane, etc.) as a result of human activities (IPCC, 2001). This altered climate which is modelled by general circulation models (GCMs) may have a profound impact on fire activity in Canada and elsewhere in the near future.

In Canada, weather/climate is the most important natural factor influencing forest fires (Flannigan and Wotton, 2001; Hely et al., 2001). Weather determines fuel moisture, influences lightning ignitions, and contributes to fire growth through wind action. However, the long term average of area burned across a landscape is determined by a complex set of variables including the size of the sample area, the

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period under consideration, the extent of the forest, the topography, fragmentation of the landscape (rivers, lakes, roads, agricultural land), fuel characteristics, season, latitude, fire suppression policies and priorities, fire control, organizational size and efficiency, fire site accessibility, ignitions (people and lightning), and simultaneous fires, as well as the weather.

The objective of this study is to estimate the magnitude of area burned that will occur in Canada by the end of the 21st century. Most previous work has addressed how fire weather will change with a changing climate (Flannigan et al., 1998; Stocks et al., 1998; Flannigan et al., 2000). These studies suggested that there would be a significant increase in the severity of fire weather although there would be large regional variation with some regions having no change or even a decrease in fire weather severity. There are a number of methods available to estimate future area burned. Options include using dynamic vegetation models that include a fire component in the model, landscape fire models where fire ignition and spread is modelled explicitly, and lastly using historical relationships between observed area burned and the associated weather and fire weather indexes. We chose the latter method as we have had some success with the historical area burned and weather relationships (Harrington et al., 1983; Flannigan and Harrington, 1988). It is also the best method based on actual data, where we can develop relationships using past observations. These relationships can then be related to future GCM scenarios to provide estimates of future area burned. However, there is the potential problem of extrapolation of relationships beyond the range of observed values and for future efforts we hope to use dynamic models of climate and vegetation to estimate future fire activity.

2. Data and Methods

Area burned data was taken from the large fire data base for the 1959–1997 period (Stocks et al., 2002). These data include start date, location, cause and final size. Area burned was sorted into half month periods, monthly periods and seasons for May to September by modified ecoregions and ecozones (Ecological Stratification Working Group, 1996). The modified ecoregions are defined as ecogroups and were based on fire activity (Figure 1). Ecoregions with little or no area burned were dropped from the analysis. Ecozone 6, the Boreal Shield, was modified by dividing the ecozone into east and west components near Lake Nipigon as there are significant differences in fire activity between the east and west sections of this ecozone (Harrington, 1982; Harrington et al., 1983) (Figure 2). Ecozone 5 was also modified by adding ecoregions 216 and 217 from ecozone 15 as these ecoregions had significant fire activity but were relatively small spatial units; the rest of ecozone 15 (regions adjacent to southwestern Hudson Bay) was not included as there was no significant fire activity in this region. Note that April was not included in the monthly and seasonal aspects of this study as less than 2% of Canada's area burned

Figure 1. Modified ecoregions, termed ecogroups, used in this study. Triangles denote the location of meteorological stations.

occurs in April (Stocks et al., 2002). The natural logarithm of the area burned (ha) was used to normalize area burned because the raw area burned distribution is non-normal.

Meteorological data for the same period as the fire data (1959–1997) were obtained from Environment Canada. Variables included temperature, relative humidity, wind speed and 24-h precipitation at 1200 LST each day from 15 April to September 30. Stations were selected manually based on long-running representative stations within each ecogroup or ecozone. If no stations were available then nearby stations were assigned resulting in some stations being used for more than one region. In the case of an ecogroup or ecozone containing more than one station, the station values were averaged. A total of 41 stations were selected for the 31 ecogroups with 5 of the 41 stations being used for two ecogroups. Ecogroups were merged to create the ecozones and duplicate stations were removed resulting in 30 stations for the 8 ecozones with 3 of the 30 stations being used for two ecozones.

Figure 2. Ecozones of Canada used in this study were modified from Ecological Stratification Working Group (1995). Triangles denote the location of meteorological stations.

The 1200 LST observations of temperature, relative humidity, wind speed and 24-h precipitation are the inputs required to calculate the components of the Canadian forest fire weather index (FWI) system (Van Wagner, 1987). The FWI system is a weather-based system that models fuel moisture using a dynamic bookkeeping system that tracks the drying and wetting of distinct fuel layers in the forest floor. There are three moisture codes that represent the moisture content of fine fuels (fine fuel moisture content, FFMC), loosely compacted organic material (duff moisture code, DMC) and a deep layer of compact organic material (drought code, DC). The drying timelags for these three fuel layers are 2/3 of a day, 15 days and 52 days respectively for the FFMC, DMC and DC under normal conditions (temperature 21.1 °C, relative humidity 45%).These moisture indexes are combined to create a generalized index of the availability of fuel for consumption (build up index, BUI) and the FFMC is combined with wind to estimate the potential spread rate of a fire (initial spread index, ISI). The BUI and ISI are combined to create the FWI which is an estimate of the potential intensity of a spreading fire. The daily severity rating (DSR) is a simple exponential function of the FWI intended to increase the weight of higher values of FWI in order to compensate for the exponential increase in area burned with fire diameter (Williams, 1959; Van Wagner, 1970). Means and extremes of the meteorological variables and FWI system components were calculated for half month, month and season periods. Extremes of the variables were used because much of the area burned occurs during extreme fire weather conditions.

The last meteorological variable used in this study was the 500 mb height anomalies that was also obtained from Environment Canada for the 1959–1997 period (Skinner et al., 2001). These data were available as half monthly and monthly anomalies in a grid with a spatial resolution of 5° latitude by 10° longitude for our study area. The data for gridpoints covering Canada were interpolated using a thin-plate cubic-spline technique (Flannigan and Wotton, 1989) to the weather station locations and averaged if necessary in the same way as the other variables. The position and strength of the 500 mb flow is related to fire activity (Newark, 1975; Skinner et al., 1999; Skinner et al., 2001). All the variables used in this study are displayed in Table I.

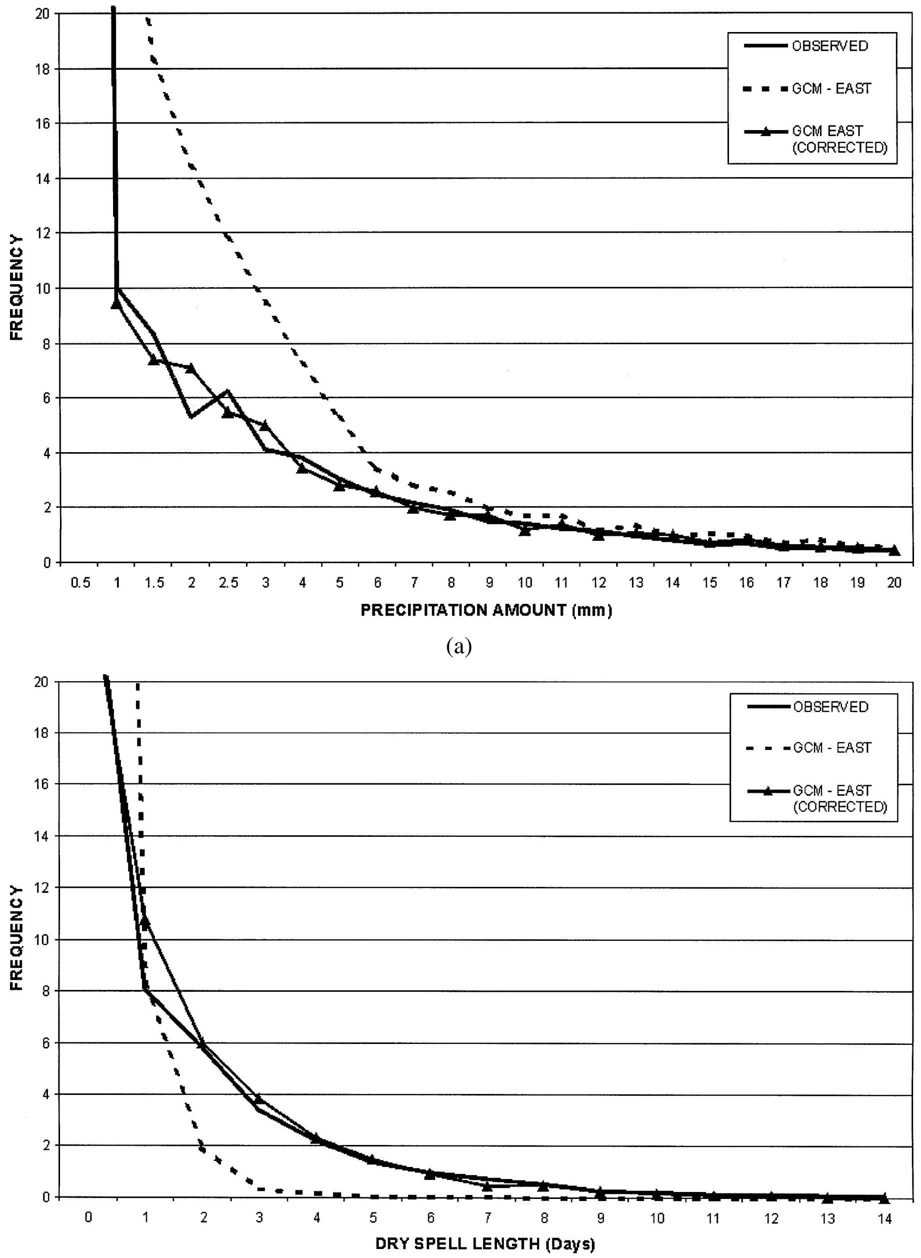
Daily data were collected from both the Canadian and the Hadley GCM for two time periods. For the Canadian model 1975–1995 was considered to correspond to a $1 \times CO_2$ scenario, while 1975–1990 was the $1 \times CO_2$ scenario for the Hadley model. The Canadian model used was the First Generation Coupled GCM (CGCM1). This model included both greenhouse gas and sulphate aerosol forcing contributing to a 1% increase in CO_2 per year. The time period 2080–2100 roughly corresponds to an equivalent $3 \times CO_2$ scenario when including the net radiative effect of all the greenhouse gases. The grid spacing is approximately 3.75 longitude by 3.75 latitude. The Hadley model, HadCM3GGa1, contained only greenhouse gas forcing and used 2080–2099 as its equivalent $3 \times CO_2$ scenario. The grid for the Hadley Model had slightly better resolution at 3.75 longitude by 2.5 latitude. The modelled variables examined from both models were maximum temperature, precipitation, wind speed, and humidity. Only daily noon values were used in the analysis. Noon temperature was estimated as the maximum daily temperature $-2.0\,^\circ$C. While studying the amount of daily precipitation for the $1 \times CO_2$ scenarios in the models, we noticed that the GCM grid cells appeared to contain more moisture than what was observed by point measurements at the weather stations. This effect has been noted in other studies (Mearns et al., 1995; Skelly and Henderson-Sellers, 1996; Osborn and Hulme, 1997) while looking at rainfall event frequencies, and various calibrations have been proposed. We calculated daily rainfall amount frequencies for representative areas in eastern and western portions of Canada and compared them with actual observed frequencies from weather stations. The frequency of duration of rain-free periods was also examined. We attempted to reduce the unrealistic incidence of small frequent daily precipitation by calibrating the modelled precipitation with a daily correction factor (Mearns et al., 1995) for the current time period of each model. The correction factor took the form of a constant

TABLE I
Meteorological and FWI system variables

ANOM	Mean 500 mb height anomaly (m)
BUI	Mean buildup index
BUIX	Maximum buildup index
DC	Mean drought code
DCX	Maximum drought code
DMC	Mean duff moisture code
DMCX	Maximum duff moisture code
DSR	Mean daily severity rating
DSRX	Maximum daily severity rating
FFMC	Mean fine fuel moisture code
FFMCX	Maximum fine fuel moisture code
FWI	Mean fire weather index
FWIX	Maximum fire weather index
ISI	Mean initial spread index
ISIX	Maximum initial spread index
PREC	Mean precipitation (mm)
TPREC	Total precipitation (mm)
RH	Mean relative humidity (%)
RHN	Minimum relative humidity (%)
TEMP	Mean temperature (°C)
TEMPX	Maximum temperature (°C)
WIND	Mean windspeed (km/h)
WINDX	Maximum windspeed (km/h)

amount subtracted off the daily precipitation value. Frequencies were recalculated and compared with the observations again. These comparisons were repeated using several different correction factors from 0 to 2.5 mm daily until the modelled frequencies were as close to observed as possible. For the Canadian model a correction of 2.0 mm per day worked best (Figure 3). For the Hadley model a correction of 1.5 mm per day was most appropriate. These corrections were applied to daily precipitation outputs from the 1 × CO_2 scenarios and 3 × CO_2 scenarios. Additional information on these GCMs can be found in Flato et al. (2000) and Gordon et al. (2000).

When doing climatic change simulations with respect to fire studies there are two common approaches. The first is to use monthly anomaly data from the GCMs and superimpose the anomalies onto observed data. For example, if the monthly anomaly of temperature for May in a 3 × CO_2 scenario for a given GCM is 5 °C one could simply add 5 °C to all the May daily temperatures in the baseline



(a)

(b)

Figure 3. Comparison of precipitation amount frequencies (a) and dry spell length frequencies (b) for 8 Environment Canada weather stations and the Canadian GCM for an area in eastern Canada represented by 4 grid cells between 44.54° to 51.96° latitude and −84.38° to −76.87° longitude. The solid line represents the observed weather data. The broken line represents the uncorrected frequencies from the Canadian GCM. The line with triangles represents the frequencies from the Canadian GCM after the correction (2.0 mm) was applied.

period (typically 1970s–1990s) from a nearby meteorological station. The second approach is to use daily data directly from the GCM but do some adjustments according to the methods described above. There are pros and cons to each approach but we prefer using the modified daily data from the GCMs primarily because if you use the monthly anomaly approach you are constraining the frequency of precipitation events to historical patterns whereas the modified daily approach allows precipitation frequency to change. This is a critical consideration as the frequency of precipitation is very important in terms of fire activity (Flannigan and Harrington, 1988).

Using SAS version 8.02 (SAS, 2000) a linear forward stepwise regression was performed for each spatial unit, ecogroup or ecozone and for each time period, half month, month or season with area burned as the predictand and the variables listed in Table I as the predictors. Terms were accepted only if they met the 0.15 significance level; terms were removed when they failed to meet the 0.15 significance level.

Once the best area burned relationships were determined these relationships were used to estimate area burned for the $1 \times CO_2$ and $3 \times CO_2$ scenarios for the Canadian and Hadley models. The $3 \times CO_2/1 \times CO_2$ ratio of averaged annual area burned was determined and then multiplied by the observed area burned for each ecozone to obtain an estimate of annual area burned in the future. This means that regions with more fire activity are weighted accordingly.

3. Results and Discussion

Table II shows the results from the forward stepwise regression of monthly area burned in ecozones across Canada. The variance explained ranges from 36–64% and all regressions were highly significant ($p < 0.0001$). Using different time periods (half month and season) and ecogroups showed similar results (not shown) although not quite as high as those presented in Table II. Therefore we opted to use monthly ecozone area burned in tandem with GCM outputs to generate future area burned values. Temperature, mean or maximum, was selected by the regressions in every ecozone except ecozones 62, 9 and 14. Figure 4 shows the relationship between area burned and monthly maximum-temperature for ecozone 5 where temperature alone explains 57% of the variance in the area burned data. In this figure, there are some data points with zero area burned despite high maximum temperatures and this may be the result of the lack of ignitions in that particular month. It is obvious that despite very severe fire weather there will be no area burned without an ignition and this might explain in part some of the unexplained variance in the regression. For future efforts we hope to model fire occurrence explicitly to address this ignition limitation. Extremes of meteorological variables and FWI system indexes are important as much of the area burned often occurs during a few critical days of rapid fire growth that coincide with severe fire weather (hot, windy and dry) (Nimchuk, 1983; Harvey et al., 1986). Mean or maximum values

TABLE II

Ecozone monthly area burned explained variance and variables selected, in order of importance, by stepwise regression

Modified ecozone	Significant variables	Variance explained (%)	N	p
4	temp, dsr	56	195	<0.0001
5	tempx, dmcx	64	195	<0.0001
61	ffmcx, temp, dmcx	60	195	<0.0001
62	dmc	42	195	<0.0001
9	isi, ffmcx, fmc, tprec	50	195	<0.0001
11	temp, dsr	36	195	<0.0001
12	fwi, ffmcx	36	195	<0.0001
14	fwi, rhx, dc	42	195	<0.0001

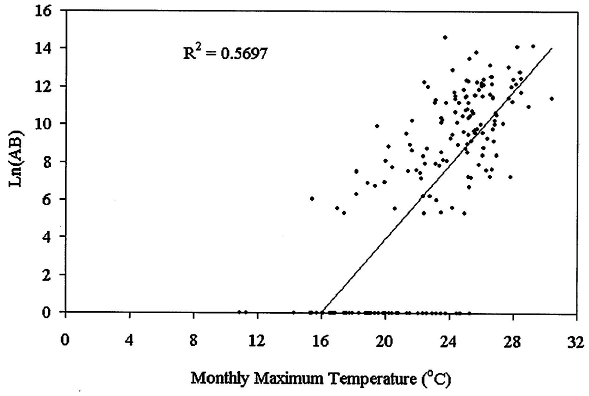


Figure 4. Monthly area burned versus monthly maximum temperature for Ecozone 5, 1959–1997.

of fuel moisture codes (FFMC, DMC and DC) were selected 8 times and were selected by regression in every ecozone except ecozones 4 and 11. This work is an updated and modified version of the work done by Harrington et al. (1983) and Flannigan and Harrington (1988) who related monthly provincial area burned to the Canadian FWI system components and to meteorological variables. The results in this study are much better than the previous efforts and this might be due to a longer period of record and the use of ecological zones as opposed to provincial units. It is interesting that the larger spatial units (ecozones) had better results than the finer spatial units (ecogroups). This might be because the factors influencing significant area burned are synoptic in scale (e.g., upper ridges in the atmosphere) which are similar to the scale of ecozones. The larger spatial units also provide some statistical smoothing, especially with a larger population of area-burned data.

TABLE III
Ratio of 3 × CO_2/1 × CO_2 area burned by ecozone using the Canadian and Hadley GCMs

Modified ecozone	Canadian	Handley
4	1.39	1.57
5	2.12	2.11
61	1.67	1.92
62	1.63	1.72
9	1.09	3.45
11	2.79	3.81
12	3.38	3.32
14	0.00	2.24
All ecozones	1.76	2.52

Table III and Figure 5 show the ratio of 3 × CO_2/1 × CO_2 area burned predictions using the two GCM models. Notice that the Hadley model predicts more area burned than the Canadian model for most ecozones. For all ecozones, the Hadley model suggested an average ratio of 2.52 whereas the Canadian model had a ratio of 1.76. Table IV shows the observed annual area burned and percent of total annual area burned by ecozone in the 1959–1997 period along with the predicted area burned for each ecozone and all ecozones for the 3 × CO_2 scenario. The ratio of predicted area burned over recently observed was 2.2 for the Hadley model as compared to 1.7 for the Canadian model. Note that these ratios are different than the average ratios in Table III as the Table IV ratios are weighted by the actual area burned in each ecozone. Table IV shows a strong increase in the percent of the total annual area burned in ecozone 9 as compared to the observed for the Hadley simulation whereas the Canadian simulation shows a decrease. The Canadian simulation shows the largest increase in the percent of total annual area burned in ecozone 5. Both models suggest a decrease in percent of total annual area burned as compared to observed in ecozone 4. The observed area burned for all ecozones used in this study accounts for 97% of the area burned in the large fire data base; that is, we only excluded regions that accounted for 3% of area burned in the large fire data base. Table IV suggests that area burned for these regions could rise from the present day ∼1.8 M ha to between 3–4 M ha by the end of the century. There is significant variation among ecozones with increases by a factor of 3–4 for ecozones 9, 11, 12 (Hadley) and ecozone 12 (Canadian) to a 57% increase in ecozone 4 (Hadley) and almost no change in ecozone 9 in the Canadian model. It is apparent that the Canadian model had trouble with ecozone 14, the montane cordilla (see Figures 2 and 5) in that for both the 1 × CO_2 and 3 × CO_2 scenarios the calculated area burned was zero ha. This was partly caused by very few large fires in this area in recent years. Also, GCMs have coarse spatial resolution and should be used with caution in complex terrain regions. Regional climate models with much higher spatial resolution may be better suited to mountainous regions (Laprise et al., 2003). The two models are in close agreement in terms of projected area burned in eastern and north central regions of Canada (ecozones 5, 61 and 62, Figure 5). However, significant differences in anticipated area burned occurs between ecozones 9 and 14 (boreal plains and montane cordilla, respectively) with the Hadley model having much larger increases in area burned.

These results suggest a significant increase in area burned in Canada that could have important implications on forests, forestry activities, community protection and carbon budgets. Direct emissions of carbon from forest fires on average over the last 40 years are equivalent to 20% of fossil fuel emissions in Canada (Amiro et al., 2001). Fire management agencies in Canada already spend half a billion dollars a year on direct suppression costs; if area burned does increase as suggested

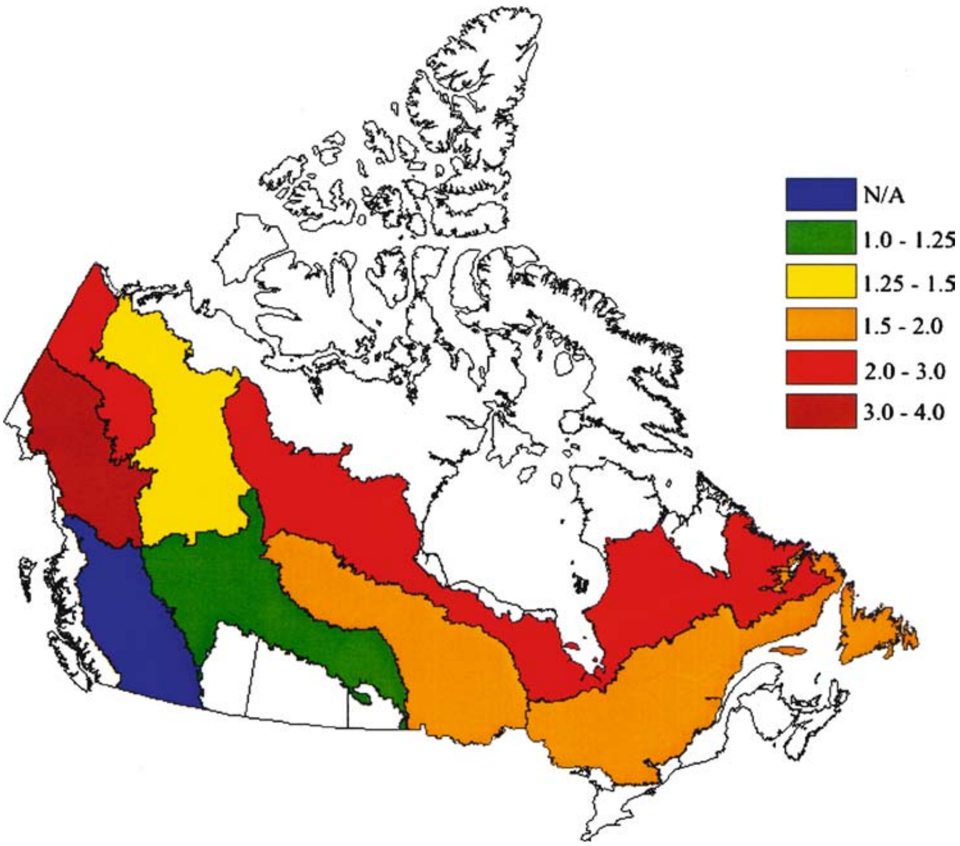


Figure 5. Ratio of $3 \times CO_2/1 \times CO_2$ area burned by Ecozone using the Canadian and Hadley GCMs, respectively. N/A, not applicable. The area burned model did not work for ecozone 14 with the Canadian GCM.

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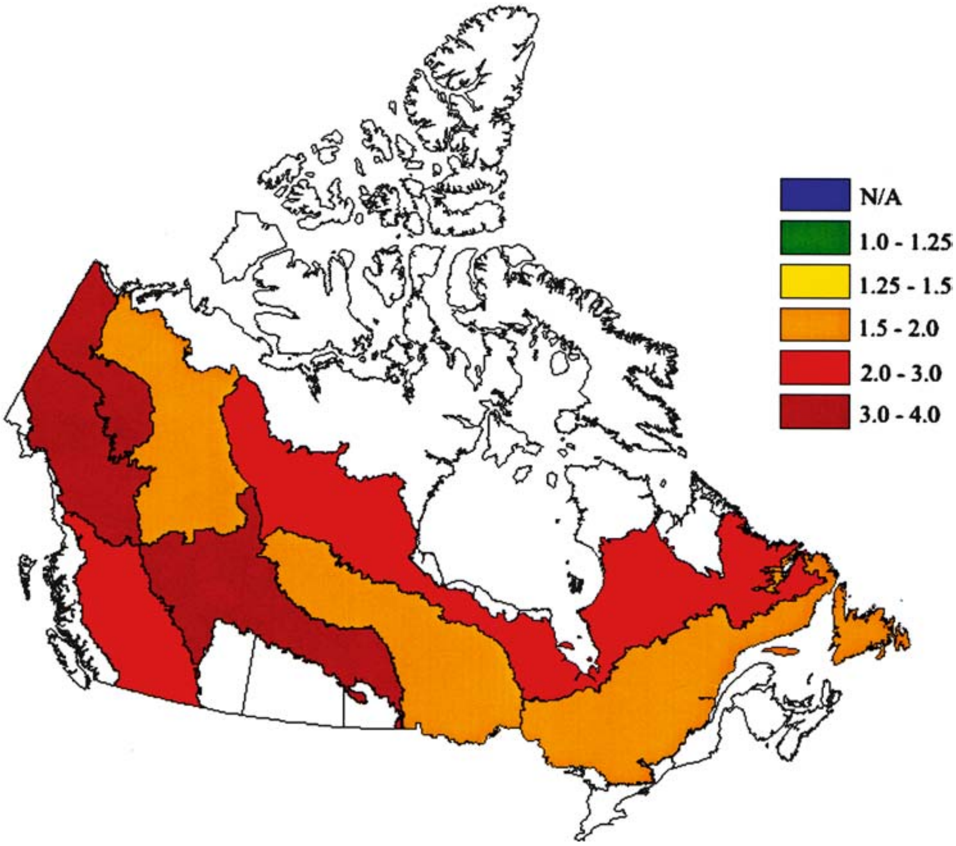

Figure 5. (Continued).

by this study these suppression costs could rise significantly. Additionally, fire management agencies operate with a narrow margin between success and failure, a disproportionate number of fires may escape initial attack under a warmer climate, resulting in an increase in area burned much greater than the corresponding increase in fire weather severity (Stocks, 1993). Lastly, the interplay between climate change and area burned could overshadow the direct effects of global warming on plant species distribution and migration (Weber and Flannigan, 1997). Thus, fire could be viewed as an agent of change in Canadian forests (Stocks, 1993).

The increases in area burned are somewhat similar to those suggested in other studies. For example, Flannigan and Van Wagner (1991) suggested that area burned in Canada would increase by 44% for a 2 × CO_2 scenario due to an increase in seasonal severity rating (SSR—the average DSR over the fire season). In the USA, Price and Rind (1994) who looked at lightning ignitions in the continental US suggested that area burned would increase by 78% for a 2 × CO_2 scenario based on a 44% increase in lightning fire ignitions. Some other studies did suggest that in regions of Canada the fire weather severity would remain unchanged or even

TABLE IV

Area burned by ecozone, observed and predicted for the Canadian and Hadley GCM 3 × CO_2 scenarios. Percent of total annual area burned by ecozone for observed and the 3 × CO_2 scenarios are below. The 3 × CO_2/1 × CO_2 ratio of averaged annual area burned was determined and then multiplied by the observed area burned for each ecozone to obtain an estimate of annual area burned in the future

	Annual area burned in 1959–1997		3 × CO_2 Canadian		3 × CO_2 Hadley	
Modified zone	Thousands of ha	(%)	Thousands of ha	(%)	Thousands of ha	(%)
4	366	(21)	508	(16)	574	(15)
5	387	(22)	821	(27)	817	(21)
61	493	(28)	824	(27)	947	(24)
62	154	(9)	252	(8)	266	(7)
9	218	(12)	237	(8)	751	(19)
11	32	(2)	88	(3)	120	(3)
12	106	(6)	360	(12)	353	(9)
14	23	(1)	0	(0)	51	(1)
All Ecozones	1,779	(100)	3,090	(100)	3,879	(100)
Ratio (3 × CO_2/observed)			1.7		2.2	

decrease in a 2 × CO_2 scenario (Bergeron and Flannigan, 1995; Flannigan et al., 1998; Flannigan et al., 2001). The differences between these studies and our current work are because those studies used the monthly anomaly approach rather than daily data (Bergeron and Flannigan, 1995) and because all those studies addressed a 2 × CO_2 scenario rather than a 3 × CO_2 scenario used in this study. Lastly, these studies addressed fire weather severity rather than the area burned in this paper. There are limitations in this study. For example, we did not explicitly address any changes in the number of ignitions but we would expect an increase in lightning-caused ignitions in Canada as well due to more thunderstorms and more receptive fuels. Recent results for people-caused ignitions suggest increases of 18% and 50% for 2050 and 2100, respectively, for Ontario (Wotton et al., 2003). Also, in this initial assessment, we assume that the future vegetation mosaic will have similar fuel characteristics to the present situation. This is probably a reasonable assumption as many forested regions in Canada were able to sustain significantly more fire activity in the past as determined by fire history studies (Flannigan et al., 1998). Future studies will include changes to fuel types in a changing climate with particular emphasis on the feedbacks caused by a changing fire regime. Changes in fire season length that are anticipated with climate change are not included in this present study. Wotton and Flannigan (1993) found that the fire season length in Canada increased by an average of 22% or 30 days using the Canadian GCM 2 × CO_2 scenario. Lastly, future human activities could impact on the area burned numbers. Humans start forest fires but they also try to suppress most of the fires. People can fragment the forest with agricultural, urban development and transportation corridors. Given all these factors that are not included in this preliminary study we feel that overall our numbers may be conservative.

The rate of change in area burned in the future is of great interest. This present study does not address this aspect of area burned but indications from historical area burned would suggest that the rate of change in area burned will not be linear (Stocks, 1993). We would anticipate that higher frequency influences like the El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) will be superimposed upon the longer-term global warming changes to area burned and the fire regime. ENSO influences the weather in Canada (Shabbar and Khandekar, 1996; Shabbar et al., 1997) and the fire activity in some parts of the world (Swetnam and Betancourt, 1990; Brenner, 1991). Thus far, however, there has been no direct connection made between ENSO and fire activity in Canada. We believe these climate oscillations may influence fire activity in Canada but the signal is more subtle and may be the result of interaction between one or more of the oscillations, e.g., ENSO and PDO.

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References

Amiro, B. D., Todd, J. B., Wotton, B. M., Logan, K. A., Flannigan, M. D., Stocks, B. J., Mason, J. A., Skinner, W. R., Martell, D. L., and Hirsch, K. G.: 2001, 'Direct carbon emissions from Canadian forest fires, 1959 to 1999', *Can. J. For. Res.* **31**, 512–525.

Bergeron, Y. and Flannigan, M. D.: 1995, 'Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest', *Water, Air, Soil Pollut.* **82**, 437–444.

Brenner, J.: 1991, 'Southern Oscillation anomalies and their relationship to wildfire activity in Florida', *Int. J. Wildland Fire* **1**, 73–78.

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

Flannigan, M. D., Bergeron, Y., Engelmark, O., and Wotton, B. M.: 1998, 'Future wildfire in circumboreal forests in relation to global warming', *J. Vegetat. Sci.* **9**, 469–476.

Flannigan, M. D., Campbell, I., Wotton, B. M., Carcaillet, C., Richard, P., and Bergeron, Y.: 2001, 'Future fire in Canada's boreal forest: Paleoecology results, and general circulation model - regional climate model simulations', *Can. J. For. Res.* **31**, 854–864.

Flannigan, M. D. and Harrington, J. B.: 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.

Flannigan, M. D., Stocks, B. J., and Wotton, B. M.: 2000, 'Forest fires and climate change', *Sci Total Environ*. **262**, 221–230.

Flannigan, M. D. and Van Wagner, C. E.: 1991, 'Climate change and wildfire in Canada', *Can. J. For. Res.* **21**, 66–72.

Flannigan, M. D. and Wotton, B. M.: 2001, 'Climate, weather and area burned', in Johnson, E. A. and Miyanishi, K. (eds.), *Forest Fires: Behavior & Ecological Effects*, Academic Press, pp. 335–357.

Flannigan, M. D. and Wotton, B. M.: 1989, 'A study of interpolation methods for forest fire danger rating in Canada', *Can. J. For. Res.* **19**, 1059–1066.

Flato, G. M., Boer, G. J., Lee, W. G., McFarlane, N. A., Ramsden, D., Reader, M. C., and Weaver, A. J.: 2000, 'The Canadian Centre for climate modelling and analysis global coupled model and its climate', *Clim. Dynam.* **16**, 451–467.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A.: 2000, 'The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments', *Clim. Dynam.* **16,** 147–168.

Harrington, J. B.: 1982, *A statistical study of area burned by wildfire in Canada 1953–1980.* Canadian Forestry Services, Information Report PI-X-16, Petawawa, National Forestry Institute.

Harrington, J. B., Flannigan, M. D., and Van Wagner, C. E.: 1983, *A study of the relation of components of the Fire Weather Index System to monthly provincial area burned by wildfire in Canada 1953–80.* Canadian Forestry Services, Information Report PI-X-25, Petawawa, National Forestry Institute.

Harvey, D. A., Alexander, M. E., and Janz, B.: 1986, 'A comparison of fire-weather severity in northern Alberta during the 1980 and 1981 fire seasons', *For. Chron.* **62**, 507–513.

Hely, C., Flannigan, M. D., Bergeron, Y., and McRae, D.: 2001, 'Role of vegetation and weather on fire behavior in the Canadian Mixedwood boreal forest using two fire behavior prediction systems', *Can. J. For. Res.* **31**, 430–441.

Intergovernmental Panel on Climate Change: 2001, *Climate Change 2001 The Scientific Basis*, Cambridge University Press, Cambridge.

Johnson, E. A.: 1992, *Fire and vegetation dynamics: Studies from the North American boreal forest*, Cambridge University Press, Cambridge, 125 pp.

Laprise, R., Caya, D., Frigon, A., and Paquin, D.: 2003, 'Current and perturbed climate as simulated by the second-generation Canadian Regional Climate Model (CRCM-II) over northwestern North America', *Clim. Dynam.* **21**, 391–404.

Mearns, L. O., Giorgi, F. Mcdaniel, L., and Shields, C.: 1995, 'Analysis of daily variability of precipitation in a nested regional climate model—comparison with observations and doubled CO_2 results', *Global and Planetary Change* **10**, 55–78.

Newark, M. J.: 1975, 'The relationship between forest fire occurrence and 500 mb ridging', *Atmosphere* **13**, 26–33.

Nimchuk, N.: 1983, *Wildfire behavior associated with upper ridge breakdown,* Alta. Energy and Nat. Resour., For. Serv., Edmonton, AB, Canada. ENR Rep. No. T/50.

Osborn, T. J. and Hulme, M.: 1997, 'Development of a relationship between station and grid-box rainday frequencies for climate model evaluation', *J. Clim.* **10**, 1885–1908.

Price, C. and Rind, D.: 1994, 'The impact of a $2 \times CO_2$ Climate on lightning-caused fires', *J. Clim.* **7**, 1484–1494.

SAS Institute Inc.: 2000, *SAS OnlineDoc®, Version 8*, SAS Institute Inc., Cary, NC.

Shabbar, A. and Khandeker, M.: 1996, 'The impact of El Nino-Southern Oscillation on the temperature field over Canada', *Atmosphere-Ocean* **34**, 401–416.

Shabbar, A., Bonsal, B., and Khandekar, M.: 1997, 'Canadian precipitation patterns associated with the southern oscillation', *J. Clim.* **10**, 3016–3027.

Skelly, W. C. and Henderson-Sellers, A.: 1996, 'Grid box or grid point: What type of data do GCMs deliver to climate impacts researchers?', *International J. Climatol.* **16**, 1079–1086.

Skinner, W. R., Flannigan, M. D., Stocks, B. J., Martell, D. M., Wotton, B. M., Todd, J. B. Mason, J. A., Logan, K. A., and Bosch, E. M.: 2001, 'A 500 mb synoptic wildland fire climatology from large Canadian forest fires, 1959–1996', *Theoret. Appl. Climatol.* **71**, 157–169.

Skinner, W. R., Stocks, B. J., Martell, D. L., Bonsal, B., and Shabbar, A.: 1999, 'The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada', *Theoret. Appl. Climatol.* **63**, 89–105.

Stocks, B. J.: 1993, 'Global warming and forest fires in Canada', *For. Chron.* **69**, 290–293.

Stocks, B. J., Fosberg, M. A., Lynham, T. J., Mearns, L., Wotton, B. M., Yang, Q., Jin, J.-Z., Lawrence, K., Hartley, G. R., Mason, J. A., and McKenney, D. W.: 1998, 'Climate change and forest fire potential in Russian and Canadian boreal forests', *Clim. Change* **38**, 1–13.

Stocks, B. J., Mason, J. A., Todd, J. B., Bosch, E. M., Wotton, B. M., Amiro, B. D., Flannigan, M. D., Hirsch, K. G., Logan, K. A., Martell, D. L., and Skinner, W. R.: 2002, 'Large forest fires in Canada, 1959–1997', *J. Geophys. Res.* **107**, 8149, doi: 10.1029/2001JD000484.

Swetnam, T. W.: 1993, 'Fire history and climate change in giant sequoia groves', *Science* **262**, 885–889.

Swetnam, T. W. and Betancourt, J. L.: 1990, 'Fire-Southern Oscillation relations in the southwestern United States', *Sci.* **249**, 1017–1020.

Van Wagner, C. E.: 1970, 'Conversion of Williams severity rating for use with the fire weather index', Can. Dep. Fisheries and For., Petawawa Forest Expt. Stn., Information Report PS-X-21.

Van Wagner, C. E.: 1987, 'The development and structure of the Canadian forest fire weather index system', Canadian Forest Service, Forest Technical Report 35, Ottawa, Canada.

Weber, M. G. and Flannigan, M. D.: 1997, 'Canadian boreal forest ecosystem structure and function in a changing climate: Impacts on fire regimes', *Environ. Rev.* **5**, 145–166.

Weber, M. G. and Stocks, B. J.: 1998, 'Forest fires and sustainability in the boreal forests of Canada', *Ambio* **27**, 545–550.

Williams, D. E.: 1959, 'Fire season severity rating', Can. Dep. Northern Aff. And Nat. Res., Div. Tech. Note 73, Ottawa, Canada.

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

Wotton, B. M., Martell, D. L., and Logan, K. A.: 2003, 'Climate change and people-caused forest fire occurrence in Ontario', *Clim. Change* **60**, 275–295.

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