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Reconstruction of fire history (1680–2003) in Gaspesian mixedwood boreal forests of eastern Canada

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Abstract

We describe the fire regime in the Gaspesian mixedwood boreal forest in order to improve our knowledge of the maritime fire regime through time and the role of climate on changes in fire cycle. We also investigated the importance of coarse scale spatial factors, such as topography, altitude, soil-type and vegetation-type. Fire history was reconstructed for a 6480-km^2 area using Quebec Ministry of Natural Resource archival data and aerial photographs combined with dendrochronological data, collected using a random sampling strategy. Physiographic features were not found to significantly influence the fire cycle, but an increase in the cycle (from 89 to 176 years $p \leq 0.0001$) was observed since the end of Little Ice Age (LIA) (1850). Relative agreement between the archival data (1920–2003) and the semi-parametric survival analysis approach for the 1850–2003 period provides greater confidence in our determination of a fire cycle situated between 170 and 250 years. An analysis of fluctuations in the Canadian forest fire Weather Index system, calculated for the period 1920–2003, showed a statistically significant decrease in extreme values. Given such a long fire cycle and in the context of forest management based on natural disturbance, even-aged management under short rotations should be questioned in these mixedwood boreal forests.

Keywords: Fire cycle; Climate; Little Ice Age; Natural disturbance; Mixedwood boreal forest

1. Introduction

Since 1985, studies have shown that disturbance regimes strongly affect forest dynamics (Pickett and White, 1985; Attiwil, 1994; Bergeron et al., 1999; Gauthier et al., 2001). The different fire regimes in the Canadian boreal forest represent one of the most important factors affecting the age-class distribution, stand composition, and stand structure (Bergeron and Dansereau, 1993; Weber and Stocks, 1998; Gauthier et al., 2001). Moreover, there are regional variations in fire cycles in the boreal forest, specifically, in the time needed to burn an area equivalent to the entire territory (Bergeron and Dansereau, 1993; Johnson et al., 1998; Bergeron et al., 1999; Gauthier et al., 2001). Such variations may arise due to the influence of climate and physiographic features (Rowe and Scotter, 1973; Attiwil, 1994; Bessie and Johnson, 1995).

Climate is an important factor that affects the length of the fire cycle. Many studies have shown that the frequency of fires (area burnt/year) can increase or decrease depending on climatic conditions (Stocks, 1993; Wotton and Flannigan, 1993; Flannigan et al., 2000; Bergeron et al., 2001). Indeed, for eastern boreal forest, it has been shown that climatic changes observed since the end of the Little Ice Age (≈1850) (LIA) are directly linked to changes in the fire cycle (Stocks, 1993; Bergeron, 1998). Since the end of the Little Ice Age, warm and humid air masses have replaced the cold and dry ones that characterized the Little Ice Age. This increase in humid air masses has caused fire conditions to decrease and the length of fire cycles to increase (Bergeron and Archambault, 1993; Girardin et al., 2004).

In addition to climate, fire can be influenced by many physiographic factors interacting at various spatial scales. On a continental scale, seasonal and meteorological conditions affect precipitation and, hence, the natural disturbance regime. At a

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landscape level, the disturbance regime of a given region can be influenced by topography, altitude, soil-type and vegetation-type (Rowe and Scotter, 1973; Dansereau and Bergeron, 1993; Hély et al., 2000; Ryan, 2002). At both scales, these physiographic features have an impact on the fire regime by influencing fuel moisture, humidity, and wind-dynamics, thereby affecting the probability of fire (Rowe and Scotter, 1973; Ryan, 2002).

In many maritime boreal mixedwoods windthrow, insect outbreaks (such as the spruce budworm in eastern North America), and forest fires have been described as being the dominant natural processes determining forest renewal. In the Gaspesie region of eastern Canada, it has been suggested that fires were probably infrequent but may still have played an important role in forest dynamics by covering large areas as observed in other boreal mixedwood forests (Lévesque, 1997; Grenier et al., 2005). Due to the humid maritime climate, the effect of fire on the ecosystem has only briefly been acknowledged in the literature in the region. Some authors have suggested that the fire cycle is around 300–625 years (Gauthier et al., 2001; Lévesque, 1997). However, when an objective of forest management is to emulate natural disturbance, long fire cycles should be used to question even-aged management under short rotations. This study will thus seek to improve our knowledge about the fire regime with respect to such future management. More specifically, we will analyse the spatial influence of bioclimatic domains and physiographic factors, as well as the temporal influences of climate factors on the fire regime. A better knowledge of both the spatial and the temporal variation in the fire cycle will help us to better understand the forest dynamics of Gaspesie. It is also a necessary precursor for the development of management techniques adapted to this particular region.

Our first hypothesis is that, the bioclimatic domain (the eastern balsam fir-yellow birch bioclimatic domain) with greater deciduous tree cover (a less flammable fuel source), warmer temperature and higher precipitation will have a longer fire cycle than the coniferous dominated colder and drier bioclimatic domain (the eastern balsam fir-white birch domain). Continuing this reasoning, we would expect that biophysical features such as relief, altitude, vegetation and climate should also influence fire regimes. Based on the territorial division made by Saucier et al. (1998) who used a hierarchical ecological classification system, we have separated the study area into three groups (valleys, lowlands and highlands). The groups were delimited based on their mean altitudes, degree of slope and relief. We hypothesise that, high-altitude landscapes are more likely to be struck by lightning and dry rapidly and thus have more frequent fires than low-altitude regions that are more humid, and harbour rivers and streams which constitute a natural barrier against the propagation of fires (Rowe and Scotter, 1973; Ryan, 2002). Our final hypothesis is that the fire cycle will not be constant over time. According to previous studies in the eastern boreal forest we expect to observe an increase in the fire cycle since the end of the Little Ice Age. We will also reconstruct a Fire Weather Index (FWI) for the period 1920–2003. As a result, we expect to observe a gradual decrease in FWI correlated to a decrease in fire frequency (area burnt/year).

1.1. Study area

The study area (64°22′–67°42′W; 47°49′–49°15′N) is located in the Baie-Des-Chaleurs region in Gaspesie, at the southeastern edge of Quebec (Fig. 1). This region is part of the Northern Temperate Zone and the Boreal Zone (Saucier et al., 1998). The total area of the study region is about 6480 km^2. The relief is hilly, with some large plateaus and long valleys descending to the sea. Summits vary between 300 and 900 m in altitude above sea level. Most of the territory is covered with weathered and colluvium deposits. Till deposits are found in the northern portion of the territory; while the southern portion is dominated by weathered and marine deposits. Ninety-five percent of the territory is considered to be on mesic sites, with only about 1% of the area covered by water bodies. The mean annual temperature is 2.5 °C, and the mean annual precipitation varies from 900 to 1200 mm with 35% falling as snow.

The study area is comprised of two major bioclimatic domains: the eastern balsam fir-yellow birch bioclimatic domain and the eastern balsam fir-white birch bioclimatic domain (Fig. 1). The eastern balsam fir-yellow birch bioclimatic domain, which contains more deciduous species than the fir-white birch domain, is composed primarily of yellow and white birch (*Betula alleghaniensis*; *Betula papyrifera*), balsam fir (*Abies balsamea*), white spruce (*Picea glauca*), red maple (*Acer rubrum*) and white cedar (*Thuja occidentalis*). This part of the study area is characterized by valleys or small hills, and by weathered and marine deposits. The mean annual temperature varies between 1 and 2.5 °C (Grondin et al., 1999). The eastern balsam fir-white birch bioclimatic domain is composed primarily of white birch, balsam fir, white spruce and black spruce (*Picea mariana*). The mean annual temperature varies between 0 and 1 °C (Saucier et al., 1998). This part of the study area is characterized by low- and highlands, mountains, and colluvium and till deposits (Grondin et al., 2000).

Long-term territorial occupation is relatively unknown although records show that Native Americans have been present since the 1600s (Wein and Moore, 1977). The first Europeans colonised the territory shortly before 1650 (Desjardins et al., 1999). During this time, native people and the Europeans often used fire to clear patches for hunting and agriculture (Desjardins et al., 1999). Important forestry activities only began after 1759, mainly due to logging activities concentrated on eastern white pine (*Pinus strobus*). In the forest, pine was gradually replaced by white spruce as the major valuable timber. In 1820, the first licences controlling logging activities were given out. The harvest of forest resources progressively expanded deeper into the forest as well as along rivers to facilitate the transportation of logs. By 1920, harvesting became the principal economic activity of the Gaspesie region and resulted in, large-scale industrial forest operations by 1950 (Desjardins et al., 1999). Today, there are minor agricultural activities in the southern portion of the territory but most of the territory is managed by the forest

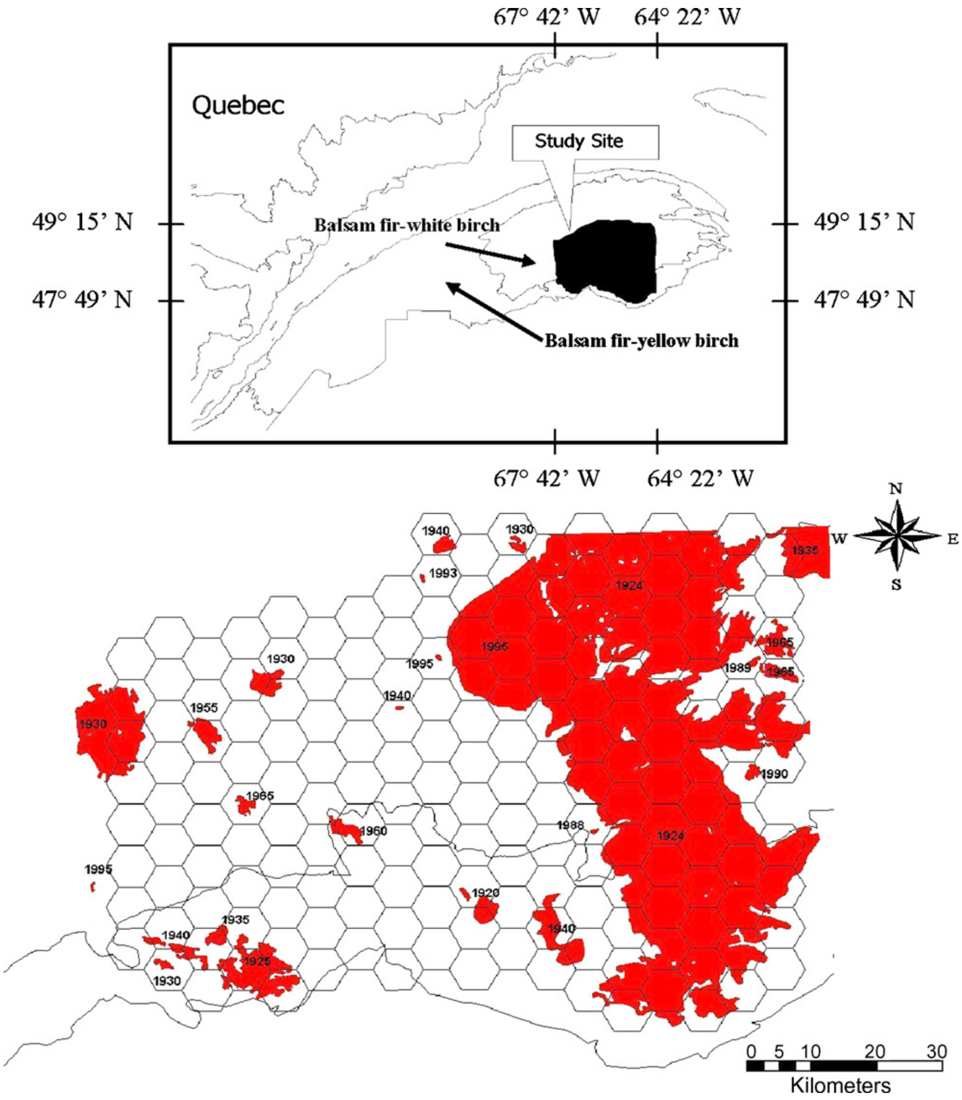

Fig. 1. Study site and firemap of the total burned area between 1920 and 2003.

industry (Robitaille and Saucier, 1998). The density of principle roads is low; however there is a high density of secondary roads. The probability of fire remains very low in the Gaspesie region because of the maritime air mass; however, during the last decade many fires have occurred because of human activities (Lévesque, 1997). Fire suppression was introduced in Quebec in the 1920s, but such activities were considered ineffective until the 1970s (Lefort et al., 2003; Bergeron, 1991).

2. Methods

2.1. Fire history reconstruction (1680–1920; 1920–2003)

To reconstruct fire history, we first used the archival data, and aerial photographs gathered since the 1930s by the Quebec Ministry of Natural Resources (QMNR) (Heinselman, 1973; Arno and Sneck, 1977; Johnson and Gutsell, 1994). These data were used to reconstruct a firemap from 1920 to 2003 (Fig. 1) that was then entered into a GIS database (Arc View). Dendrochronological analysis was then used to complete the data by allowing us to date fire-initiated stands from 1680 to 1920 in areas for which fires were not noted to have burned using aerial photographs or QMNR data.

2.2. Sampling method

The study area was first separated into 162,40 km^2 hexagons to insure systematic sampling. Only hexagons for which the last fire date was not already established by aerial photography and QMNR data were sampled (86 total). Sample sites were chosen according to an ecoforest map, which is provided by the QMNR and is based on photo-interpretation. It provides all the necessary information including stand age and composition, potential disturbance and road access. The species name and the diameter at breast-height of four trees were recorded every 20 m along a 200 m long transect. Transects were laid out according to the point-centered quarter method (Mueller-Dombois and Ellenberg, 1974).

Five to 10 disks and/or increment core samples were collected at the lowest height possible, to ensure greatest number of rings, for dendrochronological analysis (Phipps, 1986). To reconstruct fire history, it is important to use long-lived species that regenerate immediately following a fire in order to estimate the rate of tree recruitment and develop a post-fire age-class distribution throughout the territory. The preferred species were (in order): white birch, black spruce, yellow birch, and white spruce. Disks and cores were mounted, sanded and aged by counting the annual rings under a microscope (Phipps, 1986). The dendrochronological data were also added to the GIS database (Dansereau and Bergeron, 1993; Bergeron et al., 2001). For every hexagon, the year of fire was determined when at least 5 out of 10 individuals of a chosen transect originated from the same 20-year period. When less than five trees originated from the same 20-year period, the year of fire was determined by the age of the oldest individual tree (30% of the collected data) (Bergeron and Dubuc, 1989; Johnson and Gutsell, 1994). In such cases, the data was analysed statistically as constituting a minimal-age (censored data), in other words a value for which we only know the minimum age to which a stand survived. By means of archival data, photographs and samples, the *time since last fire* (TSF) was extrapolated for every hexagon. TSF data were used as the basis for fire-cycle estimation and survival analysis. On the same basis, spatial characteristics such as bioclimatic domains, valleys, lowlands and highlands were attributed to each hexagon for further comparison.

2.3. Fire cycle calculation

Several methods can be used to estimates fire cycle (Johnson and Gutsell, 1994; Lesieur et al., 2002). First, there are methods using survival analysis either based on parametric or semi-parametric tests. A survival analysis is used to estimate time to event data, where tree death due to fire is considered an event. The advantage of all survival analysis tests is that they take censored data into consideration, data for which a minimum age corresponding to the age of the oldest tree can be assigned. This is an important factor in estimating the fire cycle because of the proportion of old-growth and uneven-age stands in the Gaspesie region (approximately 30% of the study area). Survival analysis using parametric tests assumes that the distributions of variables belong to known parameterized families of probability distributions, such as the negative exponential or the Weibull distribution. The weakness of this approach is that it is uncommon for a distribution to perfectly fit a theoretical model. A second approach, survival analysis using semi-parametric tests, does not require the fitting of a theoretical model because the distribution is directly derived from the empirical data. However, the weakness of this approach is that if the distribution does not fit a theoretical model then the censored data (mostly at the end of the distribution) do not have the same weight in the analysis as the non-censored data, and this can lead to an underestimation of the length of the fire cycle.

Two other approaches not based on survival analysis can also be used. First, the average standing age of the forest can be used as it is more stable in time and space and it directly represents the percentage of forest affected by fire, but it does not gives an estimation of the fire cycle. Finally, the burning rate (area burned/time or number of years) gives an accurate estimation of the fire cycle, but it does not consider censored data.

The percentage of burned area was first calculated to assess the fire cycle between 1920 and 2003, using only the delimited areas burned (those obtained with archival data and aerial photographs) (Fig. 1). Additionally, survival analysis using the TSF distribution derived from both archives and dendrochronological data was used to estimate the fire cycle (Johnson and Gutsell, 1994; Allison, 1995). Survival analysis using the PROC LIFETEST was first used to evaluate the influence of spatial parameters. The PROC LIFETEST, which is a semi-parametric procedure of the SAS software (v8.02; SAS Institute Inc., 2001), produces estimates for the survivor function using the Kaplan–Meir method or life table method (for large data sets). It tests the homogeneity of survival curves for time since fire data over spatial or temporal scales (Allison, 1995). In order to better understand how fire cycles varied spatially, survival curves of the bioclimatic domains and of the valleys, lowlands and highlands were compared. We then separated the data into two bioclimatic domains: data from the balsam fir-yellow birch bioclimatic domain (Ab–Ba, $n = 41$) and data from the balsam fir-white birch bioclimatic domain (Ab–Bp, $n = 121$). Finally, the same procedure was used to compare the survival curves derived from the three other data groups (valleys $n = 40$, lowlands $n = 49$ and highlands $n = 73$).

The PROC LIFETEST procedure was also used to evaluate the influence of temporal parameters. Because we hypothesised that a climatic change occured after the end of the Little Ice Age, we evaluated cycles for the following periods: 1680–1850 and 1850–2003. The year 1850 was selected because it corresponds to the end of LIA as reported in the literature for eastern North America (Bergeron et al., 2004; Bergeron and Archambault, 1993).

The PROC LIFETEST procedure also allowed us to estimate the fire cycle based on the proportional hazard model, more commonly known as the Cox regression model (Cox, 1972). This procedure allows us to test for the hazard of burning function. It is important to first differentiate the hazard of burning from the fire hazard. Fire hazard is an index used by the forester to qualify the potential for fire based on fuel load, structure and phenology. The hazard of burning is a statistical notion which refers to a hazard rate, i.e. the instantaneous probability of fire (Johnson and Gutsell, 1994). Secondly, the hazard of burning allows us to estimate the fire cycle because Johnson and Gutsell (1994) have shown that the fire cycle is the inverse of the hazard of burning. Thus, we used the inverse of the mean hazard function to estimate fire cycles for the different spatial areas (Ab–Bp; Ab–Ba; Valleys; Lowlands; Highlands) and the different temporal periods (1680–2003; 1920–2003; 1680–1850; 1850–2003).

2.4. Fire Weather Index reconstruction

In order to assess the impact of climate on fire activity, we reconstructed the Fire Weather Index between 1920 and 2003.

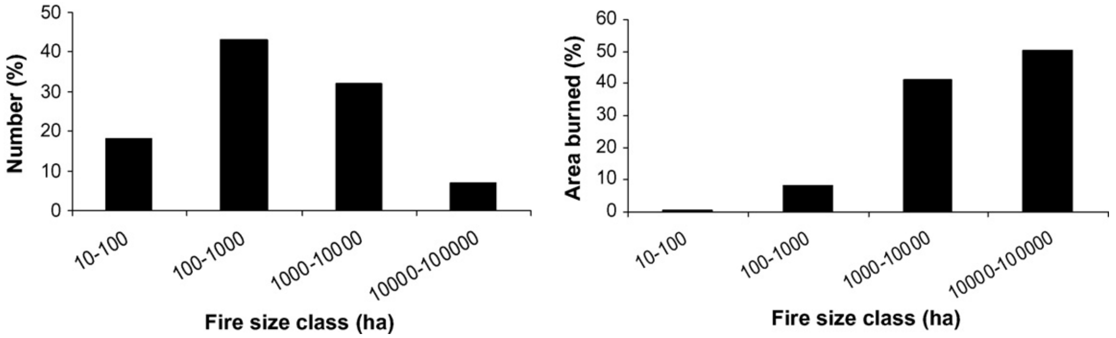

Fig. 2. Number of fires ($n = 33$) and fire size (total burned area: 241,893 ha) distribution between 1920 and 2003 in the Gaspesian mixedwood boreal forest.

We used data from the Gaspé meteorological station (48°8′N 64°5′W) located 88 km east of the western limit of the study area; as well as the Causapscal station (48°22′N 67°13′W), located 48 km west of the eastern limit of the study area. The FWI is an index developed by the Canadian Forest Service to provide a measure of the risk of potential fires across Canada (Service Canadien des Forêts, 1984). Different kinds of parameters are used to reconstruct FWI: precipitation, temperature, relative humidity, wind direction and wind speed. Linear regression was then used to test for an increase or a decrease in the degree of risk of fire through time. The results were then calculated by year and classified into five degrees of risk (low risk = FWI 0–4.6; moderate risk = FWI 4.7–10.2; high risk = FWI 10.3–14.7; very high risk = FWI 14.8–20.2; finally, extreme risk = 20.3 and more). The risk levels were developed by the Quebec Forest Protection Society against Fire (Canadian Forestry Service, 1984).

3. Results

3.1. Total area burned (1920–2003)

The total area burned between 1920 and 2003 covers about 241,893 ha, approximately 40% of the study area. The 1924 fire covers a large portion of the territory (158,459 ha of the burned area) (Fig. 1). Many fires also occurred in 1930 and 1995, burning 14,260 and 29,511 ha, respectively (Fig. 1). Causes remain unknown for the majority of the fires except for those that occurred in the 1990s (Appendix A). Fig. 2 shows that less than 10% of the fires are responsible for more than 50% of the total burned area. The largest fires (+1000 ha) are the ones that had the greatest impact on the landscape. The firemap (1920–2003) shows that the fires which occurred in 1924, 1930 and in 1995 are responsible for the majority of the total area burned.

For the 1920–2003 period, fires burned an average of 2914 ± 27,623 ha of forest per year representing 0.4% of the study area. Using these data, the fire cycle for the 1920–2003 period was established at 250 years (Table 2).

3.2. Age-class distribution and hazard of burning function

Based on the age-class distribution (Fig. 3a), 48% of the forest is over 100 years old. Between 1680 and 1880, and after 1920 the distribution appears to be relatively constant and between 1880 and 1920, there is a period without any fire events (Fig. 3a). Between 1880 and 1910, there is also a period for which the hazard of burning is negative (Fig. 3b). Fig. 3a and b both show that the 1924 fire is an extreme event. It covers approximately 36% of the study area and accounts for more than 40% of the forest being less than 80 years old (Fig. 3a).

3.3. Spatial and temporal variability

The survival functions were not influenced by spatial limits (Fig. 4a and b). Indeed, there is no significant difference between the Ab–Bp and Ab–Ba and between valleys, lowlands and highlands survival curves (Table 1). The fire cycle is longer in the Ab–Ba bioclimatic domain (Ab–Bp 96 years; Ab–Ba 145 years) and in the low-altitudes regions (valleys 147 years; lowlands 120 years; highlands 61 years). Although, the survival functions are not significantly different (Table 1). There is a significant difference between the pre-1850 and post-1850 periods (Fig. 4c). Moreover, there is an increase in the fire cycle from the pre-1850 period (89 years) to the post-1850 period (176 years) (Table 1). Table 2 also shows that there is a great

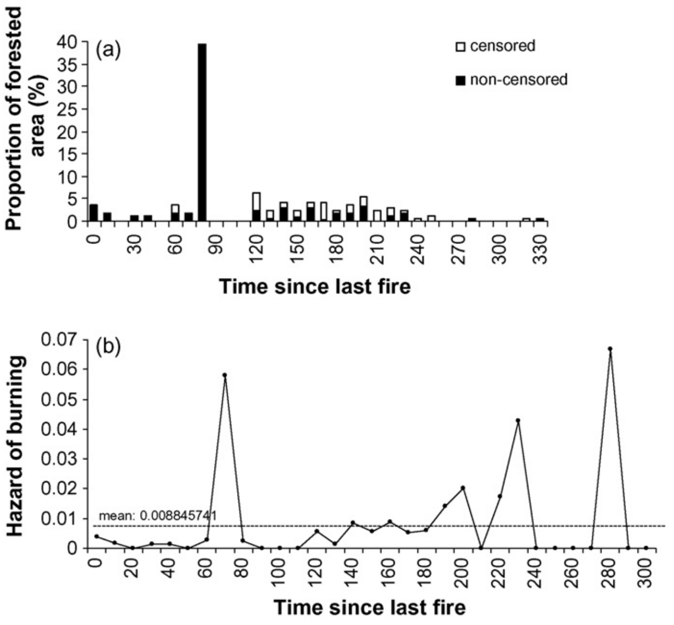

Fig. 3. (a) Time since fire distribution presented as the proportion of forest area that burned by decade and (b) hazard of burning over time.

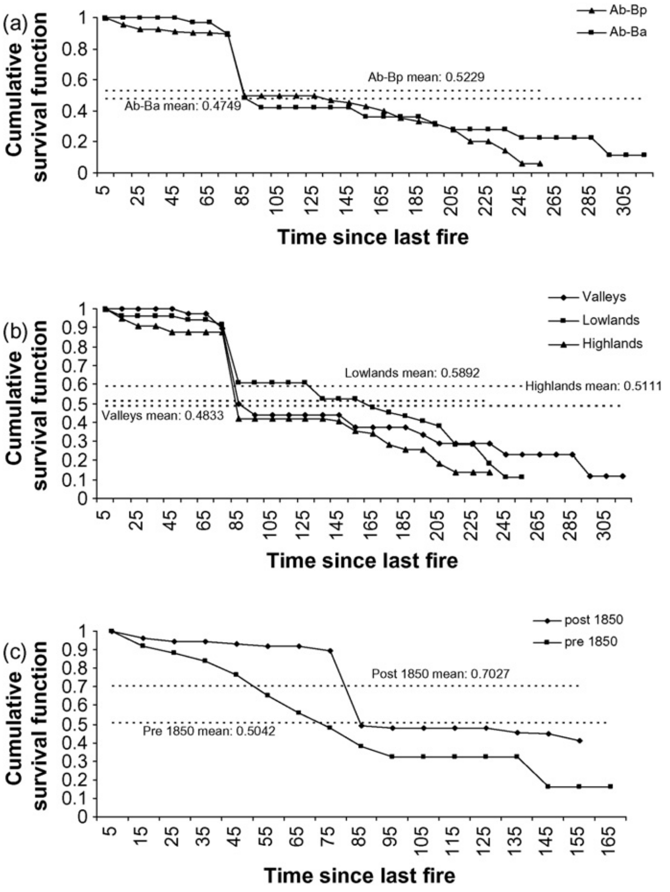

Fig. 4. Survival curves of time since fire data over spatial and temporal scales: (a) two bioclimatic domains (Ab–Bp and Ab–Ba); (b) valleys, lowlands and highlands; (c) pre-1850 and post-1850 periods.

variability between the different methods used to calculate the fire cycle. For the period 1920–2003, the fire cycle is estimated to be 116 years using semi-parametric survival analysis and 250 years with the burned rate method. Using the semi-parametric survival analysis, for the whole study period, the fire cycle is estimated to be 113 years (Table 2).

3.4. Fire Weather Index reconstruction

Both maximum and mean values of the FWI (Fig. 5a and b) decrease statistically between 1920 and 2003 (mean FWI $R^2 = 0.2961$, $p = 0.0001$, $n = 86$; maximum FWI $R^2 = 0.116$, $p = 0.0017$, $n = 86$). Between 1920 and 2003, extreme values dropped from the *very high* to *high* categories, while mean values changed from *moderate* to *low* categories (maximum FWI $R^2 = 0.1079$, $p = 0.06$, $n = 86$; mean FWI $R^2 = 0.1711$, $p = 0.01$, $n = 86$).

Table 1
Estimated fire cycles between different spatial and temporal scales, and the degree of statistical signification using the log-rank test

Spatial and temporal parameters	Estimated fire cycle (1/hazard function mean) (years)	Log-rank ($p \leq 0.05$)
Ab–Bp	96	0.6896
Ab–Ba	145	0.6896
Valleys	147	0.1937
Lowlands	120	0.1937
Highlands	61	0.1937
Pre-1850	89	0.0001
Post-1850	176	0.0001

Table 2
Fire cycles determined using different methods of calculation and different periods of time

Methods and periods	Estimated fire cycle (1/hazard function mean) (years)
Survival analysis (1920–2003)	116
Burning rate (1920–2003)	250
Survival analysis (1680–1850)	89
Survival analysis (1850–2003)	176
Survival analysis (1680–2003)	113

4. Discussion

4.1. Spatial and temporal variations in the fire cycle

The evidence we have gathered shows that the fire cycle for our study area varied between 1680 and 2003 (Table 2). This is confirmed by the differences between the pre-1850 and post-1850 survival curves (Fig. 4c). A similar trend for a lengthening of the fire cycle since the end of LIA has been observed in other studies (Bergeron et al., 2001; Lesieur et al., 2002; Lefort et al., 2003). It has been suggested that warmer, more humid air masses have lowered the frequency of the onset of fires (Bergeron and Archambault, 1993; Girardin et al., 2004). A dry warm decade in the 1920s, however, led to a dramatic increase

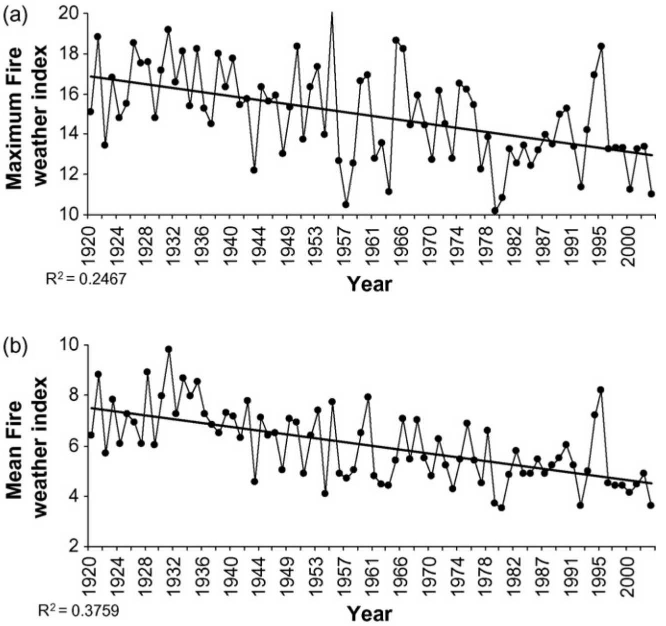

Fig. 5. Linear regressions of mean and maximum values of FWI. (a) Decreased mean values of FWI between 1920 and 2003; (b) decreased maximum values of FWI between 1920 and 2003.

in the extent of areas burned as particularly shown in 1924. As this dry phenomenon affected much of eastern Canada there are many reports of fires during this decade (Bergeron et al., 2001, 2004; Lefort et al., 2003). These fire events are exceptional and indeed, if we recalculate using a period post-1925, the fire cycle in the Gaspesian region increases to approximately 650 years. This observation suggests that fire occurrence in Gaspesie is generally very low, but that the region is occasionally affected by large fire events.

Many studies have shown that climate is the most important risk factor linked to fire occurrence and spread (Clark, 1998; Johnson et al., 1990, 1998; Bessie and Johnson, 1995; Carcaillet et al., 2001). According to our results, both the mean and maximum FWI have been decreasing since 1920 (Fig. 5a and b). This could explain the overall drop in fire frequency in the region.

Studies focusing on climate and forest fires demonstrate a link between long periods of drought and widespread fires (Clark, 1998; Bessie and Johnson, 1995; Lefort et al., 2003). Accordingly, in our study, the *high*, *very high* and *extreme* fire risk indices correspond to years in which large fires occurred. Moreover, a recent report by Girardin et al. (2004) suggests that the increase in the fire cycle in eastern Canada since the mid-1800s, could be attributed to the lower frequencies in the conditions leading to periods of extreme drought. Correspondingly, the frequency of drought in our study tends to decrease. This pattern has also been observed in other studies conducted in western and central Quebec (Lesieur et al., 2002; Lefort et al., 2003).

There were no significant variations in the fire cycle between the two bioclimatic domains or the valleys, lowlands and highlands (Fig. 4a and b) (Table 1). However, the variations observed are consistent with our first and second hypothesis. This confirms that we can not exclude differences between spatial variables at other scales, as other reports have mentioned the importance of spatial factors (Bergeron and Dansereau, 1993; Bergeron et al., 1999; Ryan, 2002). Indeed, it has been widely accepted that altitude and relief are determining factors in explaining differences in fire regime (Lertzman et al., 1998). There is an underlying link between these variables and the established factors of fire susceptibility which include: wind direction, wind speed, solar radiation and humidity (Rowe and Scotter, 1973; Ryan, 2002). The coarse scale sampling that we used ($\approx$40 km^2) may thus not have been adequate to reveal a statistically significant influence of spatial factors in our study area, or at least to identify the scale at which they are important. At the coarse scale of our analysis, climate was the main influence on fire cycle variability.

4.2. A natural fire cycle?

The fire map (1920–2003) (Fig. 1) and the length of the fire cycle suggest that fires in this maritime region are uncommon but not as rare as previously thought (Lévesque, 1997; Saucier et al., 1998; Gauthier et al., 2001). Relative agreement between the archival data (1920–2003) and the survival analysis for the 1850–2003 period (Table 2) provides greater confidence in our determination of a fire cycle situated between 170 and 250 years for this region.

Since we have only few data from before the period of colonisation, it is impossible to affirm that the values are representative of a natural fire cycle. In fact, the pre-colonisation fire regime can only be evaluated by a very small proportion of the territory which remains intact today (neither burned nor exploited). Colonisation and exploitation of this territory could have led to a decrease in the fire cycle; at least until any effective means of fire fighting was available. However, we observed a lengthening of the fire cycle as human populations increased. The distribution data shows a marked change around 1850 which we attribute to the end of the LIA since this period can not be associated with any change in human activity. No other significant change has occurred other than an intense fire period during the 1920s which was also observed in many other regions in Quebec (Bergeron et al., 2001, 2004; Lefort et al., 2003), but which again cannot be directly linked to the colonisation period. Moreover, almost all of the fires between 1920 and 1990 are of an unreported origin, making the clear establishment of an anthropogenic influence difficult (Appendix A).

The Gaspesian region presents a fire regime similar to the one observed to the south in the province of New-Brunswick (Wein and Moore, 1977). These authors estimated the global fire cycle to be 340 years. However, this value varies dramatically between regions. In northern New Brunswick, bordering our study area, the fire cycle is estimated to be 230 years. The fire cycle in east coast stands of New Brunwick is much higher (1000 years), as it is on the east coast of Gaspesie (Wein and Moore, 1977; Le Groupe Dryade, 1986; Lévesque, 1997). Finally, the fire cycle is longer in the high altitude stands of New-Brunswick, which seems to be the case in the high Gaspesian peaks as well (Lévesque, 1997).

4.3. Consequences for forest composition

The description that we made of the fire regime is an important step in understanding the natural dynamics which govern the Gaspesian forest. Indeed, it provides certain clues as to which types of vegetation one is likely to find in this area (i.e. a certain proportion of pyrogeneous species such as black spruce as well as their evolution to greater balsam fir dominance in time). Our findings show that this region has been subjected to important variations in fire cycle. The study area has seen lengthy periods of time without fire, but these were interrupted by shorter periods with important fire events. Lévesque (1997) also mentioned that fires had been infrequent in the Gaspesian region, but that they could cover vast surfaces. In Labrador, Foster (1983) also points to an uneven distribution of important fire events in time and space.

5. Conclusion

It seems that fire has a more important influence on the western part of the Gaspesian region through time than previously thought. The fire cycle has been estimated to be between 170 and 250 years. The type of fire regime, characterized by lengthy periods without fire interrupted by waves of intense fire, ensures the maintenance of long-lived pyrogenic species, such as black spruce in a matrix dominated by late successional species. Our results broaden our comprehension of the actual dynamics of the mixed boreal forest. Although we cannot ascertain that this is a naturally occurring fire cycle, there is no evidence to support the opposite. In fact the weight of evidence suggests that climate is a driving factor. We have, for example, shown that the fire cycle has increased since the end of the LIA. The cycle could continue to increase if droughts become scarcer. If managers wish to respect the criteria of sustainable management and biodiversity maintenance, they will need to reconsider silvicultural practices. Indeed, more than 50% of the study region contained forests that were more than 100 years old. Although the historical fire regime may justify the use of low retention cutting in order to emulate fire, the exclusive use of even-age management under short rotations should be questioned (Bergeron et al., 2006).

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Appendix A. Year, area and causes of fires that occured between 1920 and 2003

Fire year	Area (ha)	Cause
1920	173	Unknown
1920	1,240	Unknown
1923	17,545	Unknown
1924	158,459	Unknown
1930	272	Unknown
1930	1,582	Unknown
1930	12,004	Unknown
1930	402	Unknown
1935	954	Unknown
1935	725	Unknown
1935	6,048	Unknown
1940	40	Unknown
1944	2,649	Unknown
1947	711	Unknown
1947	447	Unknown
1947	698	Unknown
1947	37	Unknown
1947	886	Unknown
1960	1,386	Unknown
1960	1,047	Unknown
1965	1,469	Unknown
1968	2,034	Unknown
1968	686	Unknown
1988	55	Lightning
1989	106	Human
1990	292	Lightning
1990	375	Lightning
1993	60	Human
1995	27	Lightning
1995	5,861	Lightning
1995	36	Lightning
1995	482	Lightning
1995	23,105	Human

References

Allison, P.D., 1995. Survival analysis using the SAS system: A practical guide. SAS Institute Inc., Cary, NC, p. 292.

Arno, S.F., Sneck, K.M., 1977. A method for determining fire history in coniferous forest in the mountain west. Gen. Tech. Rep. U.S. Department of Agri., For. Ser., Intermountain Forest and Range Experiment Station, Ogden, UT, p. 28.

Attiwil, P.M., 1994. The disturbance of forest ecosystems: the ecological basis for conservation management. For. Ecol. Manage. 63, 247–300.

Bergeron, Y., Cyr, D., Drever, C.R., Flannigan, M., Gauthier, S., Kneeshaw, D., Lauzon, E., Leduc, A., Le Goff, H., Lesieur, D., Logan, K.A., 2006. Past, current and future fire frequencies in Quebec's commercial forest: implications for the cumulative effects of haversting and fire on age-class structure and natural disturbance-based management. Can. J. For. Res. 36, 2737–2744.

Bergeron, Y., Dubuc, M., 1989. Succession in the southern part of the Canadian boreal forest. Vegetation 79, 51–63.

Bergeron, Y., 1991. The influence of island and mainland lakeshore landscape on boreal forest fire regimes. Ecology 72 (6), 1980–1992.

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". Holocene 3 (3), 255–259.

Bergeron, Y., Dansereau, P.-R., 1993. Predicting the composition of Canadian southern boreal forest in different fire cycles. J. Veg. Sci. 4, 827–832.

Bergeron, Y., 1998. Les conséquences des changements climatiques sur la fréquence des feux et la composition forestière au sud-ouest de la forêt boréale québécoise. Géogr. Phys. Quat. 52 (2), 167–173.

Bergeron, Y., Harvey, B., Leduc, A., Gauthier, S., 1999. Forest management guidelines based on natural disturbance dynamics: Stand and forest level considerations. For. Chron. 75 (1), 49–54.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., Lesieur, D., 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Can. J. For. Res. 31, 384–391.

Bergeron, Y., Gauthier, S., Flannigan, M., Kafka, V., 2004. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. Ecology 85 (7), 1916–1932.

Bessie, W.C., Johnson, E.A., 1995. relative importance of fuels and weather on fire behaviour in subalpine forests. Ecology 76 (3), 747–762.

Canadian Forestry Service, 1984. Tables for the Canadian Forest Fire Weather Index System, fourth ed. Environment Canada, fourth ed., Canadian Forestry Service, Ottawa, Ontario, p. 48 (Forest Technical Report 25).

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S., Prairie, Y.T., 2001. Change of fire frequency in the eastern Canadian boreal forest during the Holocene, does vegetation composition or climate trigger the fire regime? J. Ecol. 89, 930–946.

Clark, J., 1998. Effect of climate change on fire regime in Northwestern Minnesota. Nature 334, 233–234.

Cox, D.R., 1972. Regression models and life tables (with discussion). J. R. Stat. Soc. B 34, 187–220.

Dansereau, P.-R., Bergeron, Y., 1993. Fire history in the southern boreal forest of northwestern Quebec. Can. J. For. Res. 23, 25–32.

Desjardins, M., Frenette, Y., Bélanger, J., Hétu, B., 1999. Histoire de la Gaspésie, Nouvelle Édition. Les Presses de l'Université Laval, p. 768.

Flannigan, M.D., Stocks, B.J., Wotton, B.M., 2000. Climate change and forest fires. Sci. Tot. Environ. 262, 221–229.

Foster, D.R., 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. Can. J. Bot. 61 (9), 2459–2471.

Gauthier, S., Leduc, A., Harvey, B., Bergeron, Y., Drapeau, P., 2001. Les perturbations naturelles et la diversité écosystémique. Nat. Can. 125, 10–17.

Girardin, M.P., Tardif, J., Flannigan, M.D., Bergeron, Y., 2004. Multicentury reconstruction of the Canadian drought code from eastern Canada and its relation-ship with paleoclimatic indices of atmospheric circulation. Climate Dyn. 23, 99–115.

Grenier, D.J., Bergeron, Y., Kneeshaw, D., Gauthier, S., 2005. Fire frequency for the transitional mixedwood forest of Timiskaming, Quebec, Canada. Can. J. For. Res. 35, 656–666.

Grondin, P., Blouin, J., Racine, P., 1999. Rapport de classification écologique du sous-domaine bioclimatique de la sapinière à bouleau jaune de l'est. Service de l'évaluation de l'offre/Service de la recherche appliquée. Direction des inventaires forestiers/Direction de la recherche forestière. Forêt Québec. Ministère des Ressources naturelles du Québec.

Grondin, P., Blouin, J., Racine, P., d'Avignon, H., Tremblay, S., 2000. Rapport de classification écologique du sous-domaine bioclimatique de la sapinière à bouleau blanc de l'est. Service de l'évaluation de l'offre/Service de la recherche appliquée. Direction des inventaires forestiers/Direction de la recherche forestière. Forêt Québec. Ministère des Ressources naturelles du Québec.

Heinselman, M.L., 1973. Fire in the virgin forest of the Boundary waters Canoe Area, Minnesota. Quat. Res. 3, 329–382.

Hély, C., Bergeron, Y., Flannigan, M.D., 2000. Effects of stand composition on fire hazard in mixed-wood Canadian boreal forest. J. Veg. Sci. 11, 813–824.

Johnson, E.A., Fryer, G.I., Heathcott, M.J., 1990. The influence of man and climate on frequency of fire in the interior wet belt forest. Br. Columbia J. 78, 403–412.

Johnson, E.A., Gutsell, S.L., 1994. Fire frequency, models, methods and interpretations. Adv. Ecol. Res. 25, 239–287.

Johnson, E.A., Miyanishi, K., Weir, J.M.H., 1998. Wildfires in the western Canadian boreal forest: landscape patterns and ecosystem management. J. Veg. Sci. 9, 603–610.

Lefort, P., Gauhtier, S., Bergeron, Y., 2003. The influence of fire weather and land use on the fire activity of the laka Abitibi area, eastern Canada. For. Sci. 49 (4), 509–521.

Le Groupe Dryade, 1986. Étude de l'importance du rôle écologique du feu dans les parcs nationaux de la région du Québec. Parcs Canada, région de Québec, Québec.

Lertzman, K.P., Fall, J., Dorner, B., 1998. Three kinds of heterogeneity in fire regimes: at the crossroads of fire history and landscape ecology. Northwest Sci. 72, 4–23.

Lesieur, D., Gauhtier, S., Bergeron, Y., 2002. Fire frequency and vegetation dynamics for the south-central boreal forest of Quebec, Canada. Can. J. For. Res. 32, 1996–2009.

Lévesque, F., 1997. Conséquence de la dynamique de la mosaïque forestière sur l'intégrité écologique du Parc National Forillon. Thèse de Maîtrise. Université Laval.

Mueller-Dombois, D., Ellenberg, H., 1974. Aims and Methods of Vegetation Ecology. Wiley, New York.

Phipps, R.L., 1986. Collecting, preparing, crossdating and measuring tree increment cores. U.S. Geological Survey Water-Resources Investigations, Rep. 85-4148. Lakewood, CO, pp. 5–35.

Pickett, S.T.A., White, P.S., 1985. The Ecology of Nature Disturbance and Patch Dynamics. Academic Press, New York.

Robitaille, A., Saucier, J.P., 1998. Paysage régionaux du Québec méridional. Les Publications du Québec, Sainte-Foy, Québec, pp. 2 to 8, 117–118 and 156 to 159.

Rowe, J.S., Scotter, G.W., 1973. Fire in the Boreal Forest. Quat. Res. 3, 444–464.

Ryan, K.C., 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica 36 (1), 13–39.

Saucier, J.P., Bergeron, J.-F., Grondin, P., Robitaille, A., 1998. Les régions écologiques du Québec méridional (3e version): un des éléments du système hiérarchique de classification écologique du territoire mis au point par le ministère des Ressources Naturelles du Québec, Supplément de L'Aubelle. Février-Mars.

Service Canadien des Forêts, 1984. Tables for the Canadian Forest Fire Weather Index System, 4ième édition. Environnement Canada, Service canadien des forêts, Ottawa, ON. Rapport technique en foresterie, no. 25, 48 p.

Stocks, B.J., 1993. Global warming and forest fires in Canada. For. Chron. 69 (3), 290–293.

Weber, M.G., Stocks, B.J., 1998. Forest Fires and Sustainability in the Boreal Forest of Canada. Ambio 27 (7), 545–550.

Wein, R.W., Moore, J.M., 1977. Fire history and rotation in the Acadian Forest of New Brunswick. Can. J. For. Res. 7, 285–294.

Wotton, B.M., Flannigan, M.D., 1993. Length of fire season in changing climate. For. Chron. 69, 187–192.