The Influence of Fire Weather and Land Use on the Fire Activity of the Lake Abitibi Area, Eastern Canada

Patrick Lefort, Sylvie Gauthier, and Yves Bergeron

ABSTRACT. The fire history of two adjacent regions of the boreal forest, one characterized by logging (Ontario—510,000 ha) and the other by small scale agricultural activities (Quebec—140,000 ha), was studied before and after these regions were opened up to settlement in 1916. From a review of provincial forest fire records and the assessment of the age of fire-initiated forest stands, it appears that large but rare fires occurred during the presettlement period on both sides of the border. After 1916, due to slash and burn activities, the agricultural region (Que) had proportionally about twice the burned areas and ten times more fires than the forestry region (Ont). Despite differences in population density, road network, and land use, fire size class occurrence did not differ between landscapes over time. However, the occurrence of fires larger than 100 ha, considering three development phases (1916–1939; 1940–1969; 1970–1998), decreased in both regions from settlement to the present, particularly during the late phase (1970–1998) in the agricultural region. An analysis of fluctuations in the Canadian forest Fire Weather Index system (FWI), a rating of fire danger severity, showed major climatic stresses at the beginning of the century (1916–1924), followed by a decrease in the occurrence of extreme FWI values. Combined with the impact of climate, which affected the annual area burned and the number of large fires in both landscapes, the results suggest that the landscape fragmentation, the increase in the percentage of deciduous trees over time and/or effective fire detection by residents led to a decrease in the number of fires larger than 100 ha on the agricultural side for the late phase (1970–1998). For. Sci. 49(4):509–521.

Key Words: Settlement, FWI, suppression, fire size.

SINCE THE EARLY 20TH CENTURY, many changes have been observed in the disturbance regime of the boreal forest in eastern Canada. Based on Ontario Ministry of Natural Resources data, logging has become the main forest disturbance agent (Ward and Tithecott 1993). At the same time, the occurrence and extent of spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks appear to have increased (Blais 1983, Blais 1985, Morin et al. 1993). How-

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ever, the most significant change is probably a decrease in area burned (Clark 1990, Bergeron 1991, Bergeron and Archambault 1993, Larsen 1996). This change is believed to be having an effect on spruce budworm outbreaks (Anderson et al. 1987, Bergeron and Leduc 1998) and on the composition of the forest mosaic, which depends mainly on the time elapsed since the last fire (Bergeron and Dubuc 1989).

Changes in forest fire dynamics can be driven by human activities, climatic variations or both of these factors combined. No consensus has been reached regarding the effect of these different factors on the current fire regime, and a frequently cited study (Ward and Tithecott 1993) which shows the effectiveness of fire suppression efforts in eastern Canada has recently sparked heated debate (Bridge 2001, Miyanishi and Johnson 2001, Ward et al. 2001). With regard to human impact, studies done in Montana, Ontario and the Acadian Forest suggest that active fire suppression has led to a decrease in the area burned (Wein and Moore 1979, Barrett et al. 1991, Ward and Tithecott 1993, Brown et al. 1994). In contrast, other studies indicate an increase in the area burned during the post-settlement period owing to the many fires ignited by human and/or logging activities (Cwynar 1977, Hemstrom and Franklin 1982). On the other hand, climate is known to be an important factor in forest fire dynamics (Flannigan and Harrington 1988, Harrington and Flannigan 1993, Johnson and Wowchuk 1993). Climatic variations have a considerable influence on the area burned, whether the time scale is a year, decade or century (Clark 1990). A decrease in burned areas has been observed in many regions of Canada (Suffling et al. 1982, Masters 1990, Bergeron 1991, Johnson and Larsen 1991, Johnson and Wowchuk 1993). In the boreal forest of Quebec, it has been suggested that the long-term decline in area burned is linked to a decrease in drought events associated with the climatic warming that has occurred since the end of the Little Ice Age ca. 1850 (Bergeron and Archambault 1993, Flannigan et al. 1998).

Few studies have simultaneously considered the effects of fire weather and humans on fire regime. Studies in western Canada suggest that climate is the primary factor controlling forest fire dynamics, while active fire suppression and small-scale human activities (e.g., road construction) may have a minor effect during periods of high susceptibility to fire (Johnson et al. 1990, Masters 1990). To our knowledge, no studies have been conducted in Abitibi, eastern Canada, on the influence of fire weather and human activities on the dynamics of boreal forest fires during the 20th century. The Abitibi region offers the opportunity to study the effects of different land uses on fire activity. In fact, since the opening up of the territory in 1912, the Quebec section has mainly been used for agriculture whereas the Ontario region (Lake Abitibi Model Forest (LAMF)) has mainly been devoted to forest harvesting. These different land use patterns imply a denser road network, higher population density (distributed in several villages), major slash and burn activities and a lower proportion of forested areas (66%) on the Quebec side than on the Ontario side (99%). Note however that both landscapes can be considered as mainly forested (see study area section). Furthermore, roads also indirectly improve fire detection and fire suppression on the Quebec side through a more extensive network but, on the other hand, escapes from slash and burn activities may have greatly influenced the fire history (La Gazette du Nord 1923–1950, Lehtonen and Huttunen 1997, Weir and Johnson 1998).

The general goal of this study is to describe the fire activity of the two landscapes prior to and after settlement. In this study, the fire regime parameters analyzed will be limited to the occurrence of fire, the burned areas, and the distribution of fire size classes. More specifically, our objectives are (1) to estimate the natural fire activity prior to European settlement in the Abitibi region by reconstructing the fire history, (2) to evaluate the effects of fire weather on fire regime parameters, and (3) to compare the current fire activity of the agricultural (Que) and logging (Ont) landscapes. We hypothesized that total burned area and fire occurrence would be higher on the Quebec side since human population density is recognized to be linked to high fire occurrence (Cwynar 1977, Martell 1994, Lehtonen and Huttunen 1997).

Study Area

The study area is located at the southern edge of the boreal forest, in the balsam fir (*Abies balsamea*)–white birch (*Betula papyrifera*) climax domain. Both regions are part of a broad physiographic unit known as the Clay Belt, which extends across northern Quebec and Ontario over more than 400 km × 150 km. The flat topography of the Abitibi region was created by lacustrine deposits from the maximum post-Wisconsonian extension of proglacial Lake Barlow-Ojibway (Vincent and Hardy 1977). The border between the provinces of Ontario and Quebec divides the whole area of interest into two landscapes, each of which has undergone a different type of development (McDermott 1961). The region characterized by forest management is situated in Ontario. It encompasses the southern portion of the LAMF (80°41’W to 79°31’W; 48°38’N to 49°15’N; Figure 1). The Ontario region covers about 510,000 ha and includes a large body of water, Lake Abitibi, with a surface area of 99,000 ha. In Quebec, the region underwent conversion to agriculture (79°31’W to 79°05’W; 48°34’N to 49°00’N) and has an area of 140,000 ha.

When the two regions were opened up in 1912, the forest engineers’ evaluation reports indicated that spruce, and to a lesser extent jack pine, were the dominant species (Perron 1989, p. 15). From an analysis of aerial photos taken in 1926, the proportion of coniferous forest in each province was estimated at nearly 80%. GIS databases for the two provinces indicate that regenerating stands (0–30 yr) cover 30% of the LAMF and 6% of the agricultural study area at present. However, pasturelands and urban zones cover 34% of the Quebec side. In the LAMF, both regenerating stands and primary forests are conifer dominated (nearly 80%) whereas fallow lands and forests on the Quebec side are dominated by deciduous and mixed stands (76%).

On clay sites, mature forest stands consist primarily of black spruce (*Picea mariana*) and balsam fir (*Abies*

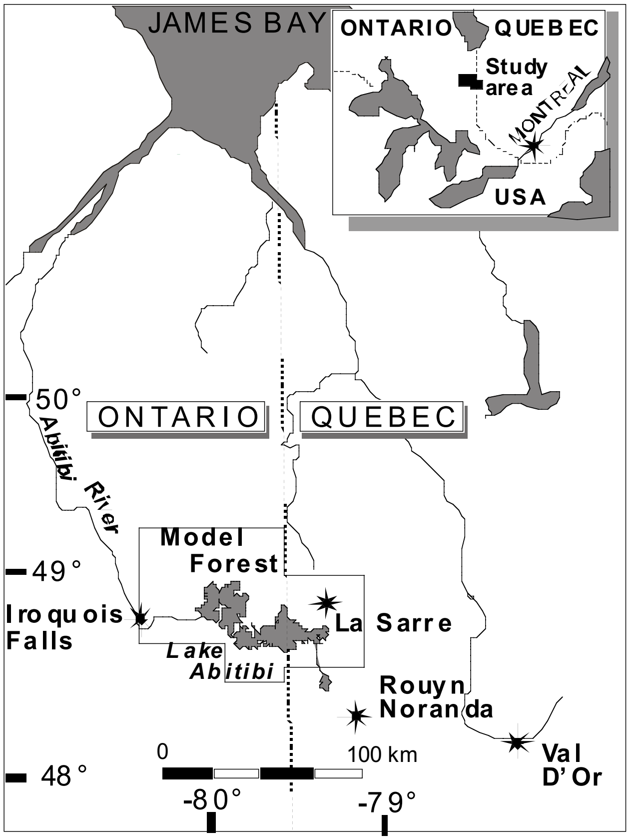

Figure 1. Geographic location of the forestry landscape (Ontario) and the agricultural landscape (Quebec).

balsamea), associated with trembling aspen (*Populus tremuloides*) and white birch (*Betula papyrifera*) in smaller proportions. On well-drained sites with sand and till deposits, jack pine (*Pinus banksiana*) often forms pure stands that are of fire origin. In locations where the fire interval is long, late-successional species like eastern white cedar (*Thuja occidentalis*), white spruce (*Picea glauca*) and balsam fir are more abundant (Bergeron and Dubuc 1989). Weather data has been collected at the Iroquois Falls weather station, located in the westernmost part of the study area (48°45'N, 80°40'W), since 1916. The mean annual temperature is 0.9°C with annual precipitation reaching 792 mm (72% as rain). The fire season runs from May to August; for that period, mean temperature is nearly 14°C and precipitation totals 337 mm. There are 1,366 degree-days above the base of 5°C (Environment Canada 1993).

Abitibi History

Archaeological studies stated that native peoples had occupied the Lake Abitibi area as far as 4,900 yr before the present (Vincent 1995, p.75). Population was low, and missionaries observed that natives were nomads with no permanent village; they subsisted on hunting, fishing and fruit gathering. It is recognized that natives sometimes ignited fires near camps in poorly conducive fire weather (Lewis 1982). However, no archives or reports were found on fire use by native peoples in the Abitibi area. Thus, they will be considered as a part of the natural fire regime as they occupied the whole study area.

The Abitibi region was opened up in 1912 with the completion of the transcontinental railroad, whereas important agricultural and forestry activities began in 1916. Prior to the construction of the railroad, the area was visited only sporadically by white men who were either trappers or missionaries. The late development of the region can be explained through its political history, its hydrology, and its distance from existing settlements. The provincial boundaries defining the northern division between Ontario and Quebec were not established until 1898. Moreover, the divide of the St. Lawrence/Great Lakes and James Bay watersheds is located about 20 km south of the two landscapes of interest. The drainage pattern of the study area is therefore characterized by a northern flow toward James Bay. Given that the sawmills were located in the St. Lawrence/Great Lakes drainage basin, wood floating could not take place. Finally, the remoteness of the study area, together with the absence of a land-based communication network, kept the region relatively intact until 1916 when substantial settlement and timber activities began (Perron 1989, p. 15, Vincent 1995, p. 199–212).

Differences in land use on both sides of the border cannot be attributed to major differences in landscape characteristics such as soil, vegetation, or topography. Aerial photographs taken in the 1920s showed that forest composition was similar and conifer-dominated (about 80%), suggesting, therefore, that the timber potential was essentially the same on both sides of the border. Moreover, Canada Land Inventory maps for the Abitibi area show that the potential for agricultural use is similar for the LAMF and Quebec side (www.geogratis.cgdi.gc.ca). Differences in land use between Ontario and Quebec are strictly due to different provincial politics and history. As a matter of fact, to stop the exodus of French Canadians to New England at the beginning of the 20th century, the Quebec provincial government financially supported settlers who wanted to move to the Abitibi area to develop agriculture (McDermott 1961, Vincent 1995, p. 243).

In Ontario, following the construction of the railroad, logging started up on a small scale. The whole Abitibi area was covered with stands of black spruce, a species highly prized by the forest industry. With the establishment of Abitibi Power and Paper at Iroquois Falls near Lake Abitibi at the beginning of the 1910s (Perron 1989, p. 10), harvesting of forest resources expanded substantially. In Quebec, agricultural activities started up around the mid-1910s and covered 5% between 1923 and 1936. Settlers poured into the region in greater numbers than anywhere else in the province (Vincent 1995, p. 210). Land clearing stopped in the 1960s once it became clear that the climate was not appropriate for intensive farming. At that time, some 30% of the area was either cropland or pastureland. A forest matrix still covers the rest of the landscape, despite a large number of burns and zones with young regenerating stands, which are essentially on fallow land. At present, the primary and secondary road density is 3.0 times higher on the Quebec side (44.6 km/100 km^2) than in the LAMF (14.8 km/100 km^2) (Figure 2).

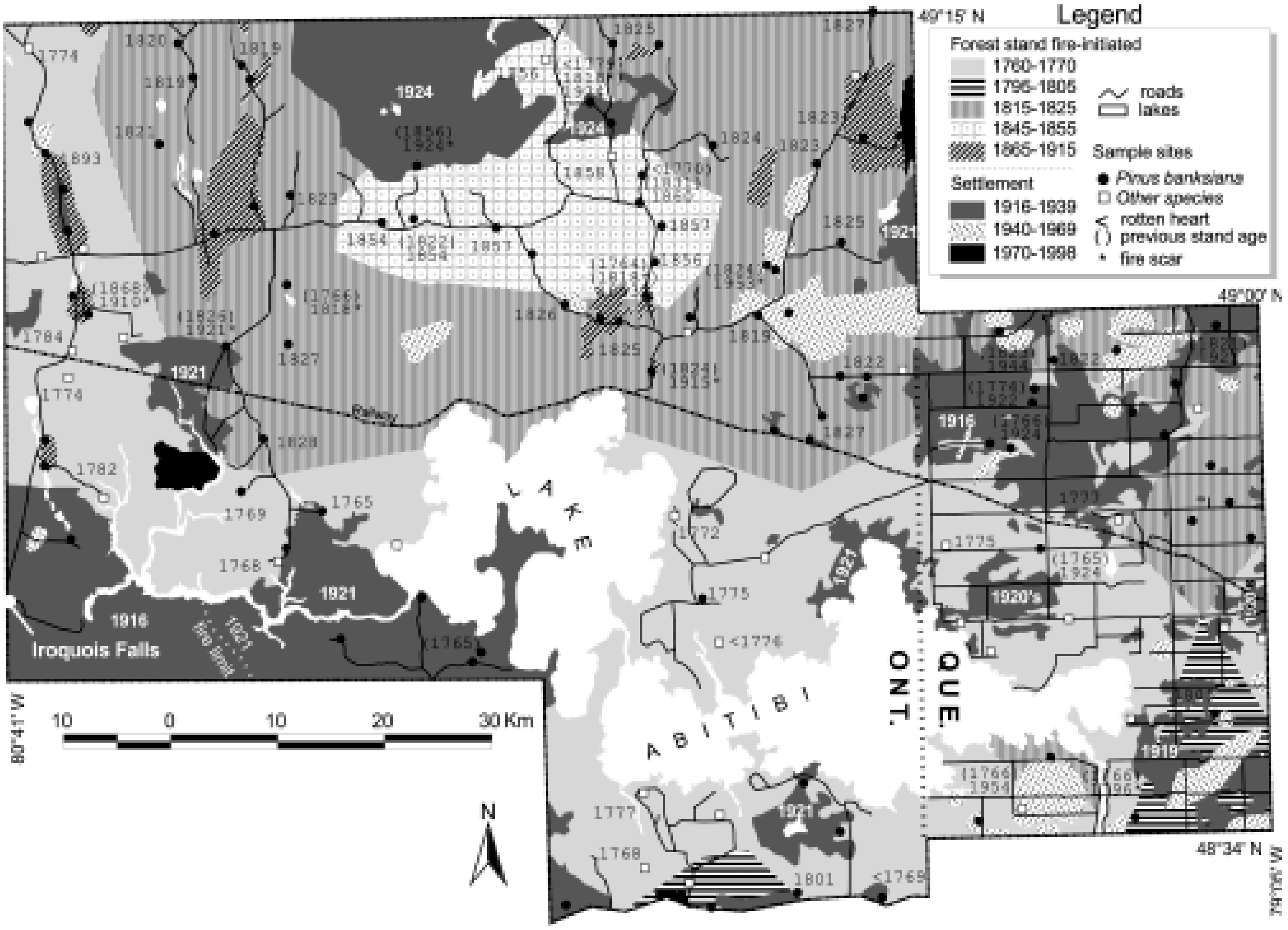

Figure 2. Time since fire map of forestry (Ontario) and agricultural (Quebec) landscapes. Fires larger than 500 ha are shown. White numbers in the 20th century fires indicate the precise year of the fire. The oldest tree in each sample site is indicated by black numbers for 50% of the 122 sites. See the legend for complete information.

Methodology

Time Since Fire Map

Ontario's fire maps (Donnelly and Harrington 1978), scientific publications on fire-initiated forest stands near or within the present study area (Shafi and Yarranton 1973, Dansereau 1991, Dansereau and Bergeron 1993, Bergeron et al. 2001) and fire reports (1923–1998) from the Great Lakes Forestry Centre (Ont) and the ministère des Ressources naturelles (Que) were used to produce the time since fire map of the study area. The local newspaper (La Gazette du Nord 1923–1950), travel notes and surveys were also consulted. All fires greater than 500 ha were drawn on 1:250,000-scale topographic maps. Archives and aerial photographs allowed us to delineate and date fires that burned between 1916 and 1998, representing 41% of the agricultural (Que) area and 23% of the LAMF (Ont).

We completed the time since fire map for the period prior to settlement by analyzing aerial photographs and by sampling forest stands using the methods of Heinselman (1973) and Johnson and Gutsell (1994). We began by studying the oldest available aerial photographs (1926) of the region that were taken at a scale of 1:18,000, thus providing a high resolution of the forest landscape. It allowed us to clearly define previous fire boundaries, particularly in stands differing in age by more than 100 yr (Romme 1982). However, old fire limits were sometimes masked by large muskeg zones or by poor tonal and textural differences on aerial photographs. In these cases, fire limits were defined by drawing a straight line through the bog areas. Fire events were differentiated from other disturbances or nonproductive sites (insect epidemics, windthrow, muskeg, etc.) by analyzing the spatial extent and shape of the openings. As an example, windthrow disturbance often presents a linear shape (Lehmann et al. 1975). On the other hand, fire boundaries generally show a more elliptical shape with sawtooth edges, whereas muskegs present smooth edges. The presence of jack pine stands in aerial photographs, validated by the analysis of forest cover maps, confirmed the fire origin of the openings.

This preliminary fire map was used to plan field sampling, which focused on primary forest stands and remnant forest islands established before 1916. Sites were selected based on road access and 1971 and 1987 forest cover maps. A total of 122 sample points were visited within the study area, resulting in 2.6 sample points/100 km^2 (Figure 2). To provide an accurate picture of the forest stands' origin, 18 sample points were also visited outside the boundaries of both landscapes within a maximum distance of 5 km. Other studies in Abitibi (Bergeron 1991, Dansereau and Bergeron 1993, Bergeron et al. 2001) have shown that the region was swept by a few large fires (>100 km^2). Thus, our sample site density was designed to detect large fires.

At each site visited, five disks or increment cores were collected above the ground level (~30 cm) from pioneer tree species. Most of the trees sampled were jack pine (n = 306 live trees and 241 snags), since this species is well distributed in both landscapes, and it generally forms even-aged stands of fire origin (Gauthier et al. 1993) as boreal forest fires are typically stand-killing fires (Johnson 1992). Moreover, the existence of a regional tree-ring chronology series allowed us to cross date available jack pine snags (Dansereau and Bergeron 1993). In the absence of jack pine, live specimens of other species such as black spruce (n = 102), white birch (n = 50), trembling aspen (n = 28) and other species (n = 9) were sampled. The disks and increment cores accounted for 86% and 14% of the samples collected respectively. The black spruce samples provide only a minimum date, given that Desrochers and Gagnon (1997) found that the root collar of black spruce is generally located below the mineral soil level. In the case of jack pine, the age obtained is fairly precise, since stem growth is rapid, and this species generally grows in well-drained environments with a thin layer of organic soil (Lafond 1966).

The cores and disks were first dried and then sanded mechanically using progressively finer emery paper. To determine stand age from samples taken from living trees, we used a binocular microscope to count the growth rings (on two radii for the disks); the fire date could be estimated to within 10 yr. We cross-dated jack pine snags by two complementary procedures. First, we determined the age of the samples through visual cross-dating. To confirm this result, we then measured the growth rings in the samples with a Henson micrometer so that the unknown tree-ring series could be cross-dated against the master chronology. We verified the cross-dating with the Cofecha software program (Holmes 1983). Afterward, the fire years were compared with travel and historical notes mentioning forest fires in the Abitibi area to assess the convergence of results (Trudelle 1937, MacLean and Bedell 1955, Perron 1989, Pollock 1995).

A final presettlement time since fire map (fires >1,000 ha) based on the fire boundaries (from aerial photographs) and the age of the sampled trees was then digitized using the Arc/Info geographic information system. The fire map shows the location of forest stands as a function of time since last fire, without considering the effect of land clearing, felling, or other disturbances. In every case, except for black spruce, the fire polygons were delineated by connecting sites that had a similar stand initiation date within a 10 yr interval. For example, the sites for which samples showed an age less than 1828 and greater than 1818 were linked to the 1818 fire scars. For black spruce, the age of the samples was used to validate the polygons as long as: (1) the minimum date was not less than 1818, and (2) the sample date was not greater than an interval of 20 years, i.e. <1838. Otherwise, dates obtained with black spruce were considered an indication of a minimum fire date. The resulting map was used to compare the presettlement fire regime of both landscapes. The area of each forest fire was computed using the ArcView geographic information system. In a few cases, the fire polygons of the largest fires were defined by extrapolating the fire limits to the mid-distance between two sample points with different forest stand ages (Niklasson and Granström 2000).

Post-Settlement Fire Activity

An effort was made to establish the relationship between fire size, type of landscape (forest and agricultural) and phase in the change of these landscapes: early phase (1916–1939), middle phase (1940–1969) and late phase (1970–1998). This differentiation between the early, middle, and late phases of landscape development is necessary because fire activity changes as a function of the available technology and regional development (Lefebvre 1972, Barney and Stocks 1983, Ward and Tithecott 1993). These different phases reflect three distinct steps in the effectiveness of active fire suppression in Abitibi that varies greatly depending on the period of technological development. This division also reflects the historical pattern of landscape development while covering similar time intervals. In the early phase (1916–1939), fire suppression was low, as fire-fighting was limited to the use of shovels, axes, and manual saws (Bernier 1948, p. 120–139; provincial fire reports of Quebec and Ontario 1923–1939); land clearing (Que) and harvesting (Ont) occurred at a local scale whereas population density (2.5 persons/km^2) was low on the Quebec side. During the middle phase (1940–1969), fire suppression became more efficient with the use of chainsaws, motorized vehicles, and water pumps (Perron 1989, p. 29; SOPFEU provincial fire agency, pers. comm.). Land clearing and harvesting activities began to be mechanized, and thus increased in extent (Vincent 1995, p. 254). Population underwent expansion (10.7 persons/km^2) on the agriculture side, while road networks increased on both sides of the border. Finally, in the late phase (1970–1998), fire suppression became more effective and homogeneous on both sides with the introduction of water bombers in 1970 (SOPFEU, pers. comm.). In the agriculture landscape, land clearing diminished during this last phase with the recognition that the regional climate was inappropriate for agriculture. On the other hand, residents (17.1 persons/km^2) of the agriculture landscape started numerous brush fires that sometimes burned adjacent forest stands when they got out of control. In the same phase, on the LAMF side, massive harvesting activities and clearcutting were taking place with the introduction of wheeled skidders, which greatly increased production (Archibald and Arnup 1993).

A contingency table was constructed to compare the effect of the type of landscape (agriculture or forestry) and the development phase (early, middle, late) on fire size occurrence in ha (10–99, 100–999 and 1000 +) using the Mantel-Haenszel chi-square (Q_{CS}) with the SAS software. The Q_{CS} statistics are well suited for fire size analysis, which often presents extreme occurrence values. It is based on total frequencies across the levels of the nominal variable more than on individual cell sizes; moreover, it requires minimal assumptions (Stokes et al. 1995, p. 106). On the other hand, inference might be limited by the use of

Q_{CS} statistics. Pearson chi-square components (χ^2_p: $[O–E]^2/E$) was used to measure the difference between observed (O) and expected (E) values, with the critical value computed using the formula: $(v\chi^2_{[1,\alpha]}/\text{no. cells})^{1/2}$, where v represented degree of freedom. Due to multiple testing, $\alpha = 0.05$ was corrected by the Bonferroni criteria ($\alpha' = \alpha/k$ where k was the number of independent tests; Legendre and Legendre 1998).

In order to assess the effect of human activity on fire size in each landscape, we performed a linear regression between fire size (in ha) and the FWI. The residuals of the regression following removal of the effect of the FWI were analyzed in relation to the three phases of landscape development using a nonparametric analysis of variance test (Kruskal-Wallis). A mean comparison test on ranks ($P = 0.05$) was then performed to detect differences in the residuals among the three development phases for each landscape.

Meteorological Data

In order to assess the impact of climate on the fire activity, we studied climatic variations by means of the Canadian forest Fire Weather Index system (FWI), which is used universally in Canada (Flannigan et al. 2000). The FWI is a rating of the daily fire danger severity, which takes into account three interrelated factors: (1) daily meteorological conditions, (2) fuel moisture codes and (3) fire behavior indices (Canadian Forestry Service 1984). Relative humidity, wind speed, temperature, and precipitation were used to build the three previous factors. Data from the Iroquois Falls weather station, which has been in operation since the region was first settled, were used to reconstruct the FWI for the post-settlement period (1916–1998, May to August). This weather station is the only one which provides data since 1916 in the entire study area. Mean values of relative humidity and wind speed from the Val d'Or (nearest) weather station had to be used because these parameters were not recorded at Iroquois Falls; as a consequence, extreme FWI values might be flattened. Autocorrelation between temporally contiguous fire seasons was tested with the *R* statistical software package (Legendre and Vaudor 1991) by using the Moran I statistics and the corresponding correlogram. Afterward, we used linear regression to test for an increase or a decrease of the FWI through time (1916–1998); we plotted the seven highest FWI of each season, which approximately corresponded to the upper 5% end of extreme day values. Burned areas (km^2/100 km^2) and fire occurrence (number/100 km^2) for the whole study area were also compiled by fire season to provide information on fire weather influence.

More specifically, to evaluate the respective effects of fire weather, land use, and years (representing the changes related to human activities: increase in fire suppression efficiency, increase in passive suppression and population density) on annual burned areas, a covariance analysis was undertaken. The dependent variable, the annual burned areas (km^2) of both sectors, was computed on a 100 km^2 area and linearized using a natural logarithm. The independent quantitative variables were FWI (mean of the highest 5% FWI of each fire season) and years, whereas the landscape type was a class variable. Thus, we tried to determine whether human activities had more of an effect than the FWI on annual burned areas.

Results

Time Since Fire Map

In both regions, the oldest stands were initiated by fire in the early 1760s (Figure 2) as shown by important recruitment of cohorts and snags. Stands from almost 30 sample points on both sides of the border were initiated during the 1760s or early 1770s; 10 of these were subsequently reburned. This suggests that the entire area of both regions most likely burned. Today, respectively 33.3% and 28.3% of the Quebec and Ontario study areas are covered by forest stands that were initiated during the 1760s (Figures 2 and 3). This (or these) fire(s) may have occurred in 1760, as fire scars of 1760 were found near the study area by Dansereau (1991). In 1818 (based on three fire scars from different jack pine stands) another large fire(s) swept through a major portion of the two sectors, corroborating the early forest survey by MacLean and Bedell (1955) and the oral history of the First Nations (Pollock 1995, p. 101–102), which suggest that a large part of the Clay Belt burned around 1820. The fire map shows 28 stands that were dated to the early 1820s. The last fire of over 50,000 ha (original size) appears to have occurred around 1853 in the Ontario region, where eight jack pine stands indicated recruitment in the 1850s. The limits of this fire were easy to observe in the aerial photographs taken in the mid-1920s. From 1853 to 1915, the burned areas were very low on both sides of the border. An intensive study of the 1926 aerial photographs confirmed, as stated by the archives, that no large burned areas occurred in that period. At present, less than 5% of the forest stands of both landscapes were initiated between 1853 and 1915, when important settlement activities began (Figure 3).

The time since fire map shows that under the influence of Europeans (1916–1998) most of the burned areas were recorded during the early (1916–1939) settlement phase, decreasing drastically in the two following phases. In the forestry sector (Ont), 88.4% of the burned areas were associated with the early phase (1916–1939), 8.7% with the middle phase (1940–1969) and 2.9% with the late phase (1970–1998). More specifically, 83.3% of the cumulative burned areas (from 1916 to 1998) in the LAMF resulted from eight major fires (>1000 ha) during three fire seasons: 1916 (1), 1921 (5), and 1924 (2). These eight fires (Figure 2, white fire year dates) burned an area equal to 21.4% of the Ontario sector. In the agricultural sector (Que), 74.3% of the burned areas were associated with the early phase, and 22.6% and 3.1% with the middle and late phases, respectively. On the Quebec side, 60.4% of the cumulative burned areas (1916–1998) stemmed from four fires that occurred in 1916 (1), 1919 (1), and in the early 1920s (2). They burned an area equal to 30.5% of the entire Quebec sector. Figure 3 shows that, in 1998, a large part of the entire study area would have been characterized by mature and old growth forest stands if human-caused and natural disturbances other than fire were not considered. More specifically, 73.7% of the forestry sector and 58.5% of the agriculture region was covered by fire-initiated

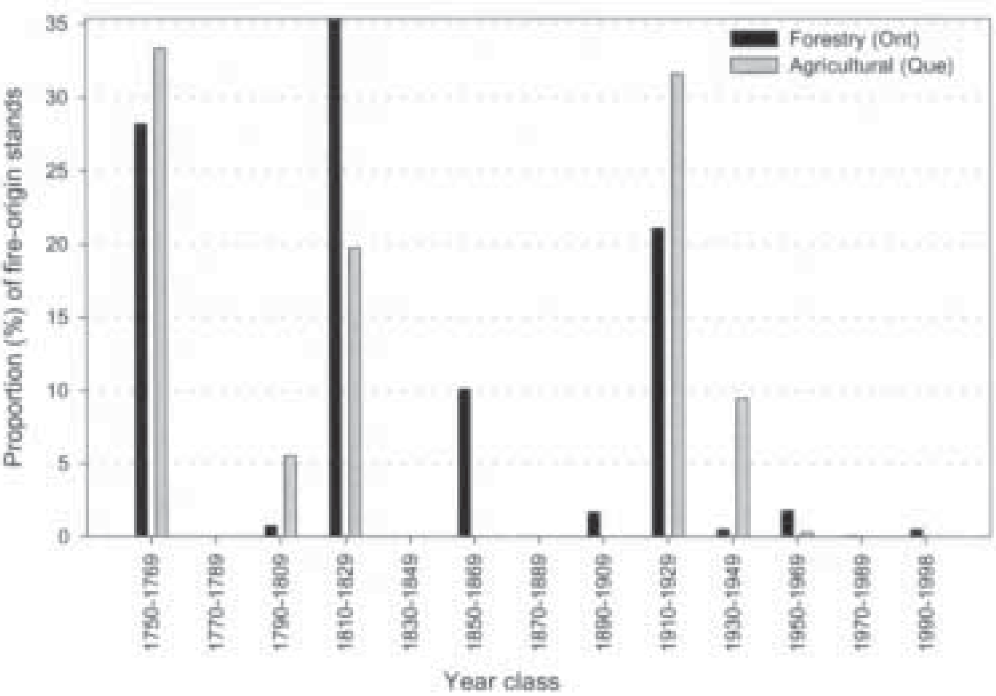

Figure 3. Proportion of fire-origin stands for both landscapes in 1998.

stands older than 145 yr (before 1855). The mean ages of all the forest stands, disregarding the effects of felling, clearing, insect outbreaks and windthrow, for the forestry and agriculture sectors are 171 and 161 yr, respectively.

Post-Settlement Fire Activity (1916–1998)

From 1916 to 1998, fires smaller than 10 ha represented 67% and 70% of all fires that were recorded in the forestry (Ont) and agriculture (Que) landscapes, respectively. However, they accounted for less than 1% of the burned areas in both regions. Considering fires larger than 10 ha, the forestry and agricultural sectors were characterized by 31.4 burned ha/yr/100 km^2 and 61.7 burned ha/yr/100 km^2, respectively (Table 1). On the other hand, fire occurrence reached 0.015 fires/yr/100 km^2 for the forestry region and 0.138 fires/yr/100 km^2 for the agricultural area. Table 1 also lists the basic descriptive statistics (total burned area and fire occurrence, mean fire size, maximum and minimum size) for the two landscapes.

The contingency table showed that, considering the 10–99 ha fire class, fire occurrence was similar in both landscapes for the three development phases (Table 2), with about 50% of the fires occurring during the late phase (1970–1998) for the two land types. For the 100–999 ha fire size class, both landscapes show a general decrease in fire occurrence from the early (1916–1939) to the late phase; however, the decrease was more significant in the agricultural landscape between the middle (47%) and the late phase (4%). Table 2 also shows that fire occurrence for the 1000 ha + fire size class was greater during the early phase for both landscapes, decreasing gradually to the present. A general trend in fire occurrence was observed simultaneously in both landscapes. Thus, no significant differences were detected between the forestry and agricultural landscapes and the development phases in all the fire size classes considered: 10–99 ha ($Q_{CS} = 0.117$, $P = 0.732$), 100–999 ha ($Q_{CS} = 0.236$, $p = 0.627$) and 1,000 ha + ($Q_{CS} = 0.072$, $P = 0.789$).

The contingency table also showed that there were important variations in fire occurrence within each landscape with regard to development phases and fire size classes (Table 2). Considering each landscape individually, during the late phase, the forestry study area had significantly more fires in the 10–99 ha fire size class than expected ($Q_{CS} = 10.38$, $P = 0.001$). On the other side of the border, the agricultural landscape had significantly fewer fires in the 10–99 ha fire size class during the middle phase, but more than expected during the late phase ($Q_{CS} = 20.97$, $P = 0.001$). On the other hand, there were fewer fires than expected for the two larger fire size classes (100–999, 1000 +) during the late phase.

The linear regression between the FWI and fire size gave rise to $R^2 = 0.3093$ ($P < 0.0001$) and $R^2 = 0.1238$ ($P < 0.0001$) for the forest and agricultural landscapes, respectively. The analysis of variance on the regression residuals did not reveal significant differences for the forest sector ($F = 1.38$, $p = 0.2596$) among the three development phases, conversely to the agricultural sector ($F = 15.13$, $P < 0.0001$). The mean rank scores in Table 3 showed, for the agricultural sector, that the

Table 1. Fire activity parameters for both landscapes from 1916 to 1998.

	Forestry (Ont)	Agricultural (Que)
Study area (ha)	511,800	142,400
Annual burned area (ha/100 km^2)	31.4	61.7
Annual fire occurrence /100 km^2	0.015	0.138
Total burned area (ha)	131,779	72,077
Total fire occurrence	65	161
Mean fire size (ha)	2,027	448
Maximum size (ha)	38,600	30,200

Table 2. Fire size class (ha) distribution (%) relative to landscape type and development phase.

Phase		Forestry (n = 65)			Agriculture (n = 161)		
		10–99	100–999	1000+	10–99	100–999	1000+
Early	(1916–1939)	32	63	75	32	49	60
Middle	(1940–1969)	21	26	17	$15^{(-)}$	47	40
Late	(1970–1998)	$47^{(+)}$	11	8	$53^{(+)}$	$4^{(-)}$	$0^{(-)}$
	Total	100 (n = 34)	100 (n = 19)	100 (n = 12)	100 (n = 106)	100 (n = 45)	100 (n = 10)

NOTE: Signs (+) and (-) indicate fire size class with significant differences (higher and lower, respectively) between observed and expected frequencies.

mean of the residuals for fire size in the late phase was significantly lower than that for the first two phases.

Fire Weather Change

The analysis of FWI revealed that the fire seasons of 1916 and of 1919 to 1924 inclusively were particularly conducive to forest fires (Figures 2 and 4a). Figure 4 (a–c) suggests that both annual burned areas and FWI decreased over time for both landscapes independently of the seasonal fire occurrence. The correlogram of the FWI between fire seasons using the Moran I showed no significant autocorrelation at the $P = 0.05$ level. Thus, we proceeded with the linear regression of the higher 5% FWI values of each fire season with time without filtering for autocorrelation. Results showed a slight but highly significant decrease in extreme values of fire danger over time, with a $R^2 = 0.0900$ and $P = 0.0001$ (Figure 4a). In order to evaluate the relationship between fire weather and annual burned areas over time, an analysis of covariance was conducted, taking into account land use and period (years), which represented improvement in both active and passive suppression. The simplified model ($F = 30.16$, $P = 0.0001$, $R^2 = 0.3641$) showed that FWI was positively related to the annual burned areas ($F = 43.43$, $P = 0.0001$, partial $R^2 = 0.2763$). Conversely, period (yr) was negatively linked to burned areas ($F = 16.43$, $P = 0.0001$, partial $R^2 = 0.0661$). Moreover, the landscape type also influenced the annual area burned ($F = 5.41$, $P = 0.0213$, partial $R^2 = 0.0217$), indicating that the burned area was higher in the Quebec landscape than in Ontario.

Discussion

Climatic Change and Effect on Area Burned

The fire history reconstructed for the presettlement period (1760–1915) suggested that the fire activity was probably similar for the two areas of interest in Ontario and Quebec. At the start of substantial European settlement in 1916, the forests in both regions had similar age class distributions, as several major fires swept through both regions simultaneously. Furthermore, in both territories, only very small areas burned from 1853 to the start of settlement. Unfortunately, the low fire occurrence (n = 3) before 1853 prevented statistical analysis. However, these different elements suggest that the presettlement fire activity was similar for the two regions, given that they were subjected to the same climatic factors. Furthermore, the overlay of fires over time probably removed all evidence of fires less than 1,000 ha in size, nor could they be detected through aerial photo analysis and the sampling grid used. However, of the 80 jack pine stands sampled in presettlement forests (<1916), only two sites had a fire origin age (1752 and ~1806) that could not be linked to other fires that had occurred in adjacent sectors. Although some of these small fires could not be mapped even after careful study of the aerial photos, the age class distribution for the two landscapes would likely be similar since the total area covered by these fires is small compared with the areas burned during the fire seasons of 1760, 1818, and ca. 1850. Some authors like Johnson and Gutsell (1994) have provided a rule of thumb for the boreal forest: the study area should be at least three times larger than the largest area burned by a single fire or fire year. Obviously, the size of the 1760 and 1818 fires breaks this rule of thumb. This fact may therefore minimize our capacity to detect potential differences among the age-class distributions of both landscapes. However, given the smaller fire size during the postsettlement period, on which this article focuses, we assume that the size of the study area did not have a significant impact on our results.

Several studies in the boreal forest have suggested that a change in fire frequency has occurred since 1850, which corresponds to the end of the Little Ice Age (Cwynar 1977, Bergeron 1991, Bergeron and Archambault 1993, Larsen 1994, Larsen and MacDonald 1995, Bergeron et al. 2001). Various aspects of our findings, for the fire regimes both prior to and since settlement, also suggest that a climatic signal may be partly responsible for the observed change in the area burned. In this study, nearly 75% of the forest stands present in the Ontario landscape in 1998, disregarding the effects of felling, clearing, insect outbreaks, and windthrow, originated from fires predating 1853. In the Quebec region, the corresponding proportion was about 60%, and very little area (less than 5%) was burned by fires between 1853 and the opening of the territories in the 1910s. A recent study encompassing

Table 3. Mean rank scores of residuals of the regression among the three development phases for each landscape.

Phase		Forestry		Agriculture	
		Mean rank	Sample size	Mean rank*	Sample size
Early	(1916–1939)	34.3	30	87.0^{A}	62
Middle	(1940–1969)	34.9	14	103.2^{A}	41
Late	(1970–1998)	26.2	19	57.1^{B}	57
Total		32.0	63	80.5	160

* Phases marked with different letters are significantly different at $P < 0.05$.

NOTE: Missing data explain differences in sampling sizes between Tables 1 and 3.

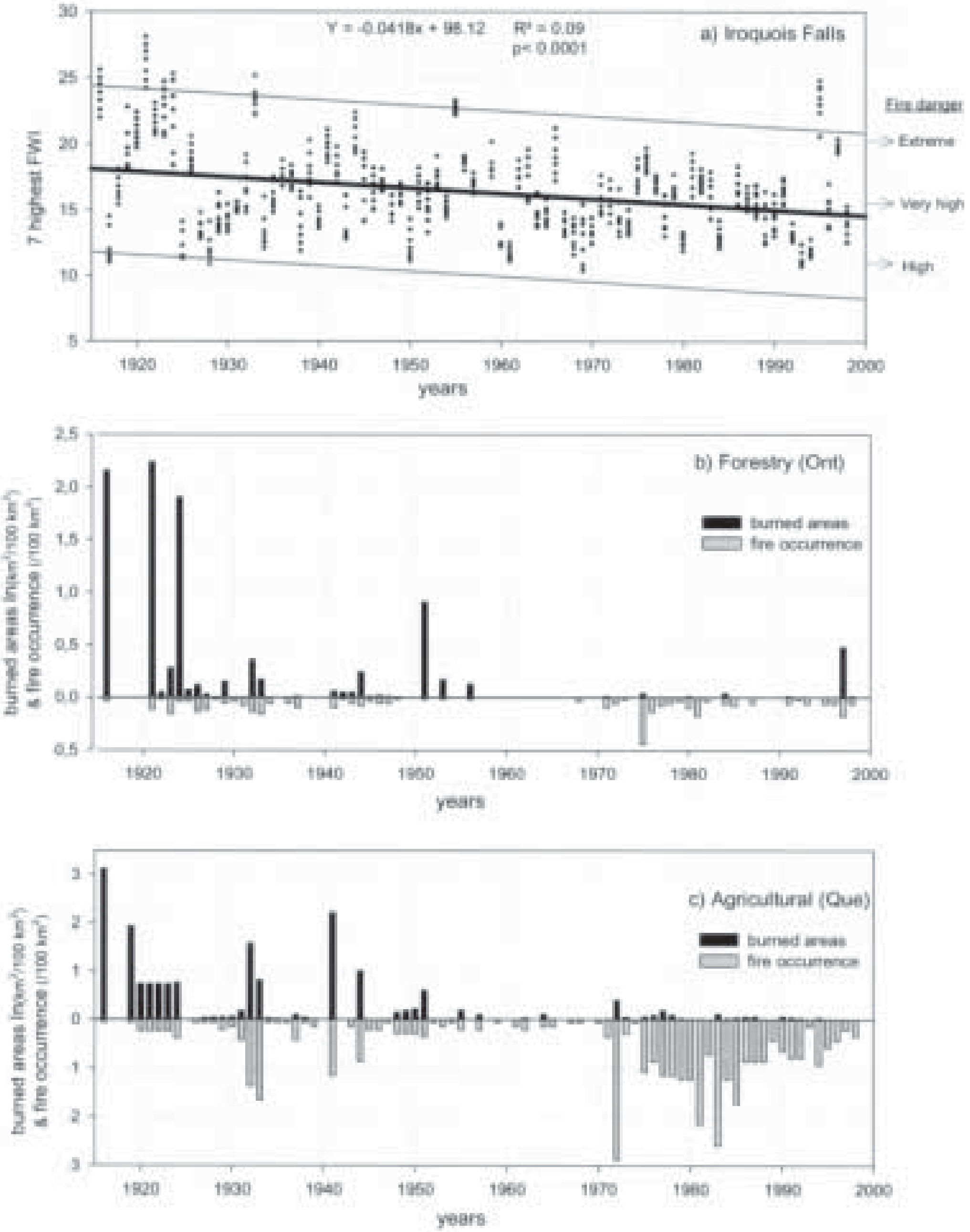

Figure 4. (a) Regression (bold line) of the highest 5% values of the FWI for each fire season. Upper and lower confidence limit intervals (95%) are drawn, whereas fire danger values are on the right side. Annual burned areas and fire occurrence of (b) forestry and (c) agricultural landscapes.

the two landscapes concerned here showed a significant lengthening of the fire cycle (i.e., a decrease in the areas burned) since 1850, possibly in response to climatic change (Bergeron et al. 2001).

Since the start of settlement, high FWI values have become less frequent over time. However, the use of average relative humidity and wind speed values in computing the FWI serves as a filter, reducing the occurrence of extreme FWI values for the period 1916–1998. Furthermore, the decrease in the FWI over time is relatively weak, although highly significant. It would nonetheless be surprising to see a stronger climatic signal since climatic change likely takes place over very long periods. Variations in FWI may explain the decrease in burned areas observed concurrently in the two regions well before the beginning of effective aerial fire suppression programs in 1970 with the use of water bombers. Moreover, our results indicate that most of the variation in the burned areas can be attributed to the FWI conditions. The literature on climate and forest fires indicates that there is a close link between long periods of drought and large burned areas (Flannigan and Harrington 1988, Johnson and Wowchuk 1993, Harrington and Flannigan 1993, Bessie and Johnson 1995). The ignition of lightning-caused fires is generally associated with conditions of high fire susceptibility (Nash and Johnson 1996). The two largest fires (1916 and 1924, in Ontario) in terms of areal extent were started by lightning during fire seasons with very high FWI values. It should be noted, however, that during the aforementioned period of high fire susceptibility (1916–1924), humans probably lit fires that burned considerable portions of territory. However, a human-caused fire can only reach a considerable size under favorable meteorological conditions and fuel availability (Flannigan and Harrington 1988). In short, these various elements suggest that the decrease in the area burned is associated with climate change that began at the end of the Little Ice Age (well before European settlement) and is still going on now in the Abitibi region. Our findings are consistent with those of Bergeron (1991), who observed a similar decrease in area burned since the end of the Little Ice Age on some islands located 15 km south of Lake Abitibi where no fire suppression efforts were carried out.

Despite the fact that our climate analysis was limited to data from a single weather station located in northern Ontario, and that important climatic stress did not fluctuate much by the use of mean values from the Val d'Or weather station, our results are in agreement with: (1) a similar decrease in extreme FWI values for the 20th century in an area located 250 km eastward (Lesieur 2000), and (2) general models predicting a decrease in the FWI in Abitibi as a result of climate warming associated with increased CO_2 emissions (Bergeron and Flannigan 1995, Flannigan et al. 1998). These findings suggest that the severity of fire seasons has decreased since the end of the Little Ice Age (ca. 1850), which is consistent with the results reported by other authors for the same region (Bergeron 1991, Dansereau and Bergeron 1993, Bergeron et al. 2001). It appears that a displacement of air masses during this period may have caused a reduction in the occurrence of drought periods responsible for large fires (Bergeron and Archambault 1993). In fact, at a nearby site, greater winter and spring precipitation was detected, beginning at the end of the Little Ice Age, by analyzing the change in the maximum reach of ice-scars (Tardif and Bergeron 1997), whereas an upward trend of summer precipitation was suggested by larger tree ring widths in old white cedars (>500 yr) growing on xeric sites (Archambault and Bergeron 1992).

Human Impact

Although our results suggest that the burned areas are related to climate and weather, they are also affected by land use pattern despite the difficulties in measuring direct human influence (Urban et al. 1987). An analysis of the historical context of the development of the Quebec region revealed that agricultural activities had a considerable influence on fire occurrence, which was 10 times higher in the agricultural sector (Que) than in the LAMF (Ont). Some authors have reported that the highest rates of fire occurrences were located in areas of denser population density (Wein and Moore 1979, Martell 1994). In the Quebec sector, most of the forest fires occurred as a result of fire being used to clear forested land for agriculture. Fire was also used to destroy logging debris. Local newspapers reported that slash fires, which were sometimes dormant, triggered forest fires when drought conditions prevailed in the Abitibi region (La Gazette du Nord, 1923–1950). Quebec's provincial fire reports confirmed that major burned areas were escaped fires from slash and burn activities and brush fires. Thus, the effect of agricultural land use on fire occurrence is strong enough to have significantly influenced the annual burned areas, which is in agreement with other studies (Lehtonen and Huttunen 1997, Weir and Johnson 1998, Niklasson and Granström 2000).

For the present study, the analysis of covariance shows that the FWI explained the largest proportion of variability in the annual area burned, 28%, versus 2% for type of landscape and 7% for the period (years). These results suggest that climate has a stronger effect on the area burned than the type of landscape management or the temporal change in fire suppression technology. These results must be interpreted with caution: (1) the variable "period" is more a substitute than a direct measure of suppression effectiveness, and (2) if it is assumed that suppression efforts did not become effective until the early 1970s with the advent of water bombers, the 1970–1998 phase is a short time frame for evaluating the potential effect of suppression measures on burned areas, and this reduces the amount of variation explained by this variable. In this regard, the large increase in fire occurrence since 1972 in the agricultural landscape resulted in small areas burned and represents an index that provides evidence of the effectiveness of fire detection and fire suppression since the introduction of water bombers. Moreover, between 1972 and 1998, firefighting methods have probably been improved continuously by enhancing their detection and initial response systems, particularly since the beginning of the 1990s. As an example, in 1994, SOPFEU (Que) was created by merging Quebec's fire protection agencies in order to increase firefighting efficiency. Currently, we cannot evaluate the impact of these improvements, as the time frame is too short.

Similarly, more effective suppression of fires, combined with climatic conditions less conducive to fires, could explain the abundance of small fires in the 10–99 ha size class that occurred in both landscapes during the late phase (1970–1998). Moreover, anthropogenic factors also appear to have contributed to the observed decrease in the number and extent of major fires (larger than 100 ha), particularly for the late phase in the agricultural region, given that there were fewer large fires than expected within this landscape. The results of the nonparametric analysis of variance of the linear regression residuals point to the same conclusion and suggest that human activities, including fire suppression, caused a significant decrease in fire size in the agricultural sector during the late phase. Major transformations in the landscape could explain the stronger impact of suppression operations in the agricultural landscape. First, there was an important conversion in forest composition on the Quebec side from coniferous stands (~80% in the 1920s) to deciduous (56%) and mixed stands (20%) in 1998, which are much less flammable than coniferous forests (Van Wagner 1983, Kafka 1997, Weir and Johnson 1998). This transition can be explained by the fact that historically most of the merchantable trees were cut down, leaving few seed trees on site (Perron 1989, p. 35) and the fact that, in addition to being harvested, many of these sites were burned, and this created favourable conditions for trembling aspen, an aggressive pioneer species which responds well to severe disturbances (MacLean and Bedell 1955). Conversely, horse-logging took place mainly in winter in the LAMF until the 1960s; this harvesting method tended to limit the extent of soil disturbance and protect the advance regeneration of conifers while also leaving many trees on site (Archibald and Arnup 1993). Second, the agricultural region shows a greater extent of landscape fragmentation by land clearing and a well-developed road system, three times more extensive than in the LAMF, which increased the number of firebreaks there (Foster 1983, Turner and Romme 1994) and improved firefighting capacity (Lefebvre 1972, p. 180–183, Wein and Moore 1979). Differential provincial fire detection and reporting may explain parts of the variation in fire size distribution between the agricultural (Que) and forestry (Ont) landscapes. However, as we used a 10 ha fire size threshold for this analysis, this bias was probably attenuated.

Our results suggest that a fragmented landscape made up of a high proportion of deciduous stands shows characteristics that may improve firefighting and may result in smaller fire size. According to the Quebec agency responsible for fire protection (SOPFEU), the success of such operations depends on the early detection of fires and a rapid response in dealing with pockets of fire, particularly when fire intensity is below 2000 kW/m (Gauthier et al. 1999). However, Johnson et al. (1990) reported that forest fire suppression does not always reduce the areas burned substantially if extreme climatic conditions exist that are conducive to fires, particularly in sparsely populated regions where fires can reach a considerable size before the first firefighting operation is launched (Wein and MacLean 1983). The firefighting tools available during the early phase (1916–1939) seem to have been insufficient to deal effectively with fires covering more than 1,000 ha or 10,000 ha when the FWI value was very high. It therefore appears that fire suppression cannot have had a major impact on fire size during the first two phases of development of the territories. In fact, despite major differences in land use and the extent of landscape fragmentation, the fire size distribution does not differ significantly between the two sectors during the three phases of development.

Conclusion

To summarize, in the Quebec sector, anthropogenic pressures were strong enough to create a dynamic of fire occurrence and annual burned areas that differed from that in the nearby region. Despite the larger annual burned areas, active suppression in recent times has likely had a greater impact in the agricultural region in terms of fire size because of major changes in the landscape (road system, landscape fragmentation, vegetation composition), which decreased the ability of fires to spread. However, based on our results, we postulate that the similar fire weather conditions have had a relatively synchronous influence on fire size and the areas burned in the two landscapes. Fire activity mainly results from major burned areas that occurred in a few fire seasons characterized by extreme fire conditions. More in-depth information including complete fire reports and complete weather datasets covering a longer time period are nonetheless needed before an effort can be made to precisely quantify the impact of suppression or climate on the dynamics of forest fires. In addition, technological developments in firefighting in the 1990s are likely to increase the impact of fire suppression. The conclusions of the present study on the respective effect of climate and human activity cannot be extrapolated to other regions because every territory evolves in a unique historical context.

As several authors have suggested (Hunter 1993, Delong and Tanner 1996, Bergeron et al. 1999), the fire history has provided the LAMF with information regarding age-class distribution and the extent and spatial arrangement of forest types, including old-growth forests. The importance of large tracts of old forest older than 150 yr in the LAMF indicates an important divergence between the natural age-class distribution observed in the LAMF and the one targeted for under an even-aged management system. Bergeron et al. (1999) and Gauthier et al. (2002) suggest that, by varying treatments and by developing forest practices that are aimed at conserving certain structural characteristics of older stands, we can minimize the differences between these two aspects. To this end, some new practices such as HARP that are currently being tested in the LAMF are promising for uneven-aged management.

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