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Dendroclimatic inference of wildfire activity in Quebec over the 20th century and implications for natural disturbance-based forest management at the northern limit of the commercial forest

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Abstract. We examined the fire–climate relationship at the northern limit of commercial forest in western Quebec, a region where forest management is currently competing with fires for mature stands. The main objective was to determine if a particular climate signal would control the fire activity in this region when compared with other parts of the Quebec boreal forest. We used 500-hPa spatial correlation maps to compare the atmospheric patterns associated with the annual area burned (AAB) in the study area, the entire province of Quebec, the intensive (southern Quebec), and the restricted (northern Quebec) fire management zones. Next, dendroclimatic analyses were used to obtain tree-ring estimates of the AAB back to 1904 and to investigate the temporal stability of the fire–climate relationship. The climate controls associated with the AAB of the study area are intermediate between those associated with the AAB of the intensive and restricted fire management zones. The 500-hPa correlation patterns for the 1948–71 and 1972–2001 periods were relatively stable through time for the study area and for the restricted fire management zone. Our results provide a plausible mechanism for explaining the link between sea surface temperature and regional fire activity established in previous studies. They also provide information complementary to the Canadian fire danger rating system that uses daily weather data.

Additional keywords: dendrochronology, dendroclimatology, fire risk, forest fire, spatial correlation maps.

Introduction

Forest fire is a major disturbance agent across the boreal forest, creating a mosaic of stands with different compositions and structures. The spatial variability of fire activity is a main challenge for boreal forest management, as laws and guidelines are generally formulated for large territories with heterogeneous fire regimes. When forest fires occur in managed forests, they can delay timber harvests by burning stands scheduled for harvest. They force the rapid development of salvage logging activities that modify management plans and annual allowable cut calculations *a posteriori* (Martell 1994; Armstrong 2004; Didion *et al*. 2007). At the landscape scale, natural disturbance-based forest management aims for a stand-age distribution similar to that produced under a natural fire regime (Harvey *et al*. 2002). The spatial variations of the fire activity correspond to different opportunities to implement such management options (Bergeron *et al*. 2006). Lefort *et al*. (2004) described the spatial variations of the fire cycle for the recent period (1945–98) across the commercial boreal forest in Quebec using provincial fire data. In particular, they identified a shorter fire cycle in the north-western commercial forest. Dendroecological reconstruction of the historical fire activity at its southern margin indeed unveiled a short fire cycle compared with other parts of the Quebec commercial forest (estimated at 280 years over the period 1940–2001; Le Goff *et al*. 2007). In this part of the Quebec boreal forest, the northern limit of the commercial forest was set partly because of the high fire frequency prevailing in the James Bay territory (south of Hudson Bay), located north of this limit (MRNQ 2000).

In Quebec, fire suppression efforts are allocated according to two fire management zones approximately located south and north of 51°N since 1966 (Langlois 1994; Fig. 1). The intensive fire management zone (south of 51°N) covers inhabited and managed forests where all fires are actively fought to be controlled before they reach 3 ha in size. In the restricted fire management zone (north of 51°N), fires are allowed to burn under surveillance and are fought only if they threaten human

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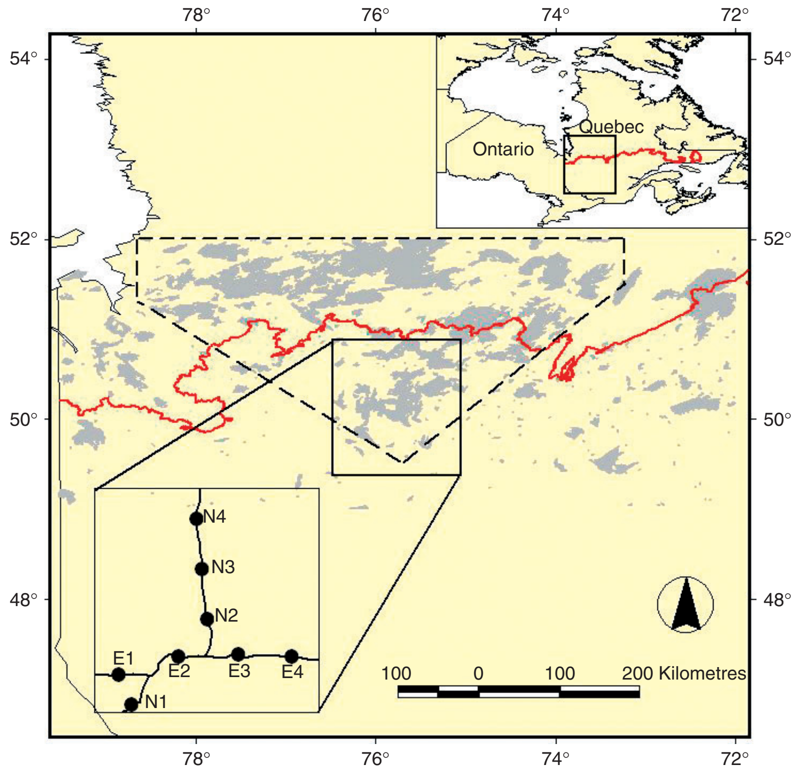

Fig. 1. The study area is delineated by a dashed line and lies over the 2005 limit between the intensive and restricted fire management zones (top chart). Area burned polygons (grey) highlight the prevailingly high area burned in the study area (1972–2002). Tree-ring chronologies were sampled at 40-km intervals along the two main road axes crossing the squared area. Site chronology code: first letter indicates transect (E for the longitudinal transect, N for the latitudinal transect); and number indicates the position on the transect (increasing eastern or northern).

lives or infrastructure, or if there is a risk that they will penetrate the intensive forest management zone. The territory identified as having a particularly high fire regime when compared with other parts of the commercial forest (Lefort *et al*. 2004; Le Goff *et al*. 2007) is crossed by the limit separating the two fire management zones (Fig. 1), which is also the northern limit of the commercial forest. This area of high fire activity is popularly known as the Fire Triangle Area.

Fire activity is controlled by several factors, namely weather and climate (Flannigan and Wotton 2001), vegetation composition and structure (Nash and Johnson 1996; Hély *et al*. 2000), anthropogenic activities (Lefort *et al*. 2003; Wotton *et al*. 2003; DeWilde and Chapin 2006), and topographic features (Kasischke *et al*. 2002; Cyr *et al*. 2007). Dry forest fuels and winds are major contributors to large stand-destroying fires (Flannigan and Wotton 2001; Westerling *et al*. 2006). The drying of forest fuels results from droughts of 3 days or more with less than 1.5 mm of total precipitation (Flannigan and Harrington 1988). These droughts have been associated with blocking high-pressure systems in the upper atmosphere, typically at the 500-hPa pressure level, over or upstream from the affected region (Nash and Johnson 1996; Skinner *et al*. 1999, 2002; Macias Fauria and Johnson 2006). The lightning activity associated with increased convective activity (creating thunderstorms) during the breakdown of these positive tropospheric anomalies (Nash and Johnson 1996) results in lightning fires. Skinner *et al*. (2006) further documented the influence of previous winter sea surface temperatures of the Atlantic and Pacific Oceans on the summer fire weather in the different forested regions across Canada. In particular, they highlighted the role of the Pacific Decadal Oscillation (PDO; Mantua *et al*. 1997) in creating a dipolar climatic control over the Quebec forest: the PDO would negatively influence the fire activity in southern Quebec and positively affect that in northern Quebec (see fig. 9*c* in Skinner *et al*. 2006). Moreover, Le Goff *et al*. (2007) found a positive correlation between changes in decadal stand-age distribution in the Fire Triangle Area and changes in the PDO phases. Macias Fauria and Johnson (2006) also confirmed that the PDO would have major control of the fire activity over north-eastern Canada. A better comprehension of climatic patterns controlling the regional fire activity, and annual area burned in particular, would allow forest managers to better anticipate the fire risk for forthcoming years.

Although the progress in characterising the spatial and temporal variability of fire, fire weather, and climate in Canada is significant (e.g. Skinner *et al*. 1999, 2002, 2006; Macias Fauria and Johnson 2006), the information is based on observational data and is limited to periods not exceeding a few decades. To address this temporal constraint, tree-ring data have been used to reconstruct past fire activities in different regions (Westerling and Swetnam 2003; Drobyshev and Niklasson 2004; Girardin *et al*. 2006*a*, 2006*b*; Girardin 2007). The rationale behind this approach is that in temperate regions, trees produce annual radial increments, where changes in ring width from one year to the next reflect changes in precipitation and temperature, as well as other factors (Hofgaard *et al*. 1999; Fritts 2001; Tardif *et al*. 2003; Girardin and Tardif 2005). Tree growth is also sensitive to climate variations that promote fire activity, such as droughts and fluctuations in the strength of atmospheric oscillations (Larsen 1996; Girardin *et al*. 2006*c*). Spatial and temporal patterns of annual tree radial increments can be used to infer area burned variability and additionally extend area burned records at times during which there was no fire recording (Girardin 2007). Here we evaluate if such an approach is applicable to modelling past fire activity in Quebec.

The aim of the present study was to characterise the Fire Triangle Area fire regime and to contrast its interannual variability against that prevailing elsewhere in the Quebec forest. First, we compared the 1972–2002 annual area burned (AAB) of the Fire Triangle Area with that of the entire province of Quebec, the intensive and the extensive fire management zones. Next, 500-hPa geopotential height spatial correlation maps were created for each area considered (spatial domain) to verify whether a particular climate signal would be associated with the Fire Triangle Area AAB. Finally, we evaluated the potential of tree-ring chronologies for extending the AAB variability further back in the past as a means for assessing the temporal stability of fire–climate relationships.

Study area

The study area, called the Fire Triangle Area, is located in the western feather moss–black spruce bioclimatic domain (Robitaille and Saucier 1998) (49°30′–52°N; 73–78°30′W; Fig. 1). Its forest consists principally of black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.) stands. The territory belongs to the Canadian Precambrian Shield, where 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). It stretches over three ecoregions: the James Bay Lowlands, the Rivière Rupert Plateau, and the Abitibi Plains (Ecological Stratification Working Group 1996). Eastman, Nemiscau, Waskaganish, Waswanipi and Mistissini are the main Native communities established in the study area. The part belonging to the intensive fire management zone (commercial forest) is entirely allocated to forest management.

Mean annual temperature ranges from −2 to 1°C with summer temperatures ranging from 11.5 to 14°C and winter temperatures ranging from −16 to −12°C. Annual precipitation ranges from 700 to 900 mm. Altitude, relief and lake density gently increase towards the west, while the frequency of bogs and poorly drained sites decreases moving away from the James Bay Lowlands (Ecological Stratification Working Group 1996). In the eastern part of the study area, the altitude is ∼350 m, with summits at ∼1065 m around Lake Mistassini (located at the far eastern end of the study area). Most of the area is underlain by Precambrian granites and gneisses, and has an undulating drift-covered surface. It consists largely of flat, poorly drained plains with subdued fluvial and marine features near James Bay while its south-western part is dominated by fine-textured, level to undulating lacustrine deposits. Intermixed within these deposits are bedrock outcrops and organic deposits (Ecological Stratification Working Group 1996).

Data and methods

This section is divided as follows. First, we describe the fire data and 500-hPa geopotential height data under use, along with the relevant statistical analyses linking these datasets. Second, we describe the development of the site tree-ring width chronologies and the analyses of climate response functions. Here we define site tree-ring width chronologies as averages of annual ring-width measurements for one to several cores per tree and from a sample of trees (typically 30) growing on similar ecological sites. Third, the statistical procedure employed to develop tree-ring estimates of past annual area burned is described. Essentially, this procedure consists in calibrating fire statistics against the tree-ring width chronologies and applying the statistical model to the chronologies at times for which there are no fire records available.

Fire data

We used the provincial fire data provided by the Ministère des Resources naturelles et de la Faune du Québec (MRNFQ) for the 1972–2002 period to calibrate our area-burned models. The period covered by these data encompasses that during which systematic fire detection in the restricted fire management zone was made by detection planes, which only began in the late 1960s (Blanchet 2003). AAB variability was examined at the scale of four spatial domains, namely the Fire Triangle Area, the entire province of Quebec, and the intensive (southern Quebec) and restricted (northern Quebec) fire management zones as set in 2005 (Fig. 1). Additionally, the large fire database (LFDB), consisting of all forest fires of a size greater than 200 ha that occurred in Canada from 1959 to 1999 (Stocks *et al*. 2002), was also used to look at systematic differences in the timing of the season of large forest fires among the four domains. The period for this analysis was restricted to 1972–99. The LFDB was also used to test the fidelity of our tree-ring estimates of AAB against independent data (procedure described further below). Although incomplete, the LFDB still contains information about extreme fire years before 1972 that may be used as independent information for validation of our AAB models.

Shapiro–Wilk normality tests indicated right-skewness in the MRNFQ AAB frequency distributions ($P = 0.000$). The logarithmic transformation (LOG) was found to provide an adequate data transformation to meet the normality requirement ($P > 0.05$). Next, a positive trend in the AAB data was removed using a linear least-squares fitting.

Fire–climate relationships

The statistical relationship between year-to-year area burned and climate variability was analysed using correlation maps with

500-hPa geopotential height (National Centers for Environmental Prediction and National Center for Atmospheric Research, NCEP/NCAR, reanalysis data from Kalnay *et al*. 1996). The NCEP/NCAR reanalysis grid has a temporal coverage from 1948 to the present and a spatial coverage of 2.5° latitude by 2.5° longitude. Geopotential height approximates the actual height of the air column above sea level (in metres) of a given constant pressure surface (here 500 hPa). As a warm layer of air is less dense and thicker than a cool one, a region of warm air appears as a region with higher atmospheric pressure. Large forest fires in Canada (>200 ha) are generally associated with blocking high-pressure systems in the upper atmosphere that cause obstruction, on a large scale, of the normal west-to-east progress of migratory storms (Skinner *et al*. 1999). Spatial correlation maps were created using the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (http://climexp.knmi.nl/, accessed 23 April 2008).

Tree-ring analyses

Sampling for tree-ring width data from jack pine and black spruce was conducted in the summers of 2002 and 2003 in stands located in the southernmost part of the Fire Triangle Area (Fig. 1). Site selection was mainly constrained by accessibility. A total of 16 sites were sampled along the two main road axes crossing the study area, drawing a latitudinal transect and a longitudinal transect of ~160 km each (Fig. 1). Dendrochronological samples were collected after scanning each 40-km road section for old-looking stands. For each sampling site, two diametrically opposite cores or one transversal section was taken from 30 trees of each species. Cores and cross-sections were dried, sanded, and dated by counting annual tree rings. Dendrochronological samples were then measured using a Velmex system (Bloomfield, NY) with the *MEDIR* packaging for Windows (available at http://web.utk.edu/~grissino/software.htm, accessed 23 April 2008). Crossdating was validated using the program *COFECHA* from the Dendrochronology Program Library (Holmes 1999). All cores with potential errors were rechecked and corrected if possible; otherwise, they were omitted from further analyses. Series having low correlation with the mean site chronology ($r < 0.3$) were excluded.

Raw tree-ring width measurements were processed to remove age and size-related trends using a cubic smoothing spline of 60 years with 50% frequency response (Cook and Peters 1981). It preserves ~99% of the variance within individual series at a wavelength of 19 years. This means that common trends (1–20 years) between trees are conserved (Hofgaard *et al*. 1999). These chronologies were then averaged by site to further remove endogenous stand disturbance effects on ring width and to enhance the common signal. Autoregressive modelling was used to remove serial persistence. All these transformations were done using the *ARSTAN* program (Cook and Holmes 1999) to obtain 16 site tree-ring width residual chronologies. Chronologies and their associate statistics are described in Appendix A1.

The common variance within the site tree-ring width residual chronologies was extracted and analysed using a non-rotated Principal Component Analysis (PCA) performed on a correlation matrix (Legendre and Legendre 1998). In this procedure, the 16 tree-ring chronologies were transformed into new sets of orthogonal variables. The first principal component (PC) accounted for the maximum possible proportion of the variance in tree growth, and succeeding PCs accounted for as much of the remaining variance as possible. Eigenvectors, or the loading of each tree-ring chronology on each component, gave the spatial representation of the PCs.

The effects of climate fluctuations (temperature and precipitation) on radial growth were analysed using correlation and bootstrap response function analyses (Briffa and Cook 1990; Guiot 1991) for the period 1916–2002 to describe the climate signal recorded by tree growth, and to evaluate the potential of dendroclimatology to extend further in the past variability in fire activity. The bootstrap response function analysis provides a test of significance of the stability of the regression coefficients between tree growth and weather variables within a specific period by repeated, random sampling of the data. A weight was associated with each monthly variable, expressing the separate relative effects of several climate factors on ring width. This method has the advantage of avoiding errors caused by colinearity among variables, thus providing a more realistic estimate of tree response to climate. Bootstrap response functions (processed through 500 iterations) and correlations were performed using *PRECON* 5.17 (Fritts *et al*. 1991). Monthly mean temperature from Chapais-Chibougamau and total monthly precipitation data from the Roberval Airport were obtained from the Adjusted Historical Canadian Climate Database (Environment Canada 2004). This database provides rehabilitated precipitation and homogenised temperature datasets where data have been adjusted to account for changes in the instrumental equipment or for station relocation (Mekis and Hogg 1999; Vincent and Gullett 1999). The selected stations were the closest to our area covering a relatively long common interval (1916–2002). For the correlations and response functions, a sequence of 16 months was used, from May of the year before ring formation ($t - 1$) to August of the year current to ring formation (t). Correlation and response functions were computed for the 1916–2001 period. This time period was limited by the availability of temperature and precipitation records. Although the AAB are available until 2002, the time period used for the analysis ends in 2001 because of the forward lag used for the PCs.

Tree-ring estimates of annual area burned

As a means of evaluating the potential of the site tree-ring width chronologies for reconstruction of past annual variations in fire activity, a stepwise multiple regression using a backward selection was computed using *SYSTAT* 11 (Systat Software Inc. 2004) to fit a linear model relating the detrended LOG-transformed AAB records (period 1972–2001) to the PCs (including their forward lag). Once the regression coefficients were estimated for the calibration period, they were applied to the PCs for as far back as possible to produce a series of AAB estimates (Girardin *et al*. 2006*b*; Girardin 2007). The short length of the instrumental AAB series (31 years) prevented us from conducting a split-sample calibration scheme commonly employed in tree-ring-based climate reconstructions (Cook and Kairiukstis 1990).

We used the LFDB fire data for the 1959–71 time period to verify whether the tree-ring estimates could detect high fire years out of the calibration time period (1972–2001). The difference in mean of estimated fire activity at the time of the 4 highest and remaining 9 fire years between 1959 and 1971 from the LFDB was tested using the non-parametric Mann–Whitney U test statistic (Zar 1999). A significant test result indicates a tendency for the statistical fire estimates to reproduce with confidence years of high fire activity (Girardin *et al.* 2006*a*). In addition, we created 500-hPa geopotential height correlation maps of AAB estimates for the precalibration period (1948–71) and for the calibration period (1972–2001), and compared these with those obtained from the instrumental AAB data (1972–2002). We postulated that for an effective reconstruction, when applied to the period 1948–71, the spatial correlation patterns should resemble that of the period 1972–2001. We also repeated the procedure on temperature and precipitation data from the Climate Research Unit TS 2.1 database (Mitchell and Jones 2005) for two subperiods: 1904–50 and 1951–2001. All correlation maps were computed using the KNMI Climate Explorer (http://climexp.knmi.nl/).

Results

Description of the AAB series

All domains under study had high AAB in 1976, 1983, 1996, 1997 and 2002, and low AAB in 1972–75, 1982, 1984, 1992, 2000–01 (Fig. 2). Conversely, 1989 was the highest fire year for the Quebec province between 1972 and 2002 (Fig. 2*b*), the 1989 fire activity being located in the restricted fire management zone (Fig. 2*d*). 1991 was the highest fire year in the intensive fire management zone only (Fig. 2*c*), but this fire year did not appear as major at the scale of the Quebec province (Fig. 2*b*). Between 1972 and 2002, ∼72% of the AAB in the entire province of Quebec (Fig. 2*b*) occurred in the restricted fire management zone (Fig. 2*d*). In spite of these few years during which the fire activity seems asynchronous between the restricted and the intensive fire management zones, both AAB series are correlated (Pearson correlation coefficient $r = 0.3933$, significant at $P = 0.05$).

June was the month with the highest area burned by large forest fires for all spatial domains (between 60 and 80% of the total area burned, Fig. 3). July was the month with the second highest area burned for the Fire Triangle Area (Fig. 3*a*) and for the restricted fire management zone (Fig. 3*d*), while May had the highest area burned for the intensive fire management zone (Fig. 3*c*).

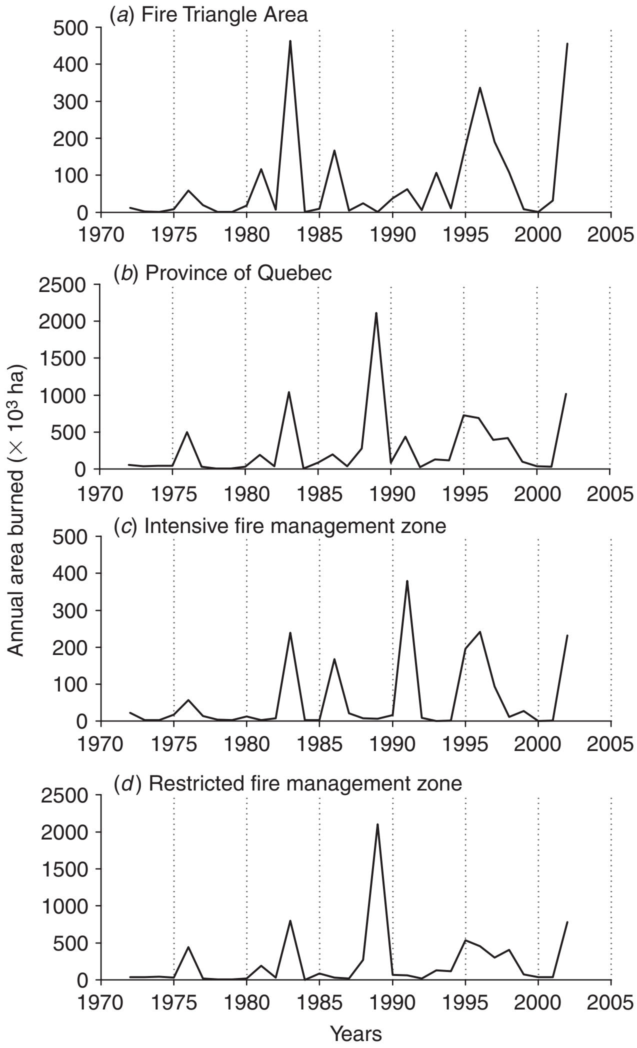

Fig. 2. Annual area burned for the different spatial domains analysed (1972–2002).

Atmospheric controls of annual area burned in Quebec

All AAB series correlated with similar atmospheric patterns, consisting of three centres-of-action (Fig. 4). High fire years are associated with (1) blocking highs south of the Hudson Bay area; (2) a trough on the Pacific Coast; and (3) another trough on the Atlantic Coast. For the intensive fire management zone (Fig. 4*c*), the Ontario High and the Pacific Low are however located south relative to the position they occupied for the other spatial domains examined. In the following section, we used dendroclimatology to obtain tree-ring estimates of AAB further back in time and verify whether these atmospheric patterns associated with fire activity also prevailed earlier.

Tree growth and climate

The first three principal components of the 16 residual chronologies accounted for 80% of the variance in tree growth (Fig. 5). The first principal component (PC1) captured the environmental signal held in common by the chronologies and explained 57% of the variance, whereas PC2 accounted for 16% of the variance and separated species (Fig. 5*a*), and PC3 discriminated northern and southern sites (7% of the variance, Fig. 5*b*). According to the correlation and response functions, tree growth (PC1) was negatively influenced by previous July temperatures, and positively correlated with previous October and current January to June temperatures (Fig. 6*a*). Winter and spring precipitation (mostly in the form of snow; Environment Canada 2004) negatively influenced tree growth. PC2 was negatively correlated with previous October temperatures, meaning that jack pine growth would be positively influenced by a prolonged autumn (Fig. 6*b*). PC3 (latitudinal gradient) would also be negatively influenced by previous summer temperatures (like PC1) (Fig. 6*c*).

Tree growth and fire activity

Tree-ring chronologies and AAB were negatively correlated, except for two spruce chronologies (N2E and N3E) that

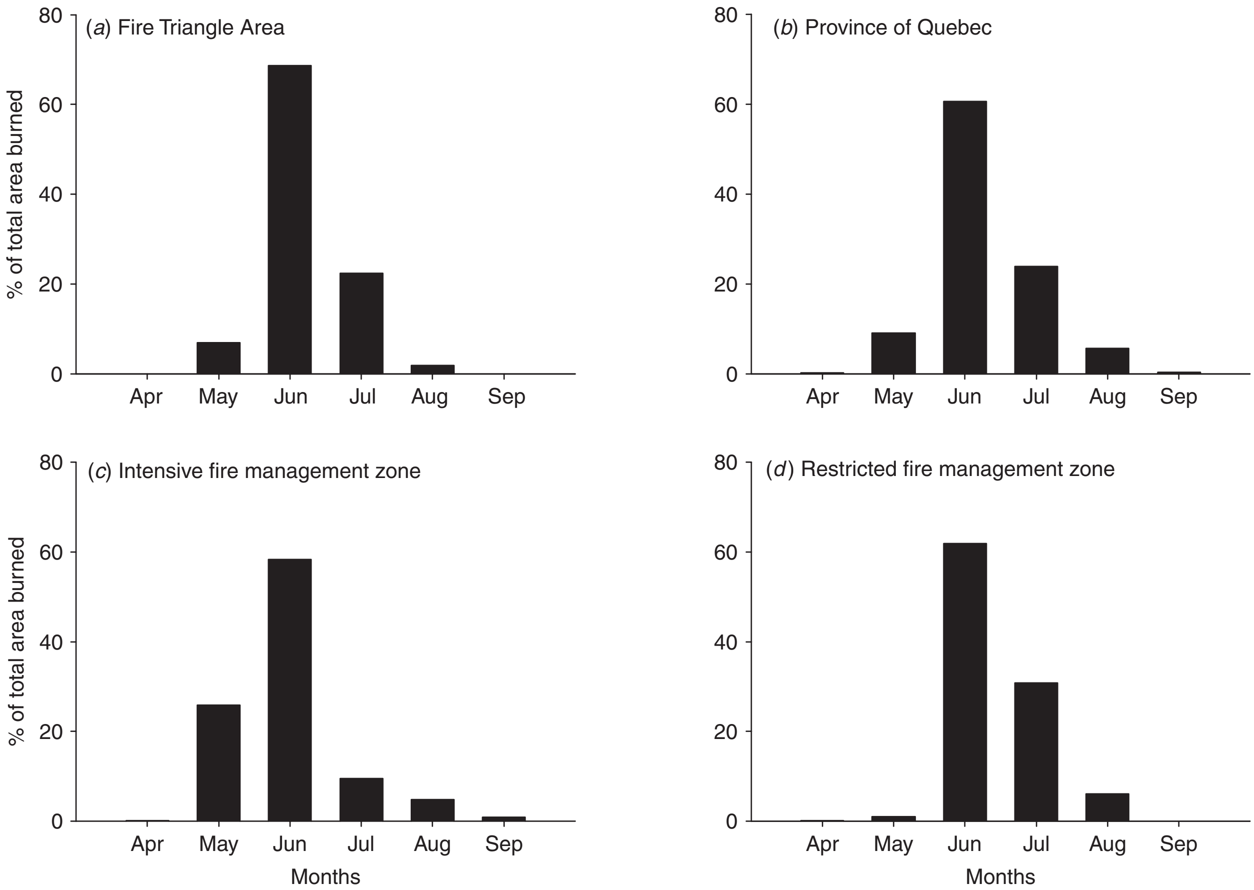

Fig. 3. Monthly distribution of the area burned across the fire season for different subsamplings of the large fire database (Stocks *et al*. 2002), 1972–99.

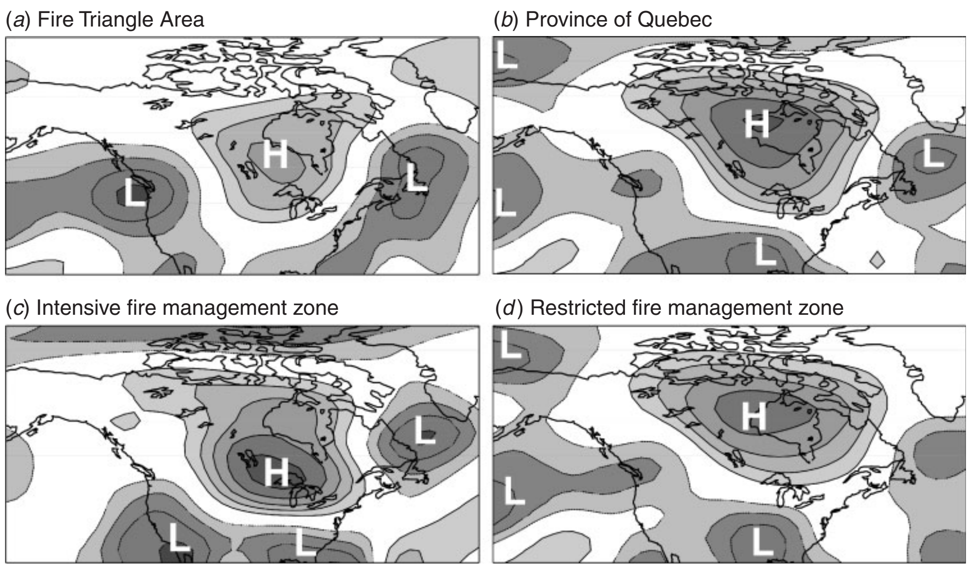

Fig. 4. Correlation maps of the instrumental (1972–2002) annual area burned (log-transformed and detrended) and June 500-hPa geopotential heights for the four domains investigated. Correlation scale ranges from −0.5 to 0.5 (darker grey indicating stronger correlations). H identifies positive 500-hPa anomalies and L identifies negative 500-hPa anomalies (anomalies correspond to correlations significant at $P < 0.10$).

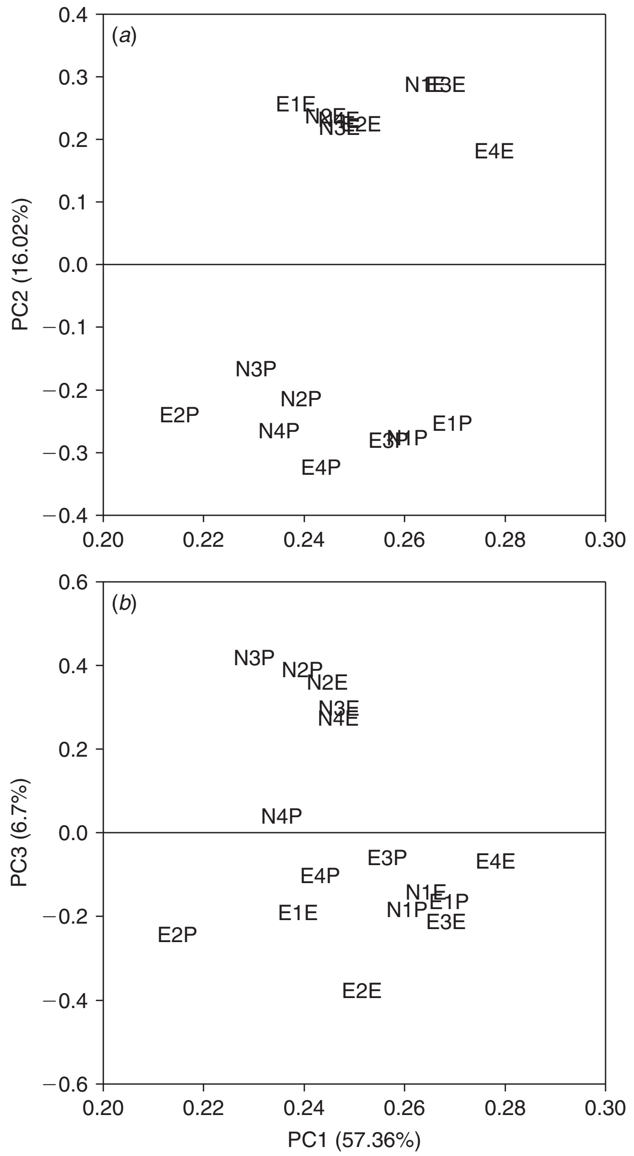

Fig. 5. Residual chronology eigenvectors along the first three axes of the principal component analysis (period 1904–2002). Percentage of variance explained is indicated for each principal component. Site chronology code: first letter indicates transect (E for the longitudinal transect, N for the latitudinal transect); number indicates the position on the transect (increasing eastern or northern); and last letter indicates the species (E for black spruce and P for jack pine).

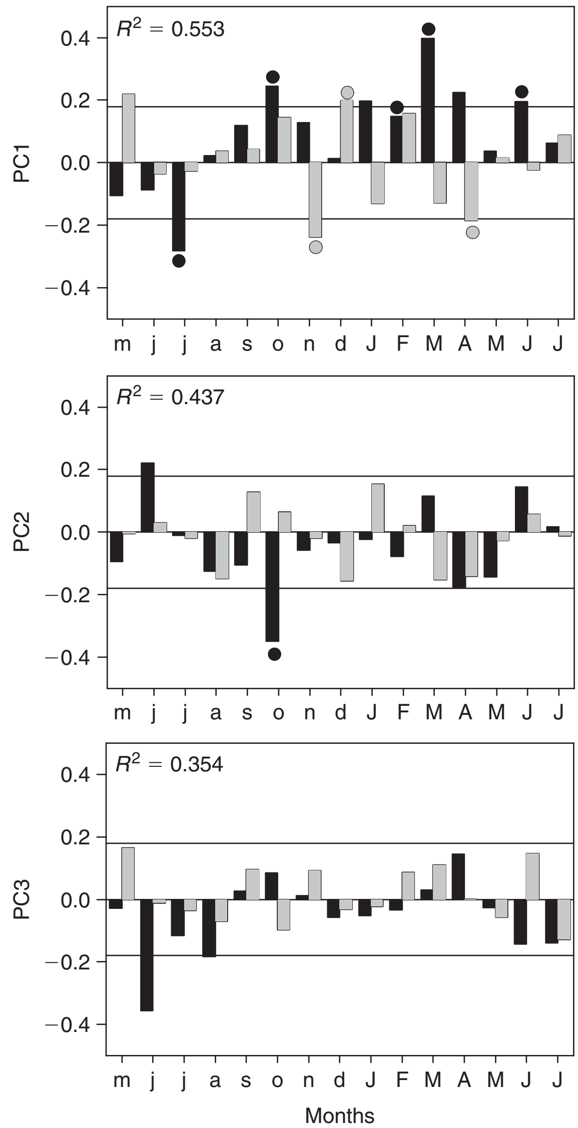

Fig. 6. Correlations and response functions of the first three principal components of the residual chronologies with monthly temperature (black bars) and precipitation (grey bars) from May of the year previous to ring formation (lower case) to September of the year current to ring formation (upper case). Dots indicate the monthly variables with significant response functions. For each principal component, the R^2 obtained with monthly temperature and precipitation taken together is indicated. Critical threshold for the correlations (at $P < 0.10$) is indicated by the upper and lower lines. The period investigated is 1916–2001.

displayed a significant positive correlation with the Fire Triangle Area AAB (Table 1). Eight of the nine chronologies that correlated with the restricted fire management zone AAB were also correlated with the Quebec AAB. The tree growth of the next year ($PC1_{t+1}$) and the latitudinal gradient in tree growth for the current year ($PC3_t$) were correlated with the AAB for the Fire Triangle Area, for the province of Quebec and for the restricted fire management zone. Tree growth variability associated with species growth for the next year ($PC2_{t+1}$) was also correlated with the AAB for the restricted fire management zone and for the province. The negative correlation between AAB of the current year and tree growth of the next year ($PC1_{t+1}$) was confirmed by the high negative correlation (and response function) between tree growth (current year, PC1) and the July temperature of the previous year (Fig. 6). Recall that June–July are the months accounting for the highest fire activity in the fire season for all spatial domains examined except the intensive fire management zone (Fig. 3). No chronologies and no PCs were correlated with the AAB of the intensive fire management zone.

Table 1. Pearson correlations between tree-ring width residual chronologies and their principal components and annual area burned (AAB) records (log-transformed and detrended) from the Fire Triangle Area (FTA), the province of Quebec (QC), and the restricted fire management zone (RES)

Only significant correlation coefficients ($P < 0.10$) are indicated. Coefficients above the critical value for $P = 0.05$ are indicated in bold. Site chronology code: first letter indicates transect (E for the longitudinal transect, N for the latitudinal transect); number indicates the position on the transect (increasing eastern or northern); and last letter indicates the species (E for black spruce and P for jack pine). Period analysed is 1972–2002. Unlagged principal components are indicated by t (current year) while lagged principal components are indicated by $t+1$ (next year). No correlations were found for the intensive fire management zone AAB

Tree-growth index	FTA	QC	RES
E1E		−0.313	−0.308
E2E		**−0.384**	**−0.414**
E3E			
E4E			
N1E			
N2E	0.305		
N3E	0.322		
N4E			
E1P		**−0.398**	**−0.414**
E2P		**−0.365**	**−0.369**
E3P		−0.319	−0.330
E4P		**−0.396**	**−0.415**
N1P			−0.316
N2P			
N3P			
N4P		−0.315	−0.343
$PC1_t$			
$PC2_t$			
$PC3_t$	0.305	**0.457**	**0.455**
$PC1_{t+1}$	**−0.453**	−0.333	−0.356
$PC2_{t+1}$		−0.321	−0.315
$PC3_{t+1}$			

Results of the stepwise multiple regressions relating AAB to tree-ring components are presented in Table 2. The most parsimonious model corresponded to the Fire Triangle Area, where tree growth of the next year ($PC1_{t+1}$) alone accounted for ~20% of the variance in AAB estimates in the equation:

$$LOG(FTA)_t = 4.1718 - 0.1341PC1_{t+1} \quad (1)$$

where $LOG(FTA)_t$ is the estimate of LOG-transformed and detrended AAB of the Fire Triangle Area for the current year. No solution was found for the intensive fire management zone. The models for the Quebec AAB and for the restricted fire management zone AAB also selected the PC3 (latitudinal gradient) and were very similar (corresponding reconstructed AAB series were highly correlated: $r = 0.999$ over 1972–2001). As the model for the restricted fire management zone AAB presented slightly better statistics (Table 2), we chose to represent only the best of both models in Fig. 7. A total of 48.3% of the variance in the AAB of the restricted fire management zone over the period 1972–2001 was accounted for by estimates obtained from the equation:

$$LOG(RES)_t = 4.8063 - 0.1071PC1_t - 0.2034PC3_t - 0.1081PC1_{t+1} \quad (2)$$

where $LOG(RES)_t$ is the estimate of LOG-transformed and detrended AAB of the restricted fire management zone. Mann–Whitney U test statistics indicated that tree-ring fire estimates have some potential for reconstructing high fire years (as established by the LFDB over 1959–71), with Mann-Whitney U test t-values ranging from −3.0782 ($P = 0.0105$) for the Fire Triangle Area to −10.7194 ($P = 0.0001$) for the restricted fire management zone.

Over the calibration period 1972–2001, 500-hPa geopotential heights correlation maps indicated similar patterns between the Fire Triangle Area AAB observations (Fig. 4*a*), and estimates (Fig. 8*b*). Specifically, year-to-year AAB changes, for both the observations and estimates, were positively correlated with heights over the Hudson Bay area and negatively to heights over the Pacific and Atlantic coasts. When applied to the period 1948–71 (Fig. 8*a*), the spatial correlation pattern for the Fire Triangle Area AAB estimates resembles that of the interval 1972–2001 (Fig. 8*b*), albeit weaker, and with a slight eastern displacement of the centres-of-action between both subperiods. For the restricted fire management zone, the correlation patterns between AAB estimates and 500-hPa geopotential heights were also weaker for the earlier period (Fig. 8*c*) than for the later (Fig. 8*d*). AAB estimates were associated with the same three centres-of-action as AAB observations (Fig. 4*d*), although slightly different positions and weaker correlations were found for the earlier period.

The weakening of the AAB–climate relationships between both subperiods examined is elucidated with spatial correlation maps between AAB estimates and temperatures and precipitation (Fig. 9). For the later interval (1951–2001), AAB estimates displayed positive correlations with temperature (Fig. 9*c*, *d*) and negative correlations with precipitation (Fig. 9*g*, *h*). For the earlier period, correlation patterns with temperature were similar but weaker than for the recent period (Fig. 9*a*, *b*) for the Fire Triangle Area (Fig. 9*a*). Correlation patterns with precipitation for both areas examined were weaker for the precalibration period (Fig. 9*e*, *f*) than for the calibration period (Fig. 9*g*, *h*), but stayed negative. Hence, although the estimates are tracking seemingly well the AAB–climate relationships during the second half of the 20th century, weaker correlation patterns obtained during the precalibration period highlight some temporal instability in the AAB estimates. When considering the entire province of Quebec, the correlation between AAB estimates and the $PC1_{t+1}$ was constant over 1904–2001, but it also showed that the $PC3_t$ (latitudinal gradient, unlagged) has been correlated with AAB estimates only since 1951 (Table 3).

Discussion

The Fire Triangle Area fire regime

The 1989 and 1991 AAB illustrate the importance of spatial location of fire across the province: whereas major conflagrations

Table 2. Regressions of the annual area burned (log-transformed and detrended) of the Fire Triangle Area (FTA), the province of Quebec (QC), and the restricted fire management zone (RES) using the principal components of the residual chronologies (*t* unlagged, *t* + 1 lagged 1 year forward)

No regression was found for the intensive fire management zone. In-and-out thresholds were set at $P < 0.05$. The period investigated is 1972–2001. R^2, regression coefficient; s.e., standard error associated with the regression coefficient; D stat., Durbin–Watson statistics; AR1, first-order autoregressive error. The F-ratio is the ratio of the model mean square divided by the error mean square. The null hypothesis that the model has no predictive skill is rejected when the F-ratio is large, and accepted if the F-ratio is around 1

Variable	R^2	Adj. R^2	s.e.	*P*	F-ratio	D stat.	AR1	Selected variable
FTA	0.2054	0.1770	0.7977	0.0119	7.2374	2.0291	−0.0346	$PC1_{t+1}$
QC	0.4391	0.3743	0.5121	0.0016	6.7834	2.5634	−0.3070	$PC1_t$
								$PC3_t$
								$PC1_{t+1}$
RES	0.4829	0.4232	0.5560	0.0006	8.0935	2.6302	−0.3271	$PC1_t$
								$PC3_t$
								$PC1_{t+1}$

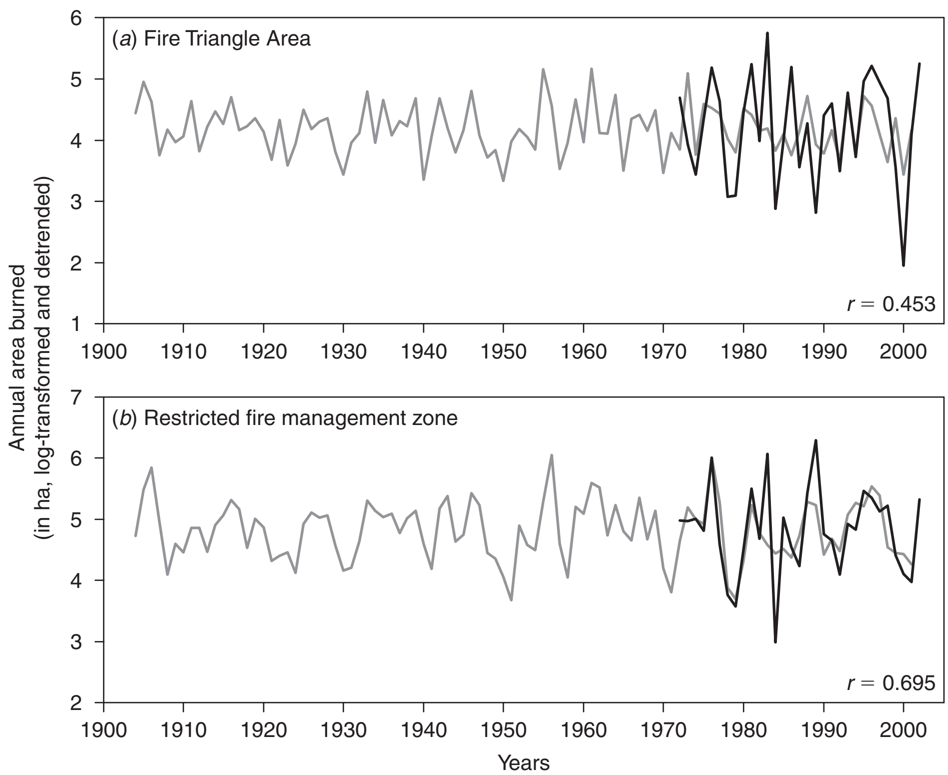

Fig. 7. Tree-ring estimates of the log-transformed and detrended annual area burned at different spatial domains for the 1904–2001 period (grey) against the instrumental annual area burned records (black). The Pearson correlation coefficient for the common period (1972–2001) is indicated on each graph ($n = 30$, critical r at $P < 0.05$ is 0.361). The model for the province of Quebec (not represented) was similar to the model for the restricted fire management zone (see Table 2), and had a similar correlation to the instrumental data ($r = 0.663$).

occurred in 1989 in the north of the boreal forest at the James Bay latitudes (in the restricted fire management zone; Couturier and Saint-Martin 1990), the 1991 fires occurred in the North Shore area (in the intensive fire management zone; Lavoie *et al*. 1997). These particular fire events illustrated how extreme fire years may be determined by a few large fire events located in a specific geographic area. Based on AAB, the monthly distribution of AAB and the associated atmospheric patterns, we identified

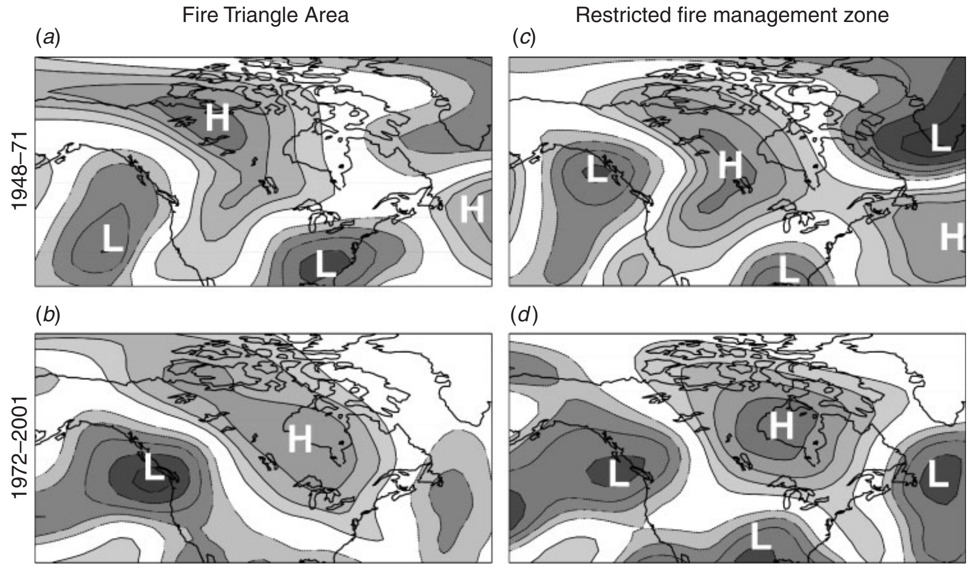

Fig. 8. Correlation maps between annual area burned estimates with June 500-hPa geopotential heights for the Fire Triangle Area (left), and for the restricted fire management zone (right). Correlation maps were computed for two different periods to verify the stationariness of the models: 1948–71 and 1972–2001. Correlation scale ranges from −0.5 to 0.5 (darker grey indicates stronger correlations). H identifies positive 500-hPa anomalies and L identifies negative 500-hPa anomalies (anomalies correspond to correlations significant at $P < 0.10$).

the fire regime of the Fire Triangle Area as intermediate between those of the intensive and the extensive fire management zones.

The intensive fire management zone was the only spatial domain for which no residual chronology was correlated with its AAB time series. This suggests that the climate pattern controlling fire activity in the Fire Triangle Area and the restricted fire management zone was different from the one controlling fire activity in the intensive fire management zone. Fire suppression history, easier fire detection, better accessibility to fire suppression means, and the composition and distribution of forest fuels in the southern part of the intensive fire management zone are other factors that could have altered the fire–climate relationship in this zone. In the Fire Triangle Area, although the fire cycle followed the historical trends observed in other parts of the commercial forest in Quebec (i.e. lengthening of the fire cycle since 1850, 1910–40 higher fire period), it was generally shorter (Le Goff *et al*. 2007) than in other parts of the intensive fire management zone (commercial forest).

Tree-ring analyses

The dendroclimatic response of black spruce and jack pine that we obtained was consistent with those obtained by Hofgaard *et al*. (1999) and by Girardin *et al*. (2006*c*). In particular, spring temperatures have a strong positive influence on tree growth by determining the start of the growing season. Late previous summer temperatures have conversely a negative effect on tree growth by slowing or preventing trees from building reserves necessary for the next growing season. The response of trees to precipitation seems more variable from one study to another, probably owing to the higher spatial variability in precipitation data (while the spatial variability in temperature acts over larger areas). Tree growth in our study area responded negatively to winter and spring precipitation. In the Fire Triangle Area, precipitation falls as snow from September to May (Environment Canada 2004). Winter and spring precipitation is thus associated with a thicker snow depth that takes more time to melt, and that can delay the start of the growing season and the fire season.

Tree growth and AAB are generally negatively correlated as they are both influenced by drought. Drought events, dry forest fuels, and the lack of water may slow tree growth. However, two spruce chronologies were positively correlated with the Fire Triangle Area AAB. Both chronologies were sampled on the northern part of the latitudinal transect. At these latitudes, the transect crossed several recent burns (1986, 1983) inside the Fire Triangle Area (Fig. 1). Living old black spruce stands were only located in topographic depressions that had escaped these recent fires, probably because of their poor drainage, creating fire breaks (all other chronologies were typically sampled on well-drained sites). Their positive correlation with the AAB may be explained by the positive effects on spruce growth of a lowering of the watertable. Fire-prone (dry) years would allow spruce to grow better on these sites where nutrient uptake in coniferous species usually is slowed by oxygen deficiency in roots when compared with stands growing in well-drained sites (Zinkan *et al*. 1974). In dendroclimatology, it is generally recognised that chronologies should be sampled in well-drained sites to extract a regional drought signal, but our results suggested that chronologies from poorly drained sites can also provide a local climate signal suited for calibration against fire activity observations.

Our tree-ring AAB estimates showed good correlations with the instrumental AAB series. The 500-hPa correlation patterns for the precalibration and calibration periods were relatively stable through time for the Fire Triangle Area and for the restricted

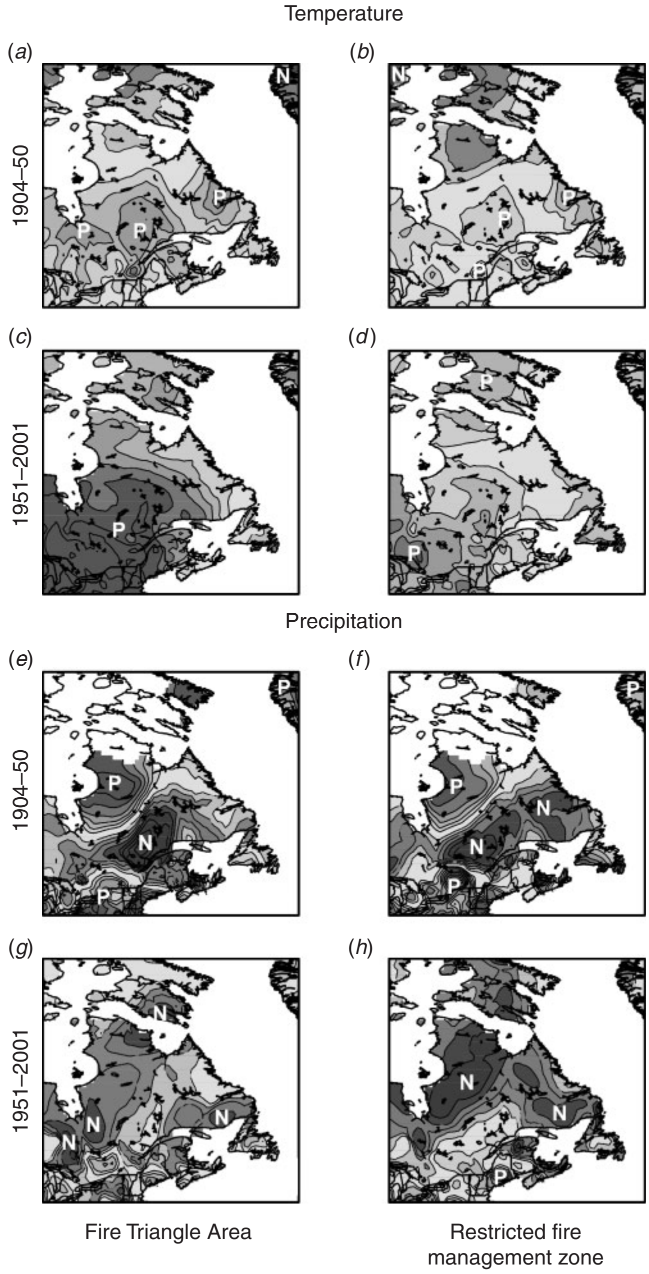

Fig. 9. Correlation maps for the tree-ring annual area burned estimates of the Fire Triangle Area, and the restricted fire management zone with June to August temperatures and precipitation from the Climate Research Unit (CRU) TS 2.1 database (Mitchell and Jones 2005), for 1904–50, and 1951–2001. Correlation scale ranges from −0.3 to 0.3, darker grey indicating stronger correlations (P for positive, N for negative).

Table 3. Pearson correlations between estimates of the annual area burned (log-transformed and detrended) of the Fire Triangle Area (FTA), the province of Quebec (QC), and the restricted fire management zone (RES) and principal components (unlagged *t* and lagged *t* + 1) of the residual chronologies for the 1904–2001 period and for two subperiods (1904–50, 1951–2001)

Only significant correlations at $P = 0.05$ are indicated. No correlations were found significant for $PC2_t$, $PC2_{t+1}$, and $PC3_{t+1}$

	$PC1_t$	$PC3_t$	$PC1_{t+1}$
		1904–2001	
FTA			−1.000
QC	−0.568	−0.491	−0.594
RES	−0.588	−0.454	−0.600
		1904–50	
FTA		0.312	−1.000
QC	−0.690		−0.665
RES	−0.701		−0.669
		1950–2001	
FTA			−1.000
QC	−0.499	−0.654	−0.555
RES	−0.522	−0.621	−0.558

fire management zone. The weaker correlation patterns obtained with the analyses of temperatures and precipitation before 1950 bring us to question the reliability of our estimates to adequately model past AAB. The higher correlation of temperature, precipitation, and PC3 for the recent period could be a confounding consequence of tree age rather than an actual shift in climate responses of trees. Indeed, most chronologies started in 1840, and tree age can alter tree growth response to climate (Carrer and Urbinati 2004). However, the correlation between AAB estimates and 500-hPa geopotential heights indicated a relatively stable fire–climate relationship for both subperiods. The suitability of our AAB estimates to infer multidecadal variability is also questionable owing to the detrending and prewhitening procedures applied to the tree-ring width measurement series (Cook *et al*. 1995). They however provide good estimates of the frequency of high (or low) fire years (interannual variations in AAB; Girardin *et al*. 2006*a*). Moreover, the correlations obtained with the geopotential heights and with tree growth (PC1) are constant enough to consider the potential of using tree rings in this region to reconstruct past fire activity. A larger tree-ring chronology sampling design would increase the likelihood of extracting the seasonal drought signal that most strongly relates to fire activity. A sampling design that would encompass a large corridor across the boreal forest could also track more efficiently the upper atmosphere oscillation responsible for much of the AAB (Girardin 2007).

Fire–climate relationship in the Fire Triangle Area

The atmospheric circulation pattern related to AAB was similar for the Fire Triangle Area and for the restricted fire management zone, but differed from the pattern controlling the intensive fire management zone AAB. The Ontario High co-occurring with a Pacific Low could have controlled AAB in Quebec since at least 1948 (the period examined was limited by the availability of geopotential height data). The Atlantic Low has correlated with AAB since ∼1972, and could have been a more recent climate feature than the two previous centres-of-action of the climate pattern associated with AAB. Interestingly the position of the Atlantic Low identified here is close to another well-documented low over Iceland that corresponds to the positive phase of the North Atlantic Oscillation (NAO) reported since 1970 (Hurrell and van Loon 1997). Le Goff *et al*. (2007) reported that this recent positive phase of the NAO could have contributed to the increase in area burned observed in the Fire Triangle Area for the last 30 years. These results were in relatively good agreement with those of Macias Fauria and Johnson (2006), who reported that the Arctic Oscillation (a teleconnection highly correlated with the NAO; see Ambaum *et al*. 2001) could partly explain the recent increase in area burned observed over northern Quebec. We might speculate that the Atlantic Low reported here could be related to the recent positive NAO phase as both phenomena seem synchronous.

The 500-hPa correlation maps presented here provided a plausible step for the mechanism underlying the influence of changes in the Pacific sea surface temperatures (SST) on the fire activity of the Fire Triangle Area (Macias Fauria and Johnson 2006; Le Goff *et al*. 2007), as well as on the fire activity of the other spatial domains examined. Recent studies demonstrated how SST anomalies of the North Atlantic and the North Pacific Oceans may influence global atmospheric circulation in the northern hemisphere (Lau 1997; Czaja and Frankignoul 1999, 2002; Frankignoul and Sennéchael 2007). The survey of the frequency, intensity, and length of these climate patterns can provide complementary information to the daily monitoring of fire risk using the Fire Weather Index System (Van Wagner 1987). Tracking changes in SST patterns would allow us to forecast high and low fire seasons ~6 months before the beginning of the fire season (Macias Fauria and Johnson 2006; Skinner *et al*. 2006), while the monitoring of 500-hPa anomalies over the Hudson Bay and Ontario, the Pacific and the Atlantic coasts could provide complementary information allowing us to anticipate fire risk in the different sectors of forested Quebec a few weeks in advance. This information could contribute to the planning and strategic deployment of fire management efforts throughout the territory.

Fire and forest management in the Fire Triangle Area

Le Goff *et al*. (2007) and Macias Fauria and Johnson (2006) documented that fire activity in the Fire Triangle Area has been increasing since 1970 in spite of the development of fire suppression efforts over the same period. Our results suggest that fire suppression did not alter the fire–climate relationship (which has been stable since at least 1948) and would not contribute to significantly decreasing the AAB in this part of the boreal forest. Conversely, the fact that we did not obtain AAB tree-ring estimates for the intensive fire management zone suggests either that suppression could have interfered in the fire–climate relationship earlier than the 1970s (as fire suppression in this zone started earlier than in the Fire Triangle Area), or that fire activity is controlled by a climate signal different from that of the other spatial domains. The Quebec fire suppression system was developed during a period (1950–70; Blanchet 2003) when forest fire activity was relatively low compared with the 1910–40 period and with the global increase in fire activity observed over the last 30 years (Skinner *et al*. 1999, 2002; Gillett *et al*. 2004). This situation triggers more and more situations where fire suppression capacity is overwhelmed.

In the Fire Triangle Area, forest management faces timber losses due to forest fires. Given that fire activity is high in the Fire Triangle Area when compared with other parts of the Quebec commercial forest (Le Goff *et al*. 2007), and that this fire risk will remain high in the future (Bergeron *et al*. 2006), forest fires will remain a significant constraint to the development of sustainable forest management strategies in this part of the boreal forest. Although the fire–climate relationship seems to have been stable since at least 1948, the interannual variability of fire activity challenges the fire regime criterion to set the northern limit of the commercial forest in Quebec. Owing to its climate controls, and in the context of climate variability and change, this criterion is highly dynamic, and should thus be re-evaluated to analyse the additive effects of fire and harvesting on the forest dynamics in this area. This evaluation could be done using modelling (see Fall *et al*. 2004; Didion *et al*. 2007) to compare different management scenarios and to determine which one is the best compromise between the minimum additive impacts of both disturbances on forested ecosystems and our socioeconomic expectations relative to the forest.

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Appendix A1. Description of the dendrochronological series

First-order autocorrelation refers to standard chronologies. The common interval analysed is 1904–2002 except for E2P (1915–2002), N3P (1930–2002), and N4P (1925–2002). Site chronology code: first letter indicates the transect (E for the longitudinal transect, N for the latitudinal transect), number indicates the position on the transect (increasing eastern or northern), and last letter indicates the species (E for black spruce and P for jack pine). See Fig. 1 for the location of the chronologies

Species chronology	*Picea mariana*								*Pinus banksiana*							
ident	E1E	E2E	E3E	E4E	N1E	N2E	N3E	N4E	E1P	E2P	E3P	E4P	N1P	N2P	N3P	N4P
Tree-ring chronology statistics																
No. of trees	28	25	30	31	31	31	32	27	21	30	29	33	30	33	13	27
No. of series	52	46	55	59	57	55	59	47	38	54	56	57	60	54	26	50
1st year of series	1860	1834	1858	1838	1840	1826	1802	1763	1852	1902	1853	1758	1852	1869	1864	1842
Total length	143	169	146	165	163	177	202	240	151	101	150	245	151	134	139	161
Mean length	112	103	122	102	99	131	100	122	122	85	103	90	101	107	92	93
Mean sensitivity	0.16	0.16	0.14	0.13	0.17	0.12	0.11	0.13	0.18	0.14	0.16	0.22	0.16	0.16	0.17	0.20
Standard deviation	0.14	0.14	0.12	0.11	0.14	0.11	0.10	0.12	0.15	0.13	0.14	0.19	0.13	0.14	0.15	0.17
1st-order autocorrelation	0.60	0.43	0.44	0.36	0.62	0.66	0.43	0.39	0.34	0.32	0.45	0.60	0.35	0.41	0.63	0.57
Common interval analysis																
No. of trees	24	12	27	17	14	21	11	19	18	14	14	12	10	19	11	16
No. of series	35	17	47	27	21	34	17	28	29	17	26	19	17	30	19	25
% variance in PC1	34.39	40.23	30.36	32.95	36.17	29.59	25.37	27.94	36.03	41.24	35.21	38.68	32.22	34.52	33.89	32.27
Pop. common sign.	0.92	0.87	0.91	0.87	0.86	0.88	0.67	0.85	0.89	0.89	0.86	0.86	0.76	0.89	0.81	0.86
Intercore correlation	0.32	0.36	0.28	0.30	0.31	0.27	0.17	0.24	0.33	0.37	0.32	0.35	0.26	0.31	0.30	0.29
Intertree correlation	0.31	0.35	0.27	0.29	0.30	0.26	0.15	0.23	0.32	0.36	0.30	0.33	0.24	0.31	0.28	0.28
Intratree correlation	0.70	0.71	0.64	0.62	0.63	0.64	0.51	0.61	0.70	0.58	0.67	0.74	0.61	0.56	0.64	0.64