Future fire in Canada's boreal forest: paleoecology results and general circulation model – regional climate model simulations

Mike Flannigan, Ian Campbell, Mike Wotton, Christopher Carcaillet, Pierre Richard, and Yves Bergeron

Abstract: General circulation model simulations suggest the Earth's climate will be 1–3.5°C warmer by AD 2100. This will influence disturbances such as forest fires, which are important to circumpolar boreal forest dynamics and, hence, the global carbon cycle. Many suggest climate warming will cause increased fire activity and area burned. Here, we use the Canadian Forest Fire Weather Index to simulate future forest fire danger, showing the expected increase in most of Canada but with significant regional variability including a decrease in much of eastern Canada. These results are in general agreement with paleoecological data and general circulation model results from the 6000 calendar years BP interval, which was a time of a warmer climate that may be an analogue for a future climate.

Résumé : Les simulations effectuées avec le modèle de la circulation générale indiquent que le climat de la terre se réchauffera de 1 à 3,5°C vers 2100 A.D. Ce réchauffement aura un impact sur les perturbations telles les feux de forêt, qui jouent un rôle important dans la dynamique de la forêt boréale circumpolaire et par conséquent dans le cycle global du carbone. Plusieurs avancent que le réchauffement du climat causera une augmentation des feux et des superficies brûlées. Dans cette étude, nous avons utilisé l'indice forêt météo canadien pour simuler les risques futurs de feux de forêt et démontrer l'augmentation prévue presque partout au Canada, avec cependant d'importantes variations régionales dont une diminution presque partout dans l'Est du Canada. Dans l'ensemble, ces résultats concordent avec les données paléo-écologiques et les résultats du modèle de la circulation générale pour l'intervalle correspondant à 6000 années de calendrier antérieures à aujourd'hui, qui a connu un climat plus chaud pouvant ressembler au climat futur.

[Traduit par la Rédaction]

Introduction

On average, nearly 3 × 10^6 ha of forest burn every year in Canada alone, significantly affecting the global carbon budget through direct emissions and through alterations to the dynamics of the terrestrial carbon pool (Kurz et al. 1995). Forest structure and composition, now and in the past, is influenced by the fire regime (Heinselman 1973; Wright and Bailey 1982). Typically, 3% of the fires are responsible for 97% of the area burned, and most of the fire activity occurs during a few days with severe fire weather (Flannigan and Harrington 1988). General circulation models (GCMs) have projected an increase in the Earth's mean surface temperature by 1–3.5°C over the next century; this warming is expected to be strongest in northern latitudes (IPCC 1996). This projected warming has led to fears that the frequency of extreme fire weather, and therefore extreme fire activity, will increase (Clark 1988; Clark 1989; Overpeck et al. 1990; Wotton and Flannigan 1993; Stocks et al. 1998) given the strong links between climate–weather and fire (Flannigan and Harrington 1988; Johnson 1992; Swetnam 1993). Fire, however, is strongly dependent on other weather variables as well, such as precipitation, wind speed, and relative humidity.

A possible increase in forest fire activity is of great concern. Not only are timber, infrastructure, and ecological values placed at risk by fire, but fire has also been shown to be a significant factor in determining the net carbon balance of the forest (Kurz et al. 1995). As such, an increase in fire activity could lead to an increase in atmospheric greenhouse gases, further enhancing the greenhouse effect.

Here, we test this projection of increased future extreme fire weather using three approaches. First, present and future fire weather maps are derived from the Canadian GCM and regional climate model (RCM) (Caya et al. 1995; Caya and Laprise 1999) outputs for the 1 × CO_2 and 2 × CO_2 simulations. Second, we modeled the fire weather 6000 years ago (6000 calendar years BP), a time of warmer climate often

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M. Flannigan[1] and I. Campbell. Canadian Forest Service, 5320-112 Street, Edmonton, AB T6H 3S5, Canada.
M. Wotton. Canadian Forest Service, P.O. Box 490, Sault Ste. Marie, ON P6A 5M7, Canada.
C. Carcaillet. Département de géographie, Université de Montréal, C.P. 6128 succursale Centre-ville, Montréal, QC H3C 3J7, and Groupe de recherche en écologie forestière, Université du Québec à Montréal, C.P. 8888, succursale Centre-ville, Montréal, QC H3C 3P8, Canada.
P. Richard. Département de géographie, Université de Montréal, C.P. 6128 succursale Centre-ville, Montréal, QC H3C 3J7, Canada.
Y. Bergeron. Groupe de recherche en écologie forestière, Université du Québec à Montréal, C.P. 8888, succursale Centre-ville, Montréal, QC H3C 3P8, Canada.

[1] Corresponding author (e-mail: mflannig@nrcan.gc.ca).

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used as an analogue for a future climate (e.g., COHMAP 1988) as well as the present day using a specially modified version of the Canadian GCM (Vettoretti et al. 1998, 2000). This is then compared with charcoal abundance anomalies at 6000 calendar years BP in stratigraphic records, a proxy for past fire activity (Clark et al. 1997).

Materials and methods

Fire and climate models

To model fire danger we calculated the Fire Weather Index (FWI) component of the Canadian Forest Fire Weather Index System (Van Wagner 1987). The FWI System is a system of daily meteorologically based indexes used universally across Canada to estimate fuel moisture and fire danger in a generalized fuel type. The calculated components of the FWI System are based on daily solar noon measurements of dry-bulb temperature, relative humidity, 10-m open wind speed, and 24-h accumulated precipitation. The system models fuel moisture through three moisture models, which are in fact dynamic bookkeeping systems that track the drying and wetting of distinct fuel layers in the forest floor. These moisture indexes are combined with winds to create generalized indexes of the availability of fuel for consumption and the potential spread rate of a fire. These indexes are combined to create the FWI which is an estimate of the potential intensity of a spreading fire. Though developed for a generalized fuel type, the FWI System has been found to model fire potential in a broad range of closed forest stands with deep organic layers quite well (Van Wagner 1975).

To model the fire weather we calculated the Canadian FWI from daily weather outputs of the Canadian GCM and RCM for the 1 × CO_2, 2 × CO_2, and 6000 calendar years BP scenarios. Daily rather than monthly data were used because the weather and consequently fire behavior can change dramatically from day to day. The Canadian GCM is a coupled atmosphere–ocean model with a transform grid spacing of 3.75 by 3.75° and full diurnal and annual cycles (Boer et al. 1992; McFarlane et al. 1992). We used the RCM (Caya et al. 1995; Caya and Laprise 1999) where available (western Canada), as it has better spatial resolution than does the GCM. The 1 × CO_2 simulation uses 330 ppm of CO_2 and approximates the 1960–1980 period, whereas the 2 × CO_2 simulation uses 660 ppm and might represent conditions around the 2040–2060 period. The fire season was defined as May 1 to August 31, as about 98% of the area burned occurs during this period (Harrington 1982). The same procedure was used to generate components of the FWI System for 6000 calendar years BP, and the present day using a specially modified version of the Canadian GCM (Vettoretti et al. 1998, 2000). This modified GCM modified the orbital parameters and the carbon dioxide levels to be representative of 6000 calendar years BP, and the present day.

Past fire activity

The most direct evidence of past burning activity is provided by sub-fossil charcoal. Lakes and peatlands provide stratified sediments whose chronology may be tested and established using radiometric dating (^{14}C, ^{210}Pb, etc.), marker horizons such as tephra beds, or events such as abrupt rises or declines of well-identified taxa (Berglund 1986). Two different sources of charcoal data are used here as northern North American fire proxies: first, a stratigraphic charcoal data base at the Université de Montréal (20 sites in eastern Canada, Table 1; Carcaillet and Richard 2000), and second, published literature (25 additional sites in Canada and four sites in the adjacent United States) (Table 2).

Most sites of the Université de Montréal data base were analyzed by tallying charcoal fragments (>156 mm^2) on pollen slides; three sites were analysed by tallying macro-charcoal from sediment sieved through a 150-μm mesh screen. Sites from the Montréal data base were selected from more than 60 sites studied for charcoal. The selection was based on both sedimentological and chronological criteria to reduce the variance between charcoal series resulting from taphonomical aspects (Carcaillet and Richard 2000). All lakes retained were smaller than 9 ha and were surrounded by the same type of forest at 6000 calendar years BP as at present (Table 1). Despite these rigid criteria, the variability between charcoal series remains high (Fig. 1), and the temporal analytical resolution is relatively low (mean of 14 and a minimum of 2 observations per millennium at 6000 calendar years BP). The high standard deviation results from the recent trend to increasing temporal resolution in palaeological studies to reconstruct boreal forest fire frequencies during the postglacial period (Bergeron et al. 1998; Carcaillet et al. 2001).

The charcoal accumulation rate (CHAR) is assumed to reflect local or regional burning activity (Clark et al. 1997). The CHAR have been transformed into CHAR anomalies (Carcaillet and Richard 2000) to display the differences of fire activity between 6000 calendar years BP and the present day. High-resolution charcoal time series display lognormal distributions resulting from infrequent charcoal peaks that are generally between 2 and 20 times larger than mean and background values. Consequently, the CHAR were first log transformed. Anomalies were computed using the mean CHAR for the interval 6500–5500 calendar years BP for 6000 calendar years BP versus the interval 1000–0 calendar years BP for the present day. The anomalies are reported only where the difference between the log-transformed 6500–5500 calendar years BP CHAR were different from the 1000–0 calendar years BP CHAR by more than 0.5σ of the mean reference CHAR of the site. A negative anomaly corresponds to a lower fire activity at 6000 calendar years BP than at present, and vice versa for a positive anomaly. When no significant differences were found between 6000 calendar years BP and present-day CHAR, the anomaly is reported as null.

To increase the geographic coverage of the analysis, additional, less rigorously selected sites had to be included. The other 29 sites were analyzed by various researchers over a period of 20 years, using a variety of methods. Most (21) were analyzed by counting charcoal fragments larger than some arbitrary size on pollen slides, either tallying the total area of fragments, the total number, or by point count (Table 2). In several cases, the results are reported as a "charcoal/pollen ratio," which is hypothesized to make fire events more readily distinguished from "noise" in the charcoal record (Swain 1978). Two sites (Kuhry 1994) used the frequency of visible charcoal horizons in peat cores. Two sites were analyzed by chemical assay of charcoal content (Winkler 1985; Campbell 1998). At some sites, the sediment was sieved, and large charcoal fragments were weighed or tallied simply as present or absent (Hu et al. 1993, 1996). The sites used were of varying surface area, depth, and morphological characteristics, and several peat and swamp sites are included. They include sites in the grassland as well as in the coniferous boreal, and cold or warm mixed-deciduous forest zones. Several of the western Canadian sites are in the foothills or mountains of the western cordillera. In most cases, a pollen-diagram style graph were the only available data. In many cases, the discussion in the original papers indicated whether, in the opinion of the original author, the period ca. 6000 calendar years BP was a period of relatively high or low fire activity. In all cases, a visual, subjective estimate was made, comparing the charcoal influx rate at ca. 6000 calendar years BP with that of the last 1000 years (excluding the most recent few samples if these appeared to be significantly affected by European settlement). If the charcoal curve had a high level of noise, this was taken into account subjectively. Large isolated peaks in the charcoal curve were largely ignored as possible unique events or artefacts. This procedure is similar to that previously used for identifying regional trends in pollen records (Campbell and McAndrews 1991). Anomalies were reported as negative, positive, or null as above (examples are shown in Fig. 2). Null

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Table 1. Characteristics of sites with fire occurrence records at 6000 ± 500 calendar years BP.

No.	Site	Latitude (N)	Longitude (W)	Elevation (m a.s.l.)	Depth (m)	Area (ha)	Modern and 6000 calendar years BP vegetation[a]	Site type	No. of ^{14}C dates (^{210}Pb dates)	Analysis type[b]	Anomaly[c]	Reference
1	Albion	45°40′15″	71°19′30″	320	1.0	2.5	Mixed temperate	Lake	7	AP	–	Lavoie and Richard (2000)
2	Atocas (aux)	45°32′34″	73°18′39″	114	1.0	1.2	Mixed temperate	Lake	4	AP	+	Gauthier (1981)
3	Bouchard (Petit)	48°51′14″	64°35′52″	145	1.5	2.0	Mixed boreal	Lake	10	AP	–	Asnong (2000)
4	Caribou	48°11′52″	64°56′24″	116	2.3	2.6	Mixed boreal	Lake	7	AP	+	Jetté and Richard (1992)
5	Desautels	49°27′28″	73°15′00″	480	7.0	3.0	Boreal coniferous	Lake	5	AP	0	Carcaillet and Richard (2000)
6	Dolbeau	48°58′01″	65°57′21″	965	2.2	3.1	Mixed boreal	Lake	7	AP	–	Carcaillet and Richard (2000)
7	Flévy	48°13′01″	71°13′08″	381	4.5	1.5	Mixed boreal	Lake	3	AP	+	P.J.H. Richard, unpublished data
8*a*	Francis	48°31′35″	79°28′20″	305	6.0	0.8	Mixed boreal	Lake	9 (6)	AP	–	Bergeron et al. (1998)
8*b*	Francis	48°31′35″	79°28′20″	305	6.0	0.8	Mixed boreal	Lake	9 (6)	M	–	Carcaillet et al. (2001)
9	Gabriel (St)	46°16′33″	73°28′33″	250	1.0	0.3	Mixed temperate	Lake	6	AP	0	Richard (1977)
10	J’Arrive	49°14′50″	65°22′35″	56	2.4	2.4	Mixed boreal	Lake	6	AP	–	Marcoux and Richard (1995)
11	Léonard	49°12′28″	65°48′46″	17	1.0	0.2	Mixed temperate	Lake	5	AP	0	Labelle and Richard (1984)
12	Madeleine	47°40′20″	70°43′10″	800	3.8	8.3	Mixed boreal	Lake	4	AP	0	Bussières (1992)
13	Neume	47°35′16″	77°06′39″	363	5.5	2.9	Mixed boreal	Lake	5	AP	0	Richard and Larouche (1989)
14	Ouellet	47°31′58″	68°56′38″	300	1.9	0.6	Mixed temperate	Lake	3	AP	–	Richard et al. (1992)
15	Pas-de-Fond	48°48′30″	78°48′30″	290	11.0	2.0	Mixed boreal	Lake	6 (6)	M	–	Carcaillet et al. (2001)
16	Perdu	49°10′15″	66°19′25″	152	7.0	0.5	Mixed boreal	Lake	11	AP	0	C. Labelle and P.J.H. Richard, unpublished data
17	Pessière (à la)	49°30′30″	79°14′25″	280	16.0	4.0	Boreal coniferous	Lake	7	M	0	Carcaillet et al. (2001)
18	Spearman	46°32′38″	78°30′10″	368	1.5	3.1	Mixed temperate	Lake	5	AP	+	Richard and Larouche (1989)
19	Triangle	48°42′36″	65°24′50″	465	2.0	4.0	Boreal coniferous	Lake	8	AP	–	Asnong (2000)
20	Yamaska	45°27′28″	72°52′19″	265	3.5	0.2	Mixed temperate	Lake	7	AP	–	Carcaillet and Richard (2000)

[a] Modern and 6000 calendar years BP vegetation are as follows: mixed temperate forests are mixed broadleaf deciduous forests from the cold-temperate zone; mixed boreal forest are closed mixed needleleaf-dominant forests from the southern boreal zone; and boreal forests are closed to open needleleaf forests from the northern boreal zone.

[b] AP, area count on pollen slides; M, tallying of or frequency of occurrence of macroscopic charcoal.

[c] Anomalies are shown as positive (+), null (0), and negative (–) (see text).

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Table 2. Characteristics of charcoal data sources from the literature.

Name	Latitude (N)	Longitude (W)	Elevation (m a.s.l.)	Depth (m)	Area (ha)	Modern vegetation	6000 calendar years BP vegetation	Site type	No. of dates	Analysis type[a]	Anomaly[b]	Reference
Mendota	43°06′	89°25′	257	24	3490	Oak savannah	Oak savannah	Lake	3	AS	+	Winkler (1985)
Decoy	43°14′	80°22′	260	0.5	0.42	Oak savannah	Oak savannah	Lake	5	AP	+	Szeicz and McDonald (1991)
Everitt	43°30′	66°00′	na[c]	na	na	Maple mixedwood	Hemlock mixedwood	Lake	na	AP	+	Green (1982)
High	44°31′	76°36′	192	na	2.5	Great Lakes – St. Lawrence	Great Lakes – St. Lawrence	Lake	8	PP	0	Fuller (1997)
Graham	45°11′	77°21′	381	na	2.5	Great Lakes – St. Lawrence	Great Lakes – St. Lawrence	Lake	6	PP	0	Fuller (1997)
Harp Wetland	45°20′	79°12′	389	0	1.2	Great Lakes – St. Lawrence	Great Lakes – St. Lawrence	Swamp	6	CP	+	Bunting et al. (1996)
Perch	46°02′	77°21′	156	3.5	45	Great Lakes – St. Lawrence	Great Lakes – St. Lawrence	Lake	1	CP	–	Terasmae and Weeks (1979)
Louis	47°15′	79°07′	300	7.6	25	Boreal	Boreal	Lake	3	CP	+	Terasmae and Weeks (1979)
Richter Marsh	49°01′	119°30′	450	0	15	Grassland	Grassland	Kettle marsh	0[d]	CP	0	Cawker (1983)
Wabamun	50°32′	114°35′	725	10	8180	Boreal mixedwood	Boreal mixedwood	Lake	10[e]	CP	+	Hickman et al. (1984)
Lone Fox	56°43′	119°43′	1000	3	5	Boreal	Boreal	Lake	6	PP	0	MacDonald (1987)
Klassen Bajada	50°52′	111°15′	638	0	66	Grassland	Grassland	Alluvial fan	3[e]	AS	0	Campbell (1998)
O’Hara	51°21′	116°20′	2015	42	50	Subalpine	Subalpine	Lake	3[e]	M	+	Reasoner and Hickman (1989)
Wilcox Pass	52°15′	117°13′	2355	0	na	Alpine meadow	Alpine meadow	Bog	2	CP	0	Beaudoin and King (1990)
Smallboy	53°35′	114°08′	762	7.5	1	Boreal mixedwood	Boreal mixedwood	Lake	6[e]	CP	+	Vance et al. (1983)
Mariana Lakes	55°54′	112°04′	na	0	690	Boreal mixedwood	Boreal mixedwood	Fen	3	M	+	Nicholson and Vitt (1990)
Buffalow Narrows	55°56′	108°34′	na	0	300	Boreal	Boreal	Fen	3	M	+	Kuhry (1994)
Kogaluk Plateau	56°04′	63°45′	534	na	na	Heath tundra	Shrub tundra	Lake	5	CP	–	Short and Nichols (1977)
Nain Pond	56°32′	61°49′	91	na	na	Lichen woodland	Shrub tundra	Lake	8	CP	–	Short and Nichols (1977)
Toboggan	50°46′	114°36′	1480	5	0.5	Open subalpine	Pine parkland	Lake	7[e]	PP	+	MacDonald (1989)
Legend lake	57°26′	112°57′	na	0	700	Boreal	Boreal	Fen	4	M	+	Kuhry (1994)
Farewell	62°33′	153°38′	na	10	400	Boreal	Taiga	Lake	6	M	–	Hu et al. (1996)
Wien	64°20′	152°16′	na	30	1200	Boreal	Boreal	Lake	8	M	+	Hu et al. (1996)
Black Gum Swamp	42°15′	71°30′	360	5	10	Hemlock	Hemlock	Swamp	7	PP	0	Foster and Zebryk (1993)
GB2	55°06′	75°17′	300	5	5	Boreal	Taiga	Lake	4	AP	–	Gajewski et al. (1993)
EC1	56°17′	75°06′	250	9	4	Taiga	Taiga	Lake	4	AP	–	Gajewski et al. (1993)
LB1	57°55′	75°37′	200	10	3	Taiga	Taiga	Lake	4	AP	–	Gajewski et al. (1993)
LR1	58°35′	75°15′	170	9	2	Shrub tundra	Tundra	Lake	4	AP	–	Gajewski et al. (1993)
Northwest	52°30′	92°30′	na	8	10	Boreal	Boreal	Lake	4	PP	0	A.M. Pilmanis, J.S. Clark, and B.J. Stocks, unpublished data

[a] PP, point count on pollen slides; CP, particle count on pollen slides or peels; AP, area count on pollen slides; M, count or observation of macroscopic charcoal; AS, chemical assay.

[b] Anomalies are shown as positive (+), null (0), and negative (–) (see text).

[c] na, not available.

[d] Dates inferred by correlation of pollen stratigraphy.

[e] Includes at least one tephras.

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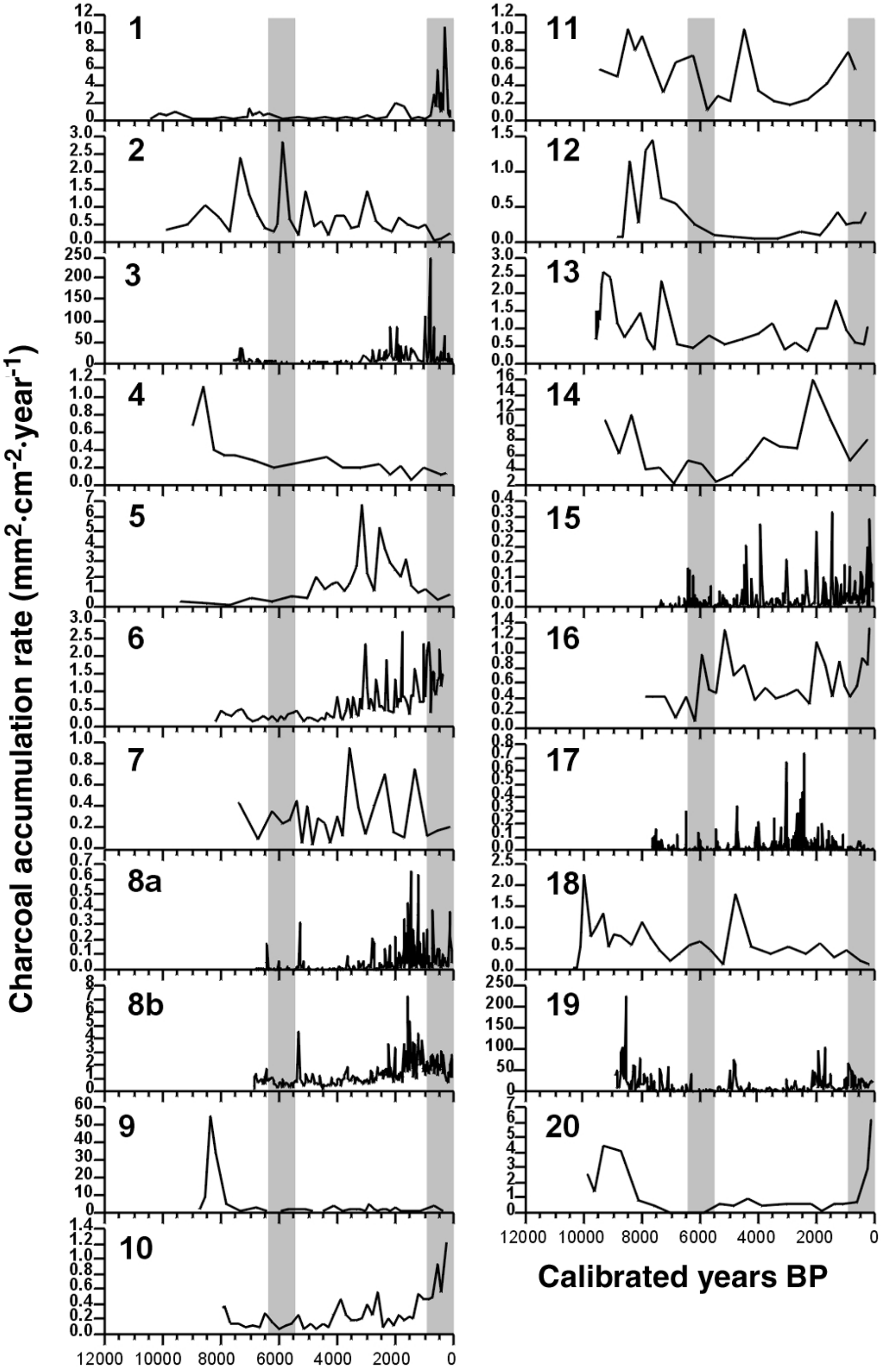
Fig. 1. Charcoal accumulation rate curves showing an apparent large variability of responses between sites for 6000 calendar years BP versus the present day, partially depending on the analytical temporal resolution.



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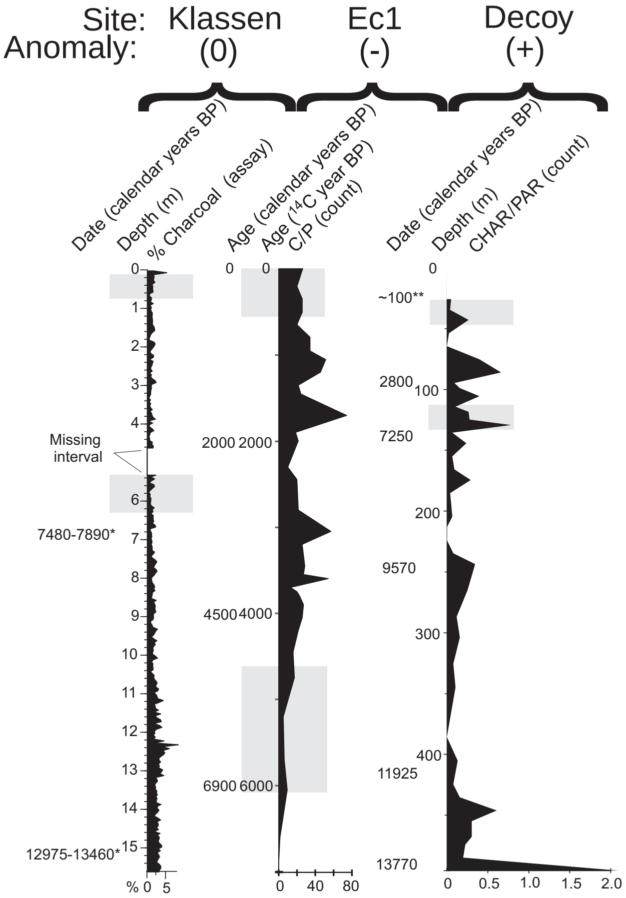


Fig. 2. Sample charcoal curves from literature sources, illustrating the subjective coding used. Shaded boxes show the portions of the curves that were visually compared; each region includes a minimum of three samples. The Klassen Bajada (curve redrawn from Campbell 1998), coded as a null anomaly, is a continuously sedimenting alluvial fan complex on the Red Deer River in southern Alberta. The uppermost two samples were ignored as probably representing stubble burning on the adjacent field. Charcoal content was analyzed by a modified form of the Winkler (1985) chemical assay method. Site EC1 (curve redrawn from Gajewski et al. (1993)), coded as a negative anomaly, is a small lake in northern Quebec. Charcoal was counted on pollen slides and presented as a charcoal/pollen (C/P) ratio. Decoy Lake (curve redrawn from Szeicz and MacDonald, 1991), coded as a positive anomaly, is a small kettle pond in southern Ontario. Charcoal content was counted on pollen slides and expressed as the ratio of the charcoal and pollen accumulation rates (CHAR/PAR). Although the uppermost few centimetres of the core were not analyzed, the uppermost samples analyzed for pollen clearly show Historic period (after AD 1850 in this region) farming activity, so the uppermost three samples were used for the comparison.

anomalies were also reported in cases where the noise level of the diagram was too high to confidently assign a positive or negative anomaly; as such, a null anomaly in this data set should not be narrowly interpreted as indicating no change in the fire regime but rather should be taken to indicate either no change or else inadequate data. The high proportion of null anomalies (8 of 29, or 28%) reflects the low sampling resolution of many studies, high noise levels, and caution in the subjective analysis.

Many objections can be raised against this procedure; however, despite the variations in site characteristics and method of analysis, the geographic pattern of negative and positive anomalies is broadly consistent (see Figs. 5 and 6). Most (7 of 8) negative anomalies in this data set occur east of 80°W, where only 3 of 13 anomalies are positive, 7 of 13 are negative, and 3 of 13 are null. West of 80°W, 10 of 16 anomalies are positive, 5 of 16 are null, and only 1 of 16 is negative. The negative anomaly west of 80°W is in Alaska and can be explained by the arrival of *Picea mariana* (Mill.) BSP in the area after 4000 calendar years BP (Hu et al. 1996), while it had arrived at the other Alaskan site by 6500 calendar years BP (Hu et al. 1993). Since, throughout the western region, the first arrival of conifers at a site is attended by a dramatic increase in charcoal, this late arrival of spruce at the site with the negative anomaly seems adequate explanation. The general consistency of these results suggests that, at least at this level of interpretation, charcoal analysis is a robust proxy for past relative fire activity levels.

Results and discussion

Figure 3 shows the difference in mean daily maximum temperature in degrees Celsius for 2 × CO_2 minus 1 × CO_2 for the May 1 to August 31 period. The forested regions of Canada are expected to be 3–4°C warmer in the 2 × CO_2 scenario as compared with 1 × CO_2. Figure 4 displays the difference in mean daily maximum temperature in degrees Celsius for 6000 calendar years BP to the present day. Similarly, the model indicates that the forested regions of Canada 6000 calendar years BP were about 1°C warmer than present. The patterns of temperature differences are similar in both figures though the temperature change is larger for Fig. 3 (2 × CO_2 minus 1 × CO_2).

Figure 5 depicts the ratio of the mean FWI for 2 × CO_2 over 1 × CO_2. Ratios greater than 1.0 indicate increased FWI with greenhouse warming, while ratios less than 1.0 indicate decreased FWI. Although there is large regional variability, FWIs generally increase over central and western Canada with values significantly greater than in the 1 × CO_2 simulation. However, there is a large region in eastern Canada and a smaller area in the northwestern interior where the FWI is expected to decrease despite the warming. Interestingly, the region of decreased FWI in the northwest is smaller in the RCM simulation than in the GCM simulation (not shown here), partly because of the RCM's greater resolution, which provides a more realistic simulation of the orographic effect of the western cordillera; it may be that as model resolution increases, this region of decreased FWI will shrink further.

Figure 6 shows the ratio of the mean FWI for 6000 calendar years BP over the present day. Because there is no RCM run available for the 6000 calendar years BP period, the GCM results have been used here; the decrease in FWI in parts of the northwestern interior may be due to the relatively crude parameterization of the western cordillera in the GCM, which results in improperly high estimates of precipitation in western Canada (Caya et al. 1995) and, therefore, low FWI values. Therefore, these low FWI values in the west should be largely discounted. The results are broadly similar to those of the 2 × CO_2 simulation, in that eastern Canada generally shows low FWIs while central and some parts of western Canada show high FWIs. However, the changes in the FWI appear to be more pronounced in the 2 ×

Fig. 3. May to September mean daily maximum temperature difference for 2 × CO_2 minus 1 × CO_2 in degrees Celsius.

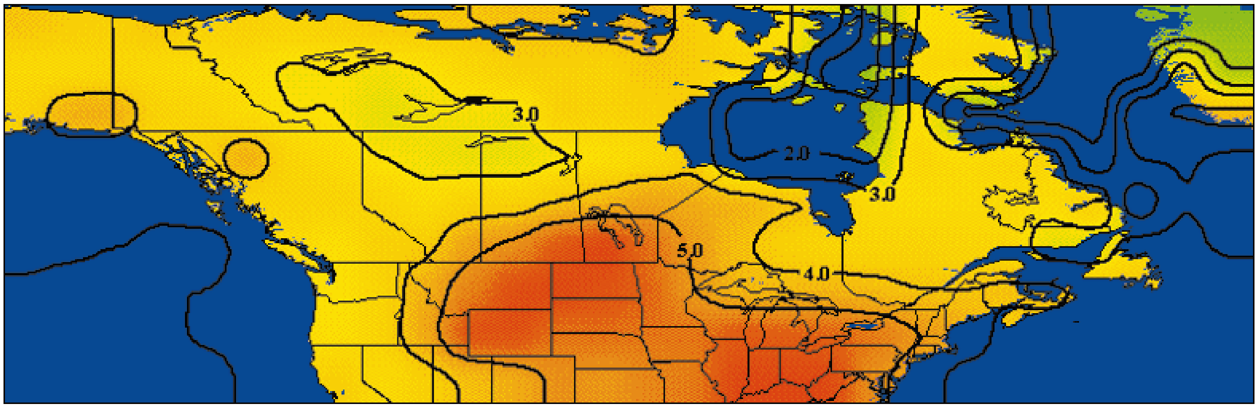
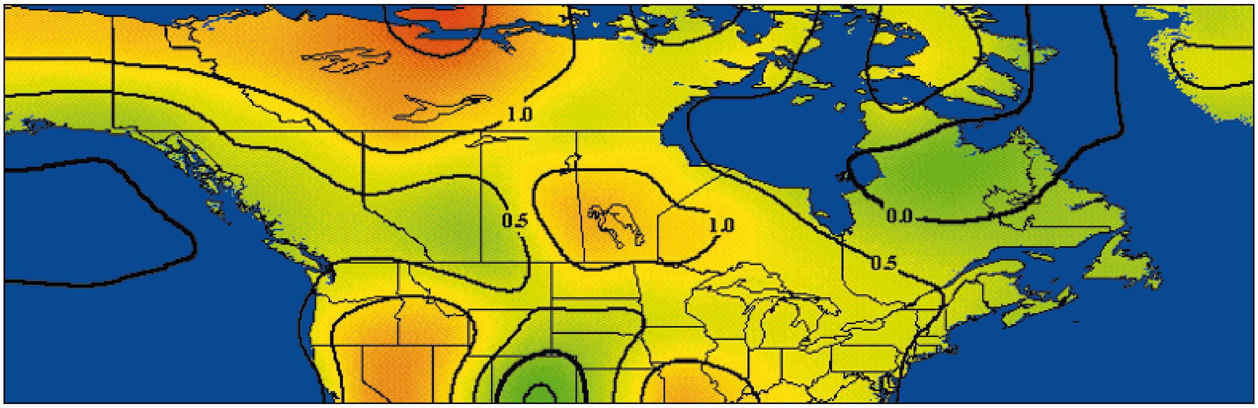


Fig. 4. May to September mean daily maximum temperature difference for 6000 calendar years BP minus present day in degrees Celsius.



CO_2 simulation, which may be due to the predicted larger changes in the climate associated with the 2 × CO_2 scenario.

It is noteworthy that the modeled FWI anomalies suggest less severe fire weather in much of eastern Canada despite the warming (Fig. 5*b*); this is due to over-compensating increases in precipitation and humidity. This is consistent with historical evidence that fire frequency in Quebec has decreased over the last 100 years despite warmer temperatures (Bergeron and Archambault 1993; Flannigan et al. 1998).

The FWIs from both the 6000 calendar years BP, and the 2 × CO_2 simulations agree well with the spatial pattern of charcoal anomalies at 6000 calendar years BP (Figs. 5 and 6). The exception to this agreement is an area in the western interior of Canada, in the lee of the cordillera, where the simulations suggest a decrease in FWI, while the charcoal data show an increase at 6000 calendar years BP. This discrepancy is likely due to the inadequate representation of the western cordillera in the climate models discussed above.

What are the implications from these results in terms of fire activity? Over the last several decades the FWI System is correlated to area burned (Harrington et al. 1983), which suggests approximately a 1 to 1 relationship between FWI and area burned; for example, if FWI increases 50% for a 2 × CO_2 simulation we could expect a similar increase in area burned. From Fig. 5, we would expect large future increases in area burned by wildfire in the forests of central and western Canada. This region where we expect large increases in area burned is also the region that historically has been the major contributor to area burned in Canada. Other areas like Quebec and northeastern Ontario, which have relatively lower burned areas, might experience a reduction in area burned because of lower fire weather severity. There are other factors that affect 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 (Weber and Stocks 1998). Indications are that lightning and lightning ignitions will increase in a 2 × CO_2 climate (Price and Rind 1994), and the fire season length in Canada on average will increase by 22% or 30 days in a 2 × CO_2 climate (Wotton and Flannigan 1993).

An altered fire regime may be more important than the direct effects of climate change in forcing or facilitating species distribution changes, migration, substitution, and extinction (Weber and Flannigan 1997). Fire may act as an agent of change to hasten the modification of the vegetation landscape. This would be true where fire activity is expected to increase in the next century and would accelerate changes in vegetation. For example, increased fire frequency at the grassland – aspen parkland – boreal forest transition in western Canada may hasten the conversion of boreal forest to aspen parkland and aspen parkland to grassland. In those areas of Canada that experience a reduced fire frequency, the transition of vegetation types may be retarded. For example, as the climate of the southern boreal forest in eastern Canada warms, species would be replaced by more thermophilous species from the mixedwood region (Great Lakes – St Law-

Fig. 5. FWI anomalies for the 2 × CO_2 simulation relative to 1 × CO_2 simulation. Green colors indicate lower FWIs in 2 × CO_2 simulation than in 1 × CO_2 simulation. Charcoal anomalies are shown as positive (red) indicating increased charcoal abundance at 6000 calendar years BP, negative (blue), or neutral (black). Squares show sites from the Université de Montréal data base; diamonds show sites from the literature. (*a*) RCM simulation for western Canada. (*b*) GCM simulation for eastern Canada.

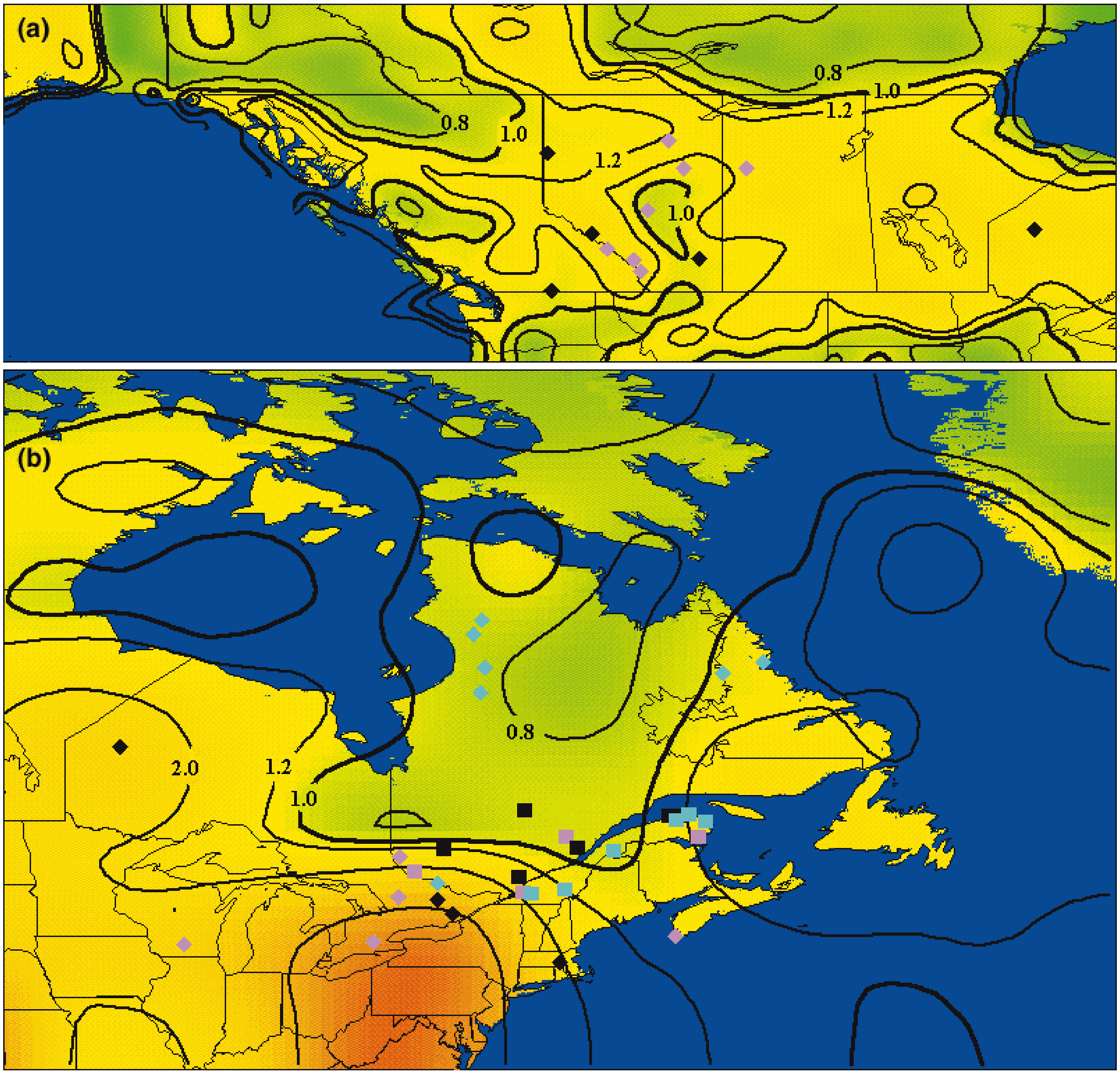
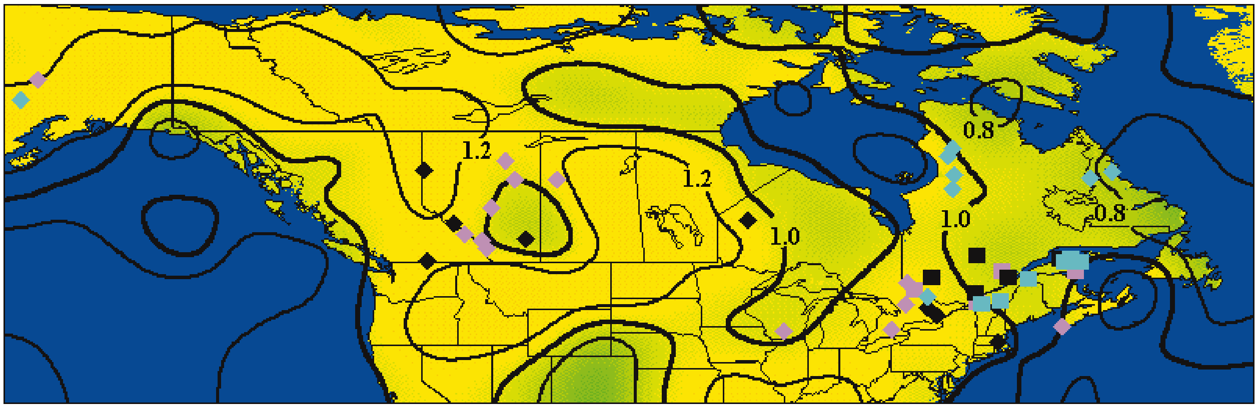


Fig. 6. FWI anomalies, 6000 calendar years BP simulation relative to present day simulation. Legend is as in Fig. 5.



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rence forest) to the south. This poleward migration of the southern species would be facilitated by the presence of disturbed areas such as burns that would allow establishment of these migrating competitors. In the absence of fire, late-successional species such as balsam fir (*Abies balsamea* (L.) Mill.) or eastern white cedar (*Thuja occidentalis* L.) could dominate the landscape and retard the poleward migration of the southern species. Of course, increases in other disturbances such as pests, diseases, and blowdown could offset any decreases in disturbed region due to decreases in area burned. Changes in climate and disturbance regimes may lead to assemblages of species that have never been encountered before (Martin 1993).

The broader implications of an intensified fire regime due to climate change on the structure and function of the central Canadian boreal forest include decreased carbon storage in soils and in biomass, reduction in old growth stands, and hence in late successional species, and increased forest fragmentation, which may in turn have significant consequences for biodiversity (Weber and Flannigan 1997). In some areas where the fire frequency is already high, such as in and near the aspen parkland of western Canada, further increases in fire frequency could lead to deforestation. In eastern Canada, our results suggest a decrease in fire activity, which may have opposite consequences. These might include increased soil carbon storage and increased abundance of old growth stands (where protected from logging and other disturbances), with consequent increases in late successional species such as balsam fir and eastern white cedar.

If the climate changes, as suggested by the Canadian GCM and RCM simulations, we would anticipate large spatial variations in the fire weather and, consequently, fire activity. Changes, both increases and decreases, in fire activity will impact the vegetation in a complicated fashion, accelerating vegetational change where fire activity increases and retarding vegetational change where fire activity decreases. The 6000 calendar years BP fire weather may be a reasonable analogue of a warmer climate to come; however, the results of the present study suggest an even more pronounced change in fire weather with greenhouse gas-induced warming. Feedbacks to global warming, through the reduction of soil and biomass carbon storage in the west, while they increase in the east, may result in a net emission of carbon to the atmosphere and in a significant net reduction of the terrestrial carbon pool.

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