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Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada

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Abstract. The synchrony of regional fire regime shifts across the Quebec boreal forest, eastern Canada, suggests that regional fire regimes are influenced by large-scale climate variability. The present study investigated the relationship of the forest-age distribution, reflecting the regional fire activity, to large-scale climate variations. The interdecadal variation in forest fire activity in the Waswanipi area, north-eastern Canada, was reconstructed over 1720–2000. Next, the 1880–2000 reconstructed fire activity was analysed using different proxies of the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). We estimated the global fire cycle around 132–153 years, with a major lengthening of the fire cycle from 99 years before 1940, to 282 years after 1940. Correlations between decadal fire activity and climate indices indicated a positive influence of the PDO. The positive influence of PDO on regional fire activity was also validated using *t*-tests between fire years and non-fire years between 1899 and 1996. Our results confirmed recent findings on the positive influence of the PDO on the fire activity over northern Quebec and the reinforcing role of the NAO in this relationship.

Additional keywords: bootstrapped Pearson correlations, fire history, Multidecadal Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation.

Introduction

Numerous studies have documented regional fire regimes throughout the boreal forest (Mann *et al.* 1995; Flannigan *et al.* 1998; Bridge 2001; Kasischke *et al.* 2002; Bergeron *et al.* 2004*a*, 2006; Parisien *et al.* 2004). These regional fire regimes result from the combination of local weather conditions, topography, forest fuels, and ignition agents (lightning and human activities). Given that volcanic activities, solar radiation and chemical composition of the atmosphere constantly influence the global climate dynamics (Bonan 2002), and that there is a strong linkage between climate and fire activity, variations in historical observations of fire activity due to changes in the climate are expected (Flannigan and Harrington 1988; Johnson 1992; Swetnam 1993). The fire regime integrates several variables describing the fire activity such as mean fire size, annual area burned, fire severity, fire frequency, and mean fire return interval (or fire cycle) (Weber and Flannigan 1997). Although regional fire regimes vary widely from one area to another, common temporal patterns in historical fire regime shifts have been reported. In the context of the past 300 years, many regional fire regimes of the Canadian boreal forest, as reconstructed from dendroecological analysis, experienced a decrease in fire frequency after 1850 (Bergeron and Archambault 1993; Larsen 1996) and a further decrease after 1940 (Bergeron *et al.* 2001, 2004*a*, 2004*b*, 2006). Conversely, analyses of fire statistics from provinces and Canadian agencies suggested that during the past three decades, area burned and fire frequency have increased throughout much of boreal Canada (Skinner *et al.* 1999, 2002; Stocks *et al.* 2003; Kasischke and Turetsky 2006). Whatever the temporal scale investigated, the synchrony of long-term temporal trends in fire activity across the Canadian territory suggests the persistence of a large-scale climatic control of fire activity (Bergeron *et al.* 2001, 2004*a*, 2006).

Large-scale climatic variations in the northern hemisphere are typically described by recurrent oceanic and atmospheric circulation patterns, some of which are originating from the Pacific and Atlantic Oceans and acting at interannual to interdecadal timescales. In Canada, several modes were held responsible for temporal and spatial variations in the countrywide weather conditions conducive to fire activity. These include the global long-term trend in ocean temperatures (Skinner *et al*. 2006), the El Niño–Southern Oscillation (ENSO) and related Pacific

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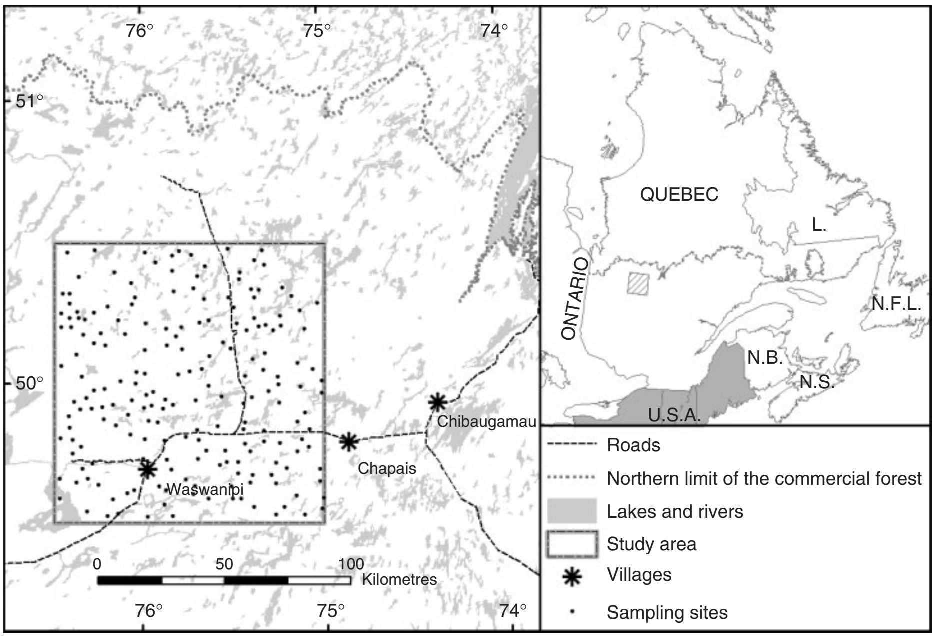

Fig. 1. Location of the study area relative to the northern limit of the commercial forest in Quebec.

Decadal Oscillation (PDO) (Girardin *et al*. 2006*a*; Macias Fauria and Johnson 2006; Skinner *et al.* 2006), the North Atlantic Oscillation (NAO) (Girardin *et al.* 2004), the Arctic Oscillation (AO) (Macias Fauria and Johnson 2006), and the Atlantic Multidecadal Oscillation (AMO) (Skinner *et al.* 2006). The influence of these modes on historical fire activity is heterogeneous across Canada and reflects the dynamics of the upper atmosphere longwave patterns (ridges and troughs) over oceans and lands (Bonsal *et al.* 1993; Bonsal and Lawford 1999; Skinner *et al.* 1999; Macias Fauria and Johnson 2006).

The present study investigated regional fire activity as measured by the decadal proportion of area burned and the frequency of fire years *v.* non-fire years in the Waswanipi area, northeastern Canada, and the long-term relationship with large-scale climate variations. First, we reconstructed the historical fire activity between 1720 and today over an area of 11 500 km^2 using dendroecological sampling along with forest inventories, aerial photographs, and ecoforest maps. The fire cycle in the Waswanipi area was estimated for different time periods to identify temporal trends in fire activity. Second, decadal fire departures obtained from the forest-age distribution were correlated with oceanic and atmospheric circulation indices and the regional fire activity was examined in light of climate index regime shifts at the interdecadal scale. Finally, fire years as documented by replicated fire scars and recent fire data were used to explore the influence of variations in oceanic and atmospheric circulation patterns. Determination of the link between fire and climate is an essential step toward understanding the dominant forcing of landscape-scale disturbance of boreal forests. Additionally, such analysis yields valuable tools for planning fire management activities and to improve forecasts of climate change impacts on the boreal forest (Duffy *et al.* 2005; Flannigan *et al.* 2005; Skinner *et al*. 2006). Several studies have documented the temporal correlation (or teleconnection) between climate and ocean circulation indices and fire activity as documented by fire scars and tree-ring chronologies (Swetnam and Betancourt 1990; Sibold and Veblen 2006). Recently, Brown (2006) documented the influence of global circulation indices on the tree recruitment dynamics in ponderosa pine forests. However, our study is the first to our knowledge linking oceanic and atmospheric circulation indices to stand-age distribution in boreal Canada.

Methods

Study area

The study area (49.5–50.5°N; 75–76.5°W; Fig. 1) lies in the north-central commercial forest of Quebec and covers more than 11 500 km^2 (Fig. 1). Situated in the western feather moss–black spruce bioclimatic domain (MRNQ 2000), the forest consists principally of black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) stands. Situated on the Canadian Precambrian Shield, the landscape has a high density of lakes and is dominated by morainal till deposits with scattered rocky outcrops covering 10–30% of the landscape (Centre for Land and Biological Resources Research 1996; Robitaille and Saucier 1998). The relief is relatively rugged, consisting of a 10–30% eastward slope that produces a well-drained landscape overall. The mean annual temperature is 0°C, with January and July being the coldest and the warmest months, respectively. The area receives an average 961 mm of total annual precipitation, about one-third of which falls as snow. The growing season is from April to October with 1235 growing degree-days above 5°C (data from Chapais weather station 1971–2000 climate normals, Environment Canada 2004).

Fire is the main disturbance of these forests. Using provincial fire data (1945–98), Lefort *et al.* (2004) identified a gradient in the fire activity (increasing northward) across the broader region containing our study area. They estimated a fire cycle between 200 and 500 years for the southern part and a fire cycle shorter than 200 years for the northern part, where the Waswanipi area lies. This relatively higher fire activity in our study area is corroborated by the high proportion of stands younger than 100 years, and is one of the criteria underlying the northern limit of the commercial forest in central Quebec (MRNQ 2000).

Colonisation in the Waswanipi area began after 1940, and it primarily hinged on mining and later on forest management, but no agricultural activities took place in the study area. Cree populations live around the Waswanipi Lake in the south-western corner of the study area (Fig. 1) and on the shores of the Waswanipi River; a small fraction is scattered across the study area. The modern Waswanipi community was established in the 1970s. The nearby Chapais village developed in the 1950s to carry out mining activities. Thus, human influence had historically little effect on the natural fire regime when compared with the adjacent Abitibi and Lac-Saint-Jean areas where colonisation started earlier, and converted forest territories to agricultural lands using slash-and-burn techniques (Lefort *et al.* 2004). Forest fires have been controlled over the study area since 1958 (Langlois 1994).

Field sampling

The fire history (1720–2000) was reconstructed using forest inventories, aerial photographs, ecoforest maps, and field sampling to determine the cumulative time-since-last-fire (TSF) distribution for the study area (Johnson and Gutsell 1994). Two hundred sampling points were randomly located over the terrestrial area of the study area (when excluding rivers and lakes) using the Generate Randomly-Distributed Points script in ArcView GIS 3.2 (ArcView GIS 1999). Of these, 84 sampling points were located inside the burned areas compiled in the provincial fire database (Ministère des Ressources naturelles et de la Faune) and were consequently dated using the most recent inventoried fire. Of the remaining 116 points, 67 were field-sampled during the summers of 2002 and 2003. At each sampling point, 10 dominant trees of typically pioneer species (jack pine, or if not available, black spruce) were sampled by taking a cross section or two opposite increment cores from the trunk base ~30 cm above the ground. Forty-nine points, located outside the documented burned areas, were considered inaccessible (≥5 km from road access). These points were situated mostly in the northern part of the study area where the road network is sparse. For 15 of these points, permanent plots of the Ministère des Ressources naturelles du Québec were sufficiently close (<2 km) to provide a non-censored estimate of TSF from the oldest tree documented in each plot. For the 34 remaining points, stand ages from the ecoforest maps were used as a censored minimum TSF estimate, with 120 years being the maximum age considered. As sampling was based on a random spatial distribution of sampling points, we assumed that each sampling point is representative of the same proportion of the study area (0.5%) and that the TSF distribution derived from the 200 random sampling points approximated the complete TSF distribution for the entire study area.

Dendrochronological analysis

Sampled cores ($n = 792$), and cross sections ($n = 430$) were dried, sanded, and aged by counting tree rings under a dissecting microscope, following standard procedures proposed by Stokes and Smiley (1968), Yamaguchi (1991) and Fritts (2001). Pith locators were used to estimate the number of missing rings to the pith on incomplete cores (Phipps 1985). Diagnostic rings allowed visual crossdating to confirm sample age. Among the sampled cross sections, 46 fire-scarred trees allowed us to accurately estimate the fire date for 31 different sampling sites. Replicated fire scars (recorded on ≥2 trees, Brown 2006) were used to develop the regional fire-year chronology. Replicated fire scars were found in distant sampling points and were generally confirmed by cohort age originating from fire that fire-scarred trees survived. All fires reported are thus stand-replacing fires. To crossdate snags and living trees, we measured tree-ring width using a Velmex system coupled with the MEASUREJ2X 3.1 package for Windows (VoorTech Consulting 2001). Cross-dating of all samples was validated with COFECHA (Holmes 1999).

Fire history

The frequency of sampled sites was computed per decade to identify major fire decades. The global TSF distribution was computed to evaluate whether the fire frequency was constant over space and time (Johnson and Gutsell 1994). Assuming that the hazard of burning is independent of stand age, the TSF distributions should follow the negative exponential model and should appear as a straight line on a semilog scale (Van Wagner 1978; Johnson and Gutsell 1994). Fire cycles were computed using the LIFEREG procedure in SAS 9.1 (SAS Institute Inc. 2000), which is a standard maximum-likelihood procedure for analysing survival data while taking into account censored data (Allison 1995). Our TSF estimates (survivorship) were considered censored when no accurate date could be attributed to the fire; in these cases, we used a minimum TSF estimate, i.e. the age of the oldest individual when no tree cohort could be clearly identified (Bergeron *et al.* 2004*b*). Thus, 31.5% of the data were censored. Finally, the LIFEREG procedure provides a Lagrange Multiplier Statistic (P_{LMS}) based on a χ^2 test to evaluate whether the scale parameter of the exponential model was significantly different from one, thereby allowing us to determine if the data distribution followed a negative exponential model ($P_{LMS} > 0.05$) or not ($P_{LMS} < 0.05$). If this is the case, then the corresponding mean forest age provides a good estimate of the fire cycle.

TSF distributions were also computed for different parts of the study area and for different time periods to determine if the variations observed in the global fire activity (slope breaks on the TSF distribution) were related to spatial or temporal variations in the fire activity. Spatial patterns were investigated by a spatial sub-sampling. The dataset was divided into four equivalent sectors containing ~50 sampling points each (north-eastern, north-western, south-eastern and south-western sectors). Different periods were delimited according to documented period of changes in the fire activity in other parts of the boreal forest (end of the Little Ice Age c.1850, and 1940) to verify if the Waswanipi area has similar temporal variations or not. The LIFEREG procedure was used to test these variations as this procedure allowed the evaluation of the effect of class covariables (sectors or time periods) using a χ^2 test, while taking into account censored data.

Reed (2006) underlined the limits of estimating the fire cycle using TSF distributions. We however chose to estimate this fire regime parameter to allow comparisons with other fire history studies using the same standard approach, and to provide a parameter useable for disturbance-based forest management. Also, the TSF distribution approach allowed us to take into account minimum TSF date when no accurate fire date could have been attributed to the sampling site. The fire cycle was also estimated using the LIFETEST procedure to estimate the hazard function (burn rate) associated with survival estimates. This allowed us to provide an estimate of the fire cycle (1/burn rate) taking into account the censored data without constraining the survival function to follow the exponential negative distribution (which is required when using the LIFEREG procedure).

Climate indices

In the present study, we used several climate indices to analyse the influence of large-scale climate variability on the Waswanipi fire history. The indices considered were the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO).

The PDO corresponds to a long-lived El Niño-like pattern acting as a decadal mode of North Pacific sea surface temperature (SST) variability (Mantua *et al.* 1997; Zhang *et al.* 1997). Pacific SST anomalies have been linked with atmospheric circulation patterns consisting in ridging over western North America during warm coastal SSTs (Bonsal *et al.* 1993; Bonsal and Lawford 1999). The blocking highs typically persist for several days to several weeks and influence the fire weather conditions and the area burned across large Canadian regions (with greater area burned occurring downstream from the ridges; Johnson and Wowchuk 1993; Skinner *et al.* 1999, 2002, 2006; Girardin *et al*. 2006*a*). The PDO index of Mantua *et al*. (1997) is an instrumental series covering the period 1900 to the present (available at http://jisao.washington.edu/pdo, accessed 2 October 2007) and is obtained from the leading principal component of North Pacific monthly SST poleward of 20°N. Smith and Reynolds (2004) extended this index back to 1854 using the most recently available SST data from the International Comprehensive Ocean–Atmosphere Data Sets (available at ftp://ftp.ncdc.noaa.gov/pub/data/ersst-v2/, accessed 2 October 2007). The remaining three PDO datasets were paleoclimatological reconstructions derived from proxy data. The annual PDO reconstruction of D'Arrigo *et al.* (2001), extending from 1700 to 1979, is based on tree-ring chronologies from coastal Alaska and Pacific North-west regions and accounts for up to 53% of the instrumental PDO variance. The annual PDO reconstruction of Biondi *et al*. (2001) is based on tree-ring data from California and extends from 1661 to 1983. The annual Shen *et al.* (2006) record is based on proxy summer rainfall of eastern China and covers the 1470–2004 period.

The NAO is based on the difference of normalised sea-level pressures (SLP) between the subtropical (Azores, Portugal) high and the subpolar (Stykkisholmur, Iceland) low pressure systems of the North Atlantic Ocean (Hurrell 1995). The strongest and most climatologically effective expression of the NAO occurs during winter when the north–south pressure gradient is particularly stable between its two centres of action. Strong positive NAO phases are usually associated with above-normal temperatures in the north-eastern United States and across northern Europe, and below-normal temperatures in Greenland and in Mediterranean regions (Visbeck *et al.* 2001). Instrumental monthly NAO series from Jones *et al.* (1997) and monthly NAO reconstructions from Luterbacher *et al*. (1999) were used. The Luterbacher monthly NAO indices, covering the period 1659–2001, are based on early European instrumental SLP, temperature and precipitation. These two monthly databases were used to calculate seasonal NAO indices (December–January–February, March–April–May, June–July–August, and September–October–November). We also used the NAO series from Glueck and Stockton (2001), which is a tree-ring-based winter reconstruction (1429–1983) calibrated against the Lisbon–Iceland NAO (from Hurrell 1995).

The PDO and the NAO reconstructions were extended to 1999 using the instrumental series (from Mantua *et al.* 1997 for the PDO, and from Jones *et al.* 1997 for the NAO) after adjusting the variance to that of the reconstructions.

The AMO corresponds to a basin-wide low-frequency (65–80 years) component of SST variability (Kerr 2000). Enfield *et al*. (2001) have documented reduced summer rainfall and river flow regimes over the United States during warm AMO phases, while Skinner *et al.* (2006) have documented a negative influence of warm AMO phase on fire weather conditions across northern Ontario and Quebec. We used the 1567–1990 annual North Atlantic sea surface temperature anomaly (SSTA) reconstruction of Gray *et al*. (2004). This annual reconstruction is based on the leading principal component of twelve tree-ring chronologies from south-eastern North America, southern Europe, Scandinavia, western North Africa and the Middle East. The corresponding AMO index is a 10-year running mean of the SSTA reconstruction. For the purpose of the present study, we used the AMO variable for the decadal correlation with TSF distribution and the SSTA reconstruction for the analysis of fire years *v*. non-fire years to avoid the autocorrelation bias associated with the 10-year smoothing.

Decadal fire–climate relationship

We were interested in characterising the departures from the average area burned per decade. Because recent fires tend to eliminate information relevant to past fires, an exponential curve (as previously computed using the LIFEREG procedure) was fit to the stand-age distribution using survival analysis. The mean forest age for the whole period was estimated at 153 years with 95% confidence intervals (128; 183). Decadal departures from the average area burned were calculated by subtracting the theoretical exponential curve from the stand-age distribution.

Next, annual values of atmospheric and oceanic circulation indices were averaged by decades and correlated with decadal fire departures. We restricted our analyses to the 1880–1990 time period as the previous fire decades had a high proportion of censored data. Pearson correlations between decadal fire departures and decadal averages of the climate indices were computed using the PEARSONT program (Mudelsee 2003). This program uses a non-parametric stationary bootstrap to calculate the 95% confidence interval associated with the Pearson correlation coefficient and resamples blocks of data pairs to account for the presence of serial correlation in the time series. When the confidence interval contains zero, the hypothesis of 'no correlation' cannot be rejected at the 95% level. The normality of the data was verified before the correlation analyses using the Shapiro–Wilk normality test (Zar 1999). All variables satisfied the normality assumption ($P > 0.2$), except the decadal averages of the PDO series of Shen *et al.* (2006), the winter NAO of Glueck and Stockton (2001) and the winter NAO computed using the monthly NAO reconstruction from Luterbacher *et al.* (1999). For the two first variables, correlations were computed on ranked data as no transformation made it possible to reach normality. For the winter NAO from Luterbacher *et al.* (1999), an exponential transformation was used to reach normality ($P = 0.65$ after transformation). Scatterplots of the decadal fire departures and decadal climate indices (not shown) confirmed that relationships were linear and that Pearson correlations were an appropriate method for analysing them.

Climate influence on the occurrence of fire years

Fire and climate relationships at the annual resolution were investigated by computing differences in mean climate indices (PDO, NAO, AMO) for fire years and non-fire years. Two-sample mean tests (Zar 1999) were computed using SYSTAT 11 (Systat Software Inc. 2004) on unlagged climate indices as well as on climate indices lagged by 1 and 2 years previous to the reported fire year. Critical *t*-values were adjusted to account for autocorrelation in data. All climate indices satisfied the normality assumption (according to the Shapiro–Wilk normality test, Zar 1999). Twelve fire years documented by replicated fire scars (1899, 1907, 1915, 1916, 1925, 1934, 1940, 1966, 1982, 1984, 1985, and 1994) were used to discriminate the fire years from the non-fire years. Also, three major fire years (1983, 1986 and 1996) that are not reported by our fire scar sampling and that accounted for more than 5% of the total area burned during the 1905–98 period were added to the regional fire year chronology.

Regime shift analyses were computed on different responsive PDO and NAO indices using the program developed by Rodionov (2006). This analysis is based on a sequential *t*-test to detect regime shifts, where the time scale to be detected is controlled primarily by the cut-off length. Both cut-off length and probability level affect the statistically significant difference between regimes, and hence the magnitude of the shifts to be detected (Rodionov and Overland 2005). These analyses aimed to verify the synchrony of regime shifts from positive to negative phase and vice versa, with decadal fire departures and with the frequency of reported fire years. Results were highly sensitive to the cut-off length chosen, primarily in relation to the amplitude of interannual variations of the climate index considered. We used a cut-off length of 10 years because we were primarily interested in the decadal influence of PDO on the TSF distribution, which also was gathered in 10-year classes.

Finally, stepwise multiple regression analyses (SYSTAT 11, Systat Software Inc. 2004) were computed to prospect potential combination effects of teleconnections from the Atlantic and the Pacific oceans.

Results

The Waswanipi fire history

The early 20th century (1900–40) was characterised by high fire activity, with 43.5% of the area burned recorded from 1720–2000 (Fig. 2). Three time periods of relatively high fire activity were observed: 1850–60, 1910–40, and 1980–90 (Fig. 2). The 1870 peak of censored data (Fig. 2) corresponded to inaccessible sampling points that were documented by the oldest age-class reported on ecoforest maps (120 years). The 1720–2000 mean forest age was estimated to be ~153 years and the survival curve suggested changes in the fire frequency through time or space (Table 1; Fig. 3*a*).

The mean forest age varied according to the different sectors ($P_{\chi^2} = 0.0121$, Table 1), but was neither due to a latitudinal (N *v.* S) nor to a longitudinal (E *v.* W) effect ($P_{\chi^2} > 0.05$, Table 1). It was instead related to the combination of latitude and longitude as only the north-eastern sector had the shorter mean

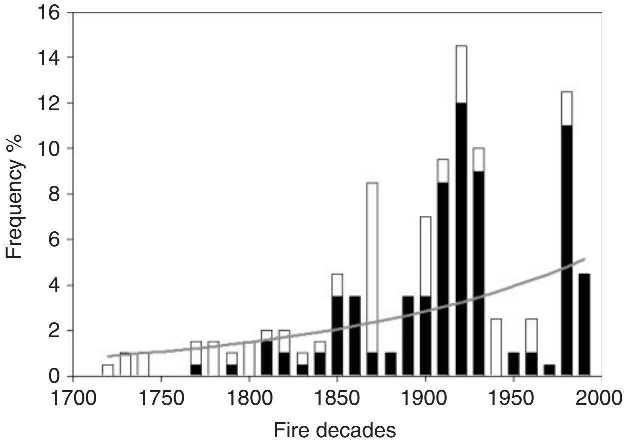

Fig. 2. Forest age distribution (% of sampling points) per decade for the entire study area; open bars indicate censored data (minimum time-since-fire) and black bars indicate non-censored data (accurate estimate of the last fire date). The solid grey line represents the theoretical stand-age distribution expected under a constant fire frequency given by the negative exponential model (corresponding to a 153-year fire cycle, see Table 1).

Table 1. Fire cycle estimates (years) for the entire dataset and for spatial sub-sampling

The associated 95% confidence interval is indicated in parentheses. The dataset ($n = 200$) was sub-sampled in four sectors (north-east, north-west, south-east, and south-west) with ~50 sampling points each; P_{LMS}, probability associated with the Lagrange Multiplier Statistics; when $P_{LMS} > 0.05$, the stand-age distribution follows the negative exponential model and the mean forest age provides a good estimate of the fire cycle; P_{χ^2}, χ^2 probability for testing the effect of the factor, significant when <0.05

Data	Fire cycle estimate	P_{LMS}	Factor	P_{χ^2}
All data	153 (128–183)	0.0390		
NE	85 (59–122)	0.9930	Sectors	0.0121
NW	188 (126–310)	0.1644		
SE	166 (120–230)	<0.0001		
SW	170 (124–234)	<0.0001		
NE + NW	129 (97–171)	0.1801	N *v.* S	0.1553
SE + SW	168 (134–211)	<0.0001		
NE + SE	130 (102–166)	0.0430	E *v.* W	0.0748
NW + SW	179 (138–232)	0.2674		
<1850	164 (85–315)	0.3526	Periods	0.3258
1850–1940	99 (80–122)	0.3449		
>1940	283 (204–392)	0.0305		

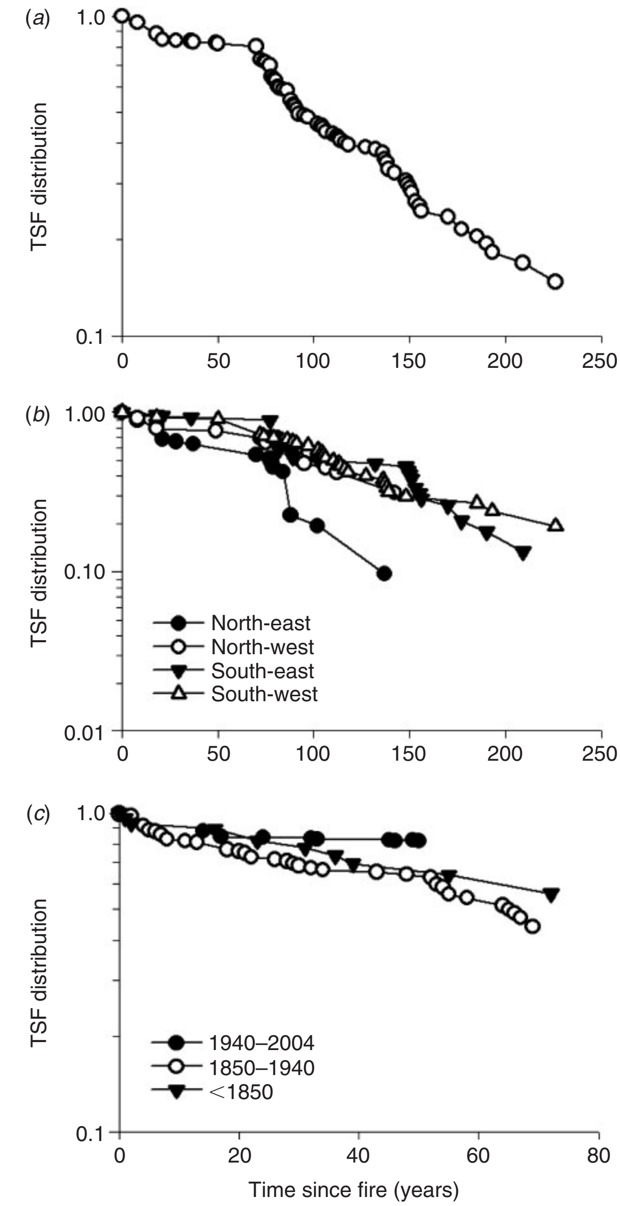

Fig. 3. (*a*) Time-since-fire (TSF) distributions for the entire study area; (*b*) for sectors of the study area (north-east, north-west, south-east, south-west); and (*c*) for time periods (<1850, 1850–1940, and 1940–2004). See Table 1 for associated statistics.

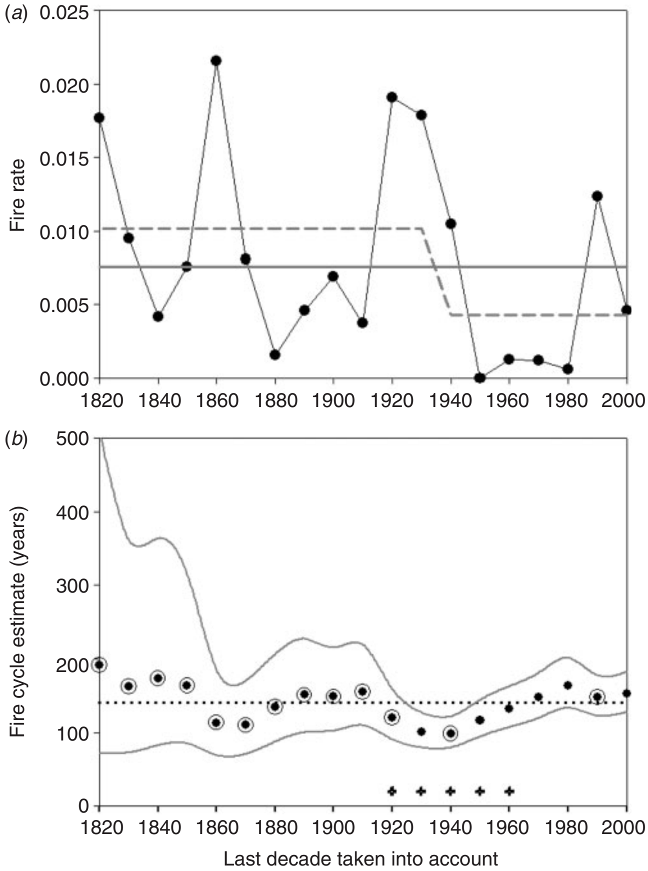

Fig. 4. (*a*) 1820–2000 variations in the decadal burn rate associated with the survival analysis of the time-since-fire data. The solid grey line indicates the 1820–2000 mean burn rate (1/mean fire cycle) corresponding to a 132-year fire cycle. The dashed line indicates the mean burn rate before and after 1940, corresponding to a 98-year and a 232-year fire cycle, respectively. (*b*) Fire cycle estimated through time. Computations were done sequentially by eliminating the most recent decade at each run. Upper and lower limits of the 95% confidence interval limits of the fire cycle estimates are indicated by the grey curves. Crosses indicate significant changes in the fire frequency before and after the corresponding decade using the χ^2 test at $P < 0.05$. Circled dots indicate fire estimates associated with distribution well fitted ($P_{LMS} > 0.05$) to the negative exponential model. The dotted line indicates the mean fire cycle for the entire time period investigated (141 years).

forest age (85 years) when compared with the three others (170 years, Fig. 3*b*; Table 1). The TSF distributions for the sectors displayed mixed distributions with synchronous changes in the fire frequency around 1940 and 1840 (Fig. 3*b*). The temporal changes of fire frequency for each sector were not tested because of insufficient sample size.

TSF distributions corresponded to relatively constant fire activity for the <1850 and the 1850–1930 periods. The 1940–2000 period had a weaker fit to the exponential model, likely due to the 1980–90 higher fire activity (Fig. 3*c*; Table 1). The mean forest age was estimated to be ~164 years before 1850, 99 years for the 1850–1940 period, and 283 years for the 1940–2000 period. Although striking, differences in the mean forest age over these intervals were not significant (Table 1).

An examination of the temporal evolution of the decadal burn rate through time (1820–2000) indicated a mean fire cycle of 132 years with a 98-year fire cycle before 1940 and a 232-year fire cycle after 1940 (Fig. 4*a*). Moreover, the sequential computation of the fire cycle estimates during the 1820–2000 period confirmed that fire cycle varied significantly before and after the decades 1920, 1930, 1940, 1950 and 1960 (Fig. 4*b*). The fire cycle oscillated around 143 years for the last 180 years, with a constant increase from 1940 to 1980 (Fig. 4*b*). Hence, the temporal change in the regional fire activity around 1940 echoed synchronous change in neighbouring forested areas documented in the literature (Bergeron *et al.* 2001, 2004*a*, 2004*b*,

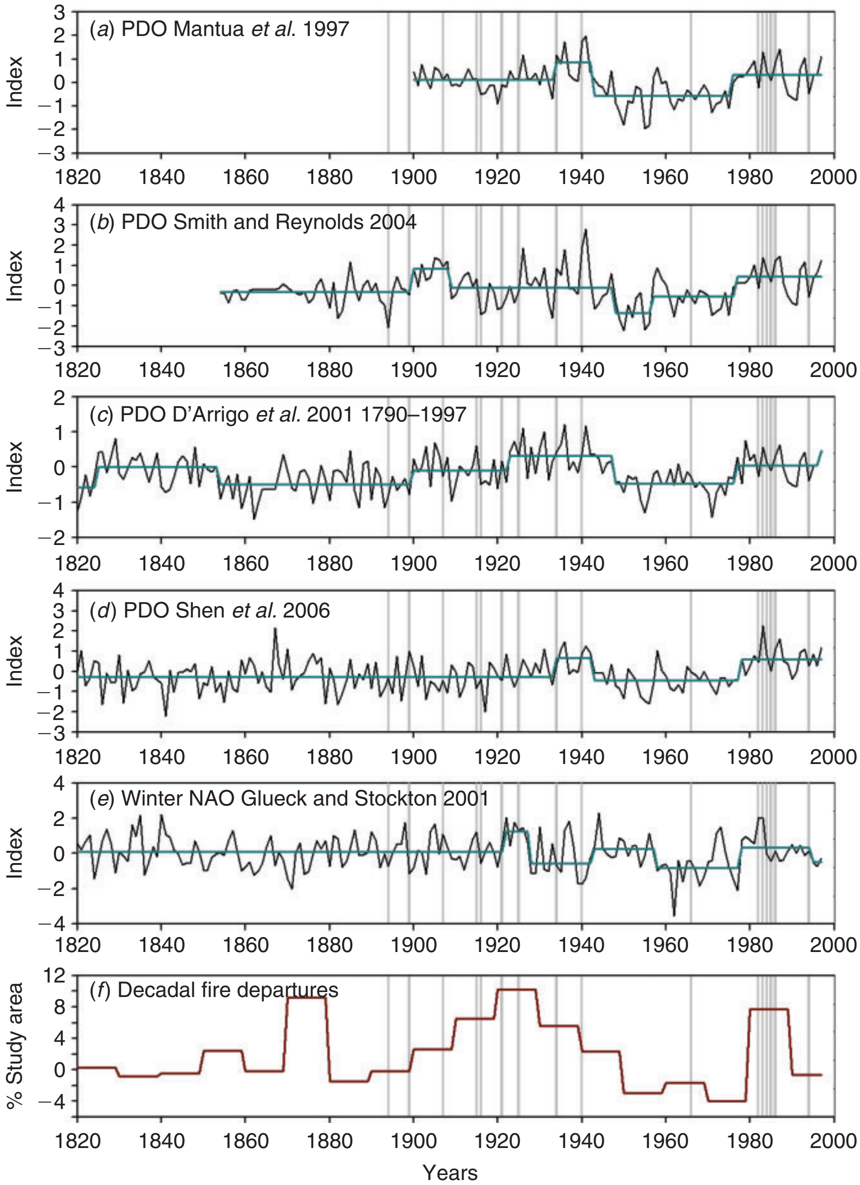

Fig. 5. Climate indices (thin line) and decadal fire departures. Vertical grey bars indicate the fire years reported by replicated fire scars and major recent fire years. Thick line on (*a*), (*b*), (*c*), (*d*), and (*e*) is regime shift detection of the corresponding climate index with correction for autocorrelation (AR(1)). Regime shift detection makes it possible to verify that changes in the mean from one period to another are not just a manifestation of a red noise process (probability $\sigma = 0.10$, cut-off length = 10 years; parameters for AR(1) were estimated using the IP4 method; see Rodionov 2006). (*f*) Decadal fire departures as calculated by subtracting the theoretical (negative exponential) decadal time-since-fire (TSF) distribution to the sampled TSF distribution presented on Fig. 2. See Table 3 for *t*-test results between fire and non-fire years.

2006), suggesting a large-scale control of multidecadal trends in regional fire activity. Below, the reconstructed Waswanipi fire activity is analysed with respect to large-scale climate variability.

Fire–climate relationship

The visual inspection of the PDO series (Fig. 5*a*–*d*) and of the decadal fire departures (Fig. 5*f*) suggested a synchrony of phases of higher PDO (around 1860, before 1947, and after 1977) and periods of high fire activity in the Waswanipi area (1900–40 and 1980–90 fire decades). Conversely, a lower PDO phase is synchronous to the 1950–70 low fire decades (Fig. 5*f*). The relationship is not as clear before 1880, perhaps because of the high amount of censored data in our fire departures before that period. All PDO time series tested were well correlated with

Table 2. 1880–1990 correlation analyses between decadal fire departures and decadal values of different climate indices

$n = 12$, excepted for the Pacific Decadal Oscillation (PDO) series from Mantua *et al.* (1997), and the Atlantic Multidecadal Oscillations (AMO) series from Gray *et al.* (2004). Correlations were calculated using PEARSONT (Mudelsee 2003), which calculated Pearson coefficient (r) on detrended time series and the associated 95% confidence interval (95% CI) using bootstrap. Pearson coefficients are significant at $P = 0.05$ when the associated 95% CI does not contain the 0 value. Note that Pearson correlation for PDO of Shen *et al.* (2006) and winter North Atlantic Oscillation (NAO) from Glueck and Stockton (2001) were calculated on ranked data

Climate indices	r	95% CI
PDO instrumental (Mantua *et al.* 1997)	0.75	0.30; 0.92
PDO (Smith and Reynolds 2004)	0.58	0.02; 0.84
PDO 1790 (D'Arrigo *et al.* 2001)	0.79	0.55; 0.90
PDO 1700 (D'Arrigo *et al.* 2001)	0.65	0.20; 0.83
PDO (Biondi *et al.* 2001)	0.69	0.33; 0.87
PDO (Shen *et al.* 2006)	0.61	0.08; 0.87
Winter NAO instrumental (Jones *et al.* 1997)	0.68	0.25; 0.91
Winter NAO (Luterbacher *et al.* 1999)	0.49	0.03; 0.82
Winter NAO (Glueck and Stockton 2001)	0.80	0.48; 0.94
AMO (Gray *et al.* 2004)	−0.07	−0.47; 0.65

Table 3. t-values for different climate indices between reported fire years ($n = 15$) and non-fire years between 1899 and 1996

Significant t-values ($P < 0.10$) are indicated in bold. Significance of the t-values was adjusted by calculating the effective sample size (n') to account for the autocorrelation (AR(1) estimated using the IP4 method described in Rodionov 2006). Fire years were documented by replicated fire scars ($n = 12$) and provincial fire data ($n = 3$). Climate indices were tested without time lag (same year as the reported fire year), and one and two years before the reported fire year. NAO, North Atlantic Oscillation; PDO, Pacific Decadal Oscillation

	PDO indices[A]					NAO indices	
	Instrumental Mantua	Smith Reynolds	D'Arrigo 1790	D'Arrigo 1700	Shen	Instrumental Jones	Glueck Stockton
AR(1)	0.37	0.32	0.04	0.00	0.26	0.07	0.43
n'	45	50	90	98	73	85	37
0	**−1.97**	−1.61	−0.73	−0.42	**−2.40**	0.00	0.63
1	−1.63	**−3.48**	**−1.96**	**−1.68**	−1.49	**−1.22**	**−2.00**
2	**−1.83**	**−1.87**	−0.92	−1.04	**−1.68**	**−1.71**	**−1.84**

[A]The Biondi *et al.* (2001) PDO index was not tested owing to a high AR(1) parameter.

the Waswanipi fire departures ($r > 0.58$, Table 2) for the 1880–1990 period. The best predictors ($r > 0.75$) of the decadal fire departures were the instrumental PDO series of Mantua *et al.* (1997), and the 1790–1997 PDO reconstructions of D'Arrigo *et al.* (2001) (Table 2). Significant positive correlation was also found with the winter NAO series of Luterbacher *et al.* (1999) and of Jones *et al.* (1997). Stepwise multiple regression (using an in-and-out probability of 0.1) suggested a combination effect of the PDO and the winter NAO according the following regression models:

$$y = 0.5655 + 8.5134PDO + 4.1304NAO_j \quad (1)$$

$$y = -3.2752 + 8.9911PDO + 5.5710EXP(NAO_{gs}) \quad (2)$$

where y are decadal fire departures, PDO is the 1790–1997 PDO reconstruction of D'Arrigo *et al.* (2001) (that alone explained ~58% of the variance in the 1880–1990 decadal fire departures, $P = 0.004$, not shown), NAO_j is the winter NAO series calculated using the Jones *et al.* (1997) dataset, and NAO_{gs} is the winter NAO reconstruction of Glueck and Stockton (2001). These models explained respectively ~71% (adjusted $R^2 = 0.64$, $P = 0.004$, NAO regression coefficient with $t = 2.0085$ and $P = 0.0755$), and 74% (adjusted $R^2 = 0.68$, $P = 0.002$, NAO regression coefficient with $t = 2.3459$ and $P = 0.0436$). The winter NAO index from Glueck and Stockton (2001) did not fully satisfy normality after an exponential transformation according to a Shapiro–Wilk normality test ($P = 0.17$). This index was used to confirm the results shown by Eqn 1. Both regression models suggested a reinforcing influence of the winter NAO on the positive relationship between PDO and the decadal fire departures.

As indicated by the correlation analysis on decadal averages of proxy climate indices, the distribution of fire years also followed well the long-term variations of the PDO. The *t*-tests indicated higher PDO values during reported fire years and for the 2 years previous to the reported fire years, and higher NAO values for one and two years previous to the reported fire year (Table 3). Regime shift analysis confirmed coherent regime shift of the PDO indices around 1950 (from a positive to a negative phase) and around 1977 (from a negative to a positive phase). Only one fire year was reported for the negative PDO phase (1947–66) whereas the other fire years were reported during higher PDO phases. The 1790–1997 PDO index of D'Arrigo *et al.* (2001) (Fig. 5*c*) also displayed a higher regime before 1850, whereas no regime shift was detected on the other PDO indices before 1900 (PDO index of Smith and Reynolds 2004; Fig. 5*b*) or 1930 (PDO index of Shen *et al.* 2006; Fig. 5*d*). The different NAO indices gave no coherent regime shifts, so only the winter NAO reconstruction of Glueck and Stockton (2001) was used to compare visually the regime shifts detected with the decadal fire departures. The winter NAO had a higher regime around 1930 and changed from a negative to a positive phase around 1977 (Fig. 5*e*).

Discussion

The Waswanipi fire history

Conversely to other studies located south of our study area (Bergeron *et al.* 2001, 2004*b*), we did not detect any change at the end of the Little Ice Age c.1850. The only significant change in the Waswanipi fire activity occurred around ~1940. The fire cycle has lengthened from 99 years (1850–1940) to 283 years (1940–2000). This lengthening at ~1940 has been also reported from central to western Quebec (Bergeron *et al.* 2001) and in south-western Quebec (Grenier *et al.* 2005; Drever *et al.* 2006). This may reflect the reported decrease in the incidence of extreme fire years at the scale of the Boreal Shield (Girardin *et al.* 2006*b*). In Quebec, the early 20th century is usually associated with the onset of European settlement and the use of slash-and-burn techniques to clear forested lands for agriculture (Bergeron *et al.* 2001; Lefort *et al*. 2003; Grenier *et al.* 2005). As the Waswanipi area was settled later (after 1940) than the neighbouring regions of Abitibi and Lac-Saint-Jean (Lefort *et al.* 2004), and given that no agricultural activities took place in this area, the higher fire activity of the early 20th century cannot be explained by settlement and was mainly prompted by climate. Girardin *et al.* (2006*b*) suggested this climate effect prevailed over the Boreal Shield. Their reconstructions of annual area burned using tree-ring data suggested that greater fire activity occurred in the first half of the 20th century than after 1950.

It should however be noted that the decades 1980 and 1990 were also marked by a high fire activity in the Waswanipi area. These decades were also reported as being major fire decades in Eastern Abitibi and in Central Quebec (Bergeron *et al.* 2001), two locations close to the Waswanipi area. These higher fire decades were also reported in other parts of the Canadian boreal forest (Skinner *et al.* 1999, 2002; Gillett *et al.* 2004; Macias Fauria and Johnson 2006). Moreover, the years 2002 and 2005, two major fire years in the Waswanipi area, are not included in our fire cycle estimates. Also, the fire cycle estimates computed using the survival analyses with the negative exponential model are very sensitive to the distribution of high fire years: although we presented a 283-year fire cycle estimate for the 1940–2000 period, the fire cycle estimate for the 1920–2000 period is ~173 years (not shown). This suggests that numerical estimates of fire cycle varied greatly depending on the inclusion or the exclusion of the 1920 and 1930 high fire decades. Given the sensitivity of the fire year distribution and the fact that we did not include the recent high fire years in our analyses, our estimates probably overestimate the recent fire cycle. However, the global 1820–2000 mean fire cycle estimates (132 and 143 years) are close to the 153-year mean forest age calculated for the 1720–2000 period using the negative exponential model.

Climate influence on recent fire activity

Our results reported a positive influence of the PDO on the fire activity in the Waswanipi area at least for the 1880–1990 period. Skinner *et al.* (2006) also reported that warm winter El Niño–PDO events lead to fire-conducive droughts in northern Ontario and Quebec. However, large spatial variability was found and some regions, such as the Great Lakes regions of southern Ontario and central Quebec, are showing an inverse relationship to these Pacific processes. The analyses by Skinner *et al.* (2006) of the relationship between fire-weather conditions across Canada during the 1953–99 period and the Pacific SSTs could reconcile our results with those of Girardin *et al.* (2006*a*), who suggested a negative influence of PDO on fire-conducive drought conditions over eastern boreal Canada (i.e. cool PDO phase associated with greater fire activity) as our study area is situated north of that of Girardin *et al.* (2006*a*). Finally, Macias Fauria and Johnson (2006) also reported a positive influence of the PDO variability on interdecadal variation of area burned in several areas east of the Canadian Rocky Mountains, including our study area. The positive influence of PDO on decadal fire departures could have prevailed earlier as suggested by the regime shift analysis computed on the D'Arrigo *et al.* (2001) PDO index. This index displayed a stronger PDO before 1860, whereas the positive 1870 decadal fire departure is related to a high proportion of censored data (suggesting that the fire activity of previous decades was more important than our data showed, see Fig. 2). The lag observed between the 1870 decadal fire departure and the higher PDO regime highlights the declining reliability of TSF dendrochronological estimates when going further back in the past. We may assume that the higher PDO regime prevailing before 1860 could also have triggered higher fire activity for periods previous to 1870.

Dendroclimatic analyses by Hofgaard *et al.* (1999) suggested that the south–north climate gradient of western Quebec between 48 and 50°N was disrupted around 1875. The authors attributed this disruption to the northern displacement of the influence of dry cold Arctic air masses from 48°N to higher latitudes. Their findings were recently corroborated by a spatio-temporal analysis of 90 multicentury chronologies distributed across the eastern half of Canada (Girardin *et al.* 2006*a*). Although fire activity in south-western Quebec decreased since ~1850 with the increasing incursion of humid air masses from the subtropical North Atlantic (Bergeron and Archambault 1993; Hofgaard *et al*. 1999; Girardin *et al.* 2006*b*), our study area (located north of 49°N) could still be under the influence of the dry cold arctic air masses. This climate disruption would explain why we did not detect any change in the fire frequency around 1850, conversely to other study areas situated south of ours (Bergeron *et al.* 2006). Similar dipolar structures have been reported in the USA. Negative PDO phases were found to be associated with periods of high fire activity in Colorado (Sibold and Veblen 2006), whereas forest fires in Washington tended to occur during positive PDO phases (Hessl *et al.* 2004). The fire–climate relationship is however not linear. Periods of relatively high and low fire activity at the regional scale would instead be controlled by the combination of different climate indices. Brown (2006), Sibold and Veblen (2006), Collins *et al.* (2006), Trouet *et al.* (2006) and Kitzberger *et al.* (2007) reported combination effects of teleconnections that modulate regional fire activity. Our stepwise regression models did identify a combination effect of PDO (positive) and NAO (positive) on the 1880–2000 decadal fire departures in our study area. Macias Fauria and Johnson (2006) also reported that the AO would modulate the interannual variability of the PDO–area burned relationship. Their results suggested that the strong positive AO phase would have contributed to further influence positively the increase in the area burned noted since 1977. As the NAO and the AO are highly correlated (Ambaum *et al.* 2001), the agreement of our results with those of Macias Fauria and Johnson (2006) is not surprising. Our results obtained using regional dendrochronological data confirmed the results of Skinner *et al.* (2006) and Macias Fauria and Johnson (2006) that were obtained using the 1959–99 Large Fire Database (Stocks *et al.* 2003).

Correlations and *t*-tests suggested a positive influence of the PDO on the fire activity in the Waswanipi area without providing any insight on the physical mechanisms underlying such a relationship. Antecedent works linking atmospheric and oceanic circulation indices to fire activity of different parts of North America (Bonsal *et al*. 1993; Bonsal and Lawford 1999; Skinner *et al*. 1999, 2002; Duffy *et al.* 2005) suggested that the statistical relation between monthly weather and teleconnections would provide a plausible mechanism underlying large-scale climate influence on fire activity. Further analyses investigating this regional fire–climate relationship at the interannual scale are needed to help us better understand how large-scale climate variability could influence long-term trends in regional fire activity.

Synchronous shifts in regional fire activity and in large-scale climate regimes imply that the fire activity criteria underlying the northern limit of the commercial forest in central Quebec (MRNQ 2000) must be viewed as a dynamic component rather than a static criterion. Moreover decadal-scale climate variability, and regime shifts in particular, can be anticipated (Enfield and Cid-Serrano 2006; Rodó and Rodríguez-Arias 2006). The anticipation of future climate regime shifts may contribute to the development of adaptation strategies of forest management to future fire regimes driven by climate variability and change.

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References

Allison PD (1995) 'Survival Analysis Using SAS: a Practical Guide.' (SAS Institute Inc.: Cary, NC)

Ambaum MHP, Hoskins BJ, Stepheson DB (2001) Arctic Oscillation or North Atlantic Oscillation? *Journal of Climate* **14**, 3495–3507. doi:10.1175/1520-0442(2001)014<3495:AOONAO>2.0.CO;2

ArcView GIS (1999) 'ArcView GIS version 3.2.' (Environmental Systems Research Institute: Redlands, CA)

Bergeron Y, Archambault S (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, Gauthier S, Kafka V, Lefort P, Lesieur D (2001) Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Canadian Journal of Forest Research* **31**, 384–391. doi:10.1139/CJFR-31-3-384

Bergeron Y, Flannigan M, Gauthier S, Leduc A, Lefort P (2004*a*) Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management. *Ambio* **33**, 356–360. doi:10.1639/0044-7447(2004)033[0356:PCAFFF]2.0.CO;2

Bergeron Y, Gauthier S, Flannigan M, Kafka V (2004*b*) Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. *Ecology* **85**, 1916–1932. doi:10.1890/02-0716

Bergeron Y, Cyr D, Drever CR, Flannigan M, Gauthier S, Kneeshaw D, Lauzon È, Leduc A, Le Goff H, Lesieur D, Logan K (2006) Past, current, and future fire frequencies in Quebec's commercial forests: implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. *Canadian Journal of Forest Research* **36**, 2737–2744. doi:10.1139/X06-177

Biondi F, Gershunov A, Cayan DR (2001) North Pacific decadal climate variability since 1661. *Journal of Climate* **14**, 5–10. doi:10.1175/1520-0442(2001)014<0005:NPDCVS>2.0.CO;2

Bonan GB (2002) 'Ecological Climatology: Concepts and Applications.' (Cambridge University Press: New York)

Bonsal BR, Lawford RG (1999) Teleconnections between El Niño and La Niña events and summer extended dry spells on the Canadian Prairies. *International Journal of Climatology* **19**, 1445–1458. doi:10.1002/(SICI)1097-0088(19991115)19:13<1445::AID-JOC431>3.0.CO;2-7

Bonsal BR, Chakravarti AK, Lawford RG (1993) Teleconnections between North Pacific SST anomalies and growing season extended dry spells on the Canadian Prairies. *International Journal of Climatology* **13**, 865–878. doi:10.1002/JOC.3370130805

Bridge SRJ (2001) Spatial and temporal variations in the fire cycle across Ontario. Ontario Ministry of Natural Resources, Northeast Science and Technology. NEST Technical Report TR-043. (South Porcupine, ON)

Brown PM (2006) Climate effects on fire regimes and tree recruitment in Black Hill ponderosa pine forests. *Ecology* **87**, 2500–2510. doi:10.1890/0012-9658(2006)87[2500:CEOFRA]2.0.CO;2

Centre for Land and Biological Resources Research (1996). Soil Landscapes of Canada, v.2.2. (Agriculture and Agri-Food Canada, Research Branch: Ottawa, ON) Available at http://nlwis-snite1.agr.gc.ca/slc-ppc22/index.phtml [Verified 8 November 2006]

Collins BM, Omi PN, Chapman PL (2006) Regional relationships between climate and wildfire-burned area in the Interior West, USA. *Canadian Journal of Forest Research* **36**, 699–709. doi:10.1139/X05-264

D'Arrigo R, Villalba R, Wiles G (2001) Tree-ring estimates of Pacific decadal climate variability. *Climate Dynamics* **18**, 219–224. doi:10.1007/S003820100177

Drever CR, Messier C, Bergeron Y, Doyon F (2006) Fire and canopy species composition in the Great Lakes-St Lawrence forest of

Témiscamingue, Québec. *Forest Ecology and Management* **231**, 27–37. doi:10.1016/J.FORECO.2006.04.039

Duffy PA, Walsh JE, Graham JM, Mann DH, Rupp TS (2005) Impacts of large-scale atmospheric–ocean variability on Alaskan fire season severity. *Ecological Applications* **15**, 1317–1330. doi:10.1890/04-0739

Enfield DB, Cid-Serrano L (2006) Projecting the risk of future climate shifts. *International Journal of Climatology* **26**, 885–895. doi:10.1002/JOC.1293

Enfield DB, Mestas-Nuñez AM, Trimble PJ (2001) The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophysical Research Letters* **28**, 2077–2080. doi:10.1029/2000GL012745

Environment Canada (2004) Canadian climate normals or averages 1971–2000. (Environment Canada: Ottawa, ON) Available at http://climate.weatheroffice.ec.gc.ca/climate_normals/ [Verified 5 July 2006]

Flannigan MD, Harrington JB (1988) A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–80). *Journal of Applied Meteorology* **27**, 441–452. doi:10.1175/1520-0450(1988)027<0441:ASOTRO>2.0.CO;2

Flannigan MD, Bergeron Y, Engelmark O, Wotton BM (1998) Future wildfire in circumboreal forests in relation to global warming. *Journal of Vegetation Science* **9**, 469–476. doi:10.2307/3237261

Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ (2005) Future area burned in Canada. *Climatic Change* **72**, 1–16. doi:10.1007/S10584-005-5935-Y

Fritts HC (Ed.) (2001) 'Tree Rings and Climate.' (Blackburn Press: Caldwell, NJ)

Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. *Journal of Geophysical Research* **31**, L18211.

Girardin MP, Tardif JC, Flannigan MD, Bergeron Y (2004) Multicentury reconstruction of the Canadian Drought Code from eastern Canada and its relationship with paleoclimatic indices of atmospheric circulation. *Climate Dynamics* **23**, 99–115. doi:10.1007/S00382-004-0417-X

Girardin MP, Tardif JC, Flannigan MD, Bergeron Y (2006*a*) Synoptic-scale atmospheric circulation and boreal Canada summer drought variability of the past three centuries. *Journal of Climate* **19**, 1922–1944. doi:10.1175/JCLI3716.1

Girardin MP, Bergeron Y, Tardif JC, Gauthier S, Flannigan MD, Mudelsee M (2006*b*) A 229-year dendroclimatic-inferred record of forest fire activity for the Boreal Shield of Canada. *International Journal of Wildland Fire* **15**, 375–388. doi:10.1071/WF05065

Glueck MF, Stockton CW (2001) Reconstruction of the North Atlantic Oscillation, 1429–1983. *International Journal of Climatology* **21**, 1453–1465. doi:10.1002/JOC.684

Gray ST, Graumlich LJ, Betancourt JL, Pederson GT (2004) A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD. *Geophysical Research Letters* **31**, L12205 doi:10.1029/2004GL019932

Grenier DJ, Bergeron Y, Kneeshaw D, Gauthier S (2005) Fire frequency for the transitional mixedwood forest of Timiskaming, Quebec, Canada. *Canadian Journal of Forest Research* **35**, 656–666. doi:10.1139/X05-005

Hessl AE, McKenzie D, Schellhaas R (2004) Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. *Ecological Applications* **14**, 425–442. doi:10.1890/03-5019

Hofgaard A, Tardif J, Bergeron Y (1999) Dendroclimatic response of *Picea mariana* and *Pinus banksiana* along a latitudinal gradient in the eastern Canadian boreal forest. *Canadian Journal of Forest Research* **29**, 1333–1346. doi:10.1139/CJFR-29-9-1333

Holmes RL (1999) 'Dendrochronology Program Library.' (Laboratory of Tree-Ring Research, University of Arizona: Tucson, AZ)

Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* **269**, 676–679. doi:10.1126/SCIENCE.269.5224.676

Johnson EA (1992) 'Fire and Vegetation Dynamics: Studies from the North American Boreal Forest. Cambridge Studies in Ecology.' (Cambridge University Press: New York, NY)

Johnson EA, Gutsell SL (1994) Fire frequency models, methods and interpretations. *Advances in Ecological Research* **25**, 239–287.

Johnson EA, Wowchuk DR (1993) Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Canadian Journal of Forest Research* **23**, 1213–1222. doi:10.1139/X93-153

Jones PD, Jónsson T, Wheeler D (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *International Journal of Climatology* **17**, 1433–1450. doi:10.1002/(SICI)1097-0088(19971115)17:13<1433::AID-JOC203>3.0.CO;2-P

Kasischke ES, Turetsky MR (2006) Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters* **39**, L09703.

Kasischke ES, Williams D, Barry D (2002) Analysis of the patterns of large fires in the boreal forest region of Alaska. *International Journal of Wildland Fire* **11**, 131–144. doi:10.1071/WF02023

Kerr RA (2000) A North Atlantic climate pacemaker for the centuries. *Science* **288**, 1984–1985. doi:10.1126/SCIENCE.288.5473.1984

Kitzberger T, Brown PM, Heyerdahl EK, Swetnam TW, Veblen TT (2007) Contingent Pacific–Atlantic Ocean influence on multicentury wildfire synchrony over western North America. *Proceedings of the National Academy of Science of the United States of America* **104**, 543–548. doi:10.1073/PNAS.0606078104

Langlois M (1994) 'Recueil d'Information sur les Incendies Forestiers au Québec de 1922 à 1993.' Ministére des Ressources Naturelles du Québec, Direction de la conservation des forêts. (Québec, QC)

Larsen CPS (1996) Fire and climate dynamics in the boreal forest of northern Alberta, Canada, from AD 1850 to 1985. *The Holocene* **6**, 449–456.

Lefort P, Gauthier S, Bergeron Y (2003) The influence of fire weather and land use on the fire activity of the Lake Abitibi area, Eastern Canada. *Forest Science* **49**, 509–521.

Lefort P, Leduc A, Gauthier S, Bergeron Y (2004) Recent fire regime (1945–1998) in the boreal forest of western Quebec. *Ecoscience* **11**, 433–445.

Luterbacher J, Schmutz C, Gyalistras D, Xoplaki E, Wanner H (1999) Reconstruction of monthly NAO and EU indices back to AD 1675. *Geophysical Research Letters* **26**, 2745–2748. doi:10.1029/1999GL900576

Macias Fauria M, Johnson EA (2006) Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. *Journal of Geophysical Research* **111**, G04008. doi:10.1029/2006JG000181

Mann DH, Fastie CL, Rowland EL, Bigelow NH (1995) Spruce succession, disturbance, and geomorphology on the Tanana River floodplain, Alaska. *Ecoscience* **2**, 184–199.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**, 1069–1079. doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2

MRNQ (2000) 'La Limite Nordique des Forêts Attribuables. Rapport Final du Comité, Ministère des Ressources Naturelles du Québec.' (Québec, QC)

Mudelsee M (2003) Estimating Pearson's correlation coefficient with bootstrap confidence interval from serially dependent time series. *Mathematical Geology* **35**, 651–665. doi:10.1023/B:MATG.0000002982.52104.02

Parisien MA, Hirsch K, Lavoie S, Todd B, Kafka V (2004). 'Saskatchewan Fire Regime Analysis.' Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre. (Edmonton, AB)

Phipps RL (1985) 'Collecting, Preparing, Crossdating and Measuring Tree Increment Cores.' USGS Water Resources Investigations Report 85–4148. pp. 5–35. (Denver, CO)

Reed WJ (2006) A note on fire frequency concepts and definitions. *Canadian Journal of Forest Research* **36**, 1884–1888. doi:10.1139/X06-096

Robitaille A, Saucier JP (1998) 'Paysages Régionaux du Québec Méridional.' (Les Publications du Québec: Sainte-Foy, QC)

Rodionov S, Overland JE (2005) Application of a sequential regime shift detection method to the Bering Sea ecosystem. *ICES Journal of Marine Science* **62**, 328–332. doi:10.1016/J.ICESJMS.2005.01.013

Rodionov SN (2006) Use of prewhitening in climate regime shift detection. *Geophysical Research Letters* **31**, L12707. doi:10.1029/2006GL025904

Rodó X, Rodríguez-Arias MÀ (2006) A new method to detect transitory signatures and local time/space variability structures in the climate system: the scale-dependent correlation analysis. *Climate Dynamics* **27**, 441–458. doi:10.1007/S00382-005-0106-4

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

Shen C, Wang WC, Gong W, Hao Z (2006) A Pacific Decadal Oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China. *Geophysical Research Letters* **33**, L03702.

Sibold JS, Veblen TT (2006) Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. *Journal of Biogeography* **33**, 833–842. doi:10.1111/J.1365-2699.2006.01456.X

Skinner WR, Stocks BJ, Martell DL, Bonsal B, Shabbar A (1999) The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada. *Theoretical and Applied Climatology* **63**, 89–105. doi:10.1007/S007040050095

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

Skinner WR, Shabbar A, Flannigan MD, Logan K (2006) Large forest fires in Canada and the relationship to global sea surface temperatures. *Journal of Geophysical Research* **111**, D14106. doi:10.1029/2005JD006738

Smith TM, Reynolds RW (2004) Improved extended reconstruction of SST (1854-1997). *Journal of Climate* **17**, 2466–2477.

Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR (2003) Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research* **108**, D18149.

Stokes MA, Smiley TL (1968) 'An Introduction to Tree-Ring Dating.' (University of Chicago Press: Chicago, IL)

Swetnam TW (1993) Fire history and climate change in giant sequoia groves. *Science* **262**, 885–889. doi:10.1126/SCIENCE.262.5135.885

Swetnam TW, Betancourt JL (1990) Fire–Southern Oscillation relations in the south-western United States. *Science* **249**, 1017–1020. doi:10.1126/SCIENCE.249.4972.1017

Systat Software Inc. (2004) 'SYSTAT 11.' (Systat Software: Richmond, CA)

Trouet V, Taylor AH, Carleton AM, Skinner CN (2006) Fire–climate interactions in forests of the American Pacific coast. *Geophysical Research Letters* **33**, L18704. doi:10.1029/2006GL027502

Van Wagner CE (1978) Age-class distribution and the forest fire cycle. *Canadian Journal of Forest Research* **8**, 220–227.

Visbeck MH, Hurrell JW, Polvani L, Cullen HM (2001) The North Atlantic Oscillation: past, present, and future. *Proceedings of the National Academy of Sciences of the United States of America* **98**, 12876–12877. doi:10.1073/PNAS.231391598

VoorTech Consulting (2001) 'MeasureJ2X V3.1.' (VoorTech Consulting: Holderness, NH)

Weber MG, Flannigan MD (1997) Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. *Environmental Reviews* **5**, 145–166. doi:10.1139/ER-5-3-4-145

Yamaguchi DK (1991) A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research* **21**, 414–416. doi:10.1139/X91-053

Zhang Y, Wallace JM, Battisti DS (1997) ENSO-like interdecadal variability: 1900–93. *Journal of Climate* **10**, 1004–1020. doi:10.1175/1520-0442(1997)010<1004:ELIV>2.0.CO;2

Zar JH (1999) 'Biostatistical Analysis.' 4th edn. (Prentice Hall: Upper Saddle River, NJ)

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