Fire frequency for the transitional mixedwood forest of Timiskaming, Quebec, Canada

Daniel J. Grenier, Yves Bergeron, Daniel Kneeshaw, and Sylvie Gauthier

Abstract: Fire history was reconstructed for a 2500-km^2 area at the interface between the boreal coniferous and northern hardwood forests of southwestern Quebec. The fire cycle, the time required for an area equal to the study site to burn once over, was described using a random sampling strategy that included dendrochronological techniques in conjunction with provincial and national government archival data. Physiographic elements were not found to spatially influence fire frequency; however, human land-use patterns were observed to significantly affect the fire frequency. A temporal shift in fire frequency was also detected, which coincided with the period of Euro-Canadian colonization and known extreme dry years for the study site. Additionally, a fire-free period was identified in the most recent times that could be associated with fire suppression and climate change. The estimated cycles (approx. 188–314 years) for the southeastern section of the study area were thought to better represent the natural cycles for this transition zone as a result of less anthropogenic influence. The importance of gap-type dynamics becomes evident with the increased presence of old-growth forest, given the derived fire cycle estimations for the region. Even-aged management with short rotations, consequently, is questioned because fire cycle estimations suggest more complex harvest systems using an ecosystem management approach.

Résumé : L'historique des feux a été reconstruit pour une superficie de 2500 km^2 à l'interface entre la forêt boréale et la forêt feuillue septentrionale du sud-ouest du Québec. Le cycle de feu (nombre d'années requises pour que soit brûlée une superficie équivalente au territoire à l'étude) a été décrit avec un dispositif d'échantillonnage aléatoire utilizant la dendrochronologie conjointement avec les archives des gouvernements provincial et fédéral. Les éléments physiographiques n'ont pas eu d'influence spatiale sur la fréquence des feux. Cependant, les patrons d'utilization des terres associés à la colonization ont significativement affecté la fréquence des feux. Un changement temporel dans la fréquence des feux a été aussi détecté. Il est synchrone avec la période de colonization euro-canadienne, ainsi qu'avec des années de sécheresse extrême pour le site d'étude. De plus, l'absence de feu notée depuis 1950 pourrait être expliquée par l'effet cumulé de la suppression du feu et des changements climatiques. Les cycles estimés (approx. 188 à 314 ans) pour la section sud-est du site d'étude ayant subi une moins grande influence anthropique représenteraient mieux les cycles naturels du territoire étudié. Avec la présence d'une proportion plus élevée de forêt ancienne, les perturbations secondaires par trouées deviennent sont importantes étant donné les estimations du cycle de feu dans la région. Par conséquent, les régimes d'aménagement équienne à rotation courte sont à remettre en question pour ce secteur. Comme le suggère les estimations du cycle de feu, des pratiques sylvicoles plus diversifiées et l'utilization d'une approche de gestion écosystémique seraient plus appropriées.

Introduction

Fire history and behavior in boreal forests have received much attention in the past two decades, which has culminated in forest management inspired by natural disturbance dynamics (MacDonald 1995; Lieffers et al. 1996; Bergeron and Harvey 1997; Angelstam 1998). This approach is thought to aid in the maintenance of biodiversity and vital ecological processes, as it allows for the maintenance of stand composition, structure, and functions similar to those occurring naturally and to which endemic species have adapted through time (Franklin 1993; Hunter 1999; Bergeron et al. 2002).

Many factors are recognized to play important roles in controlling fire regimes. Studies have shown regional-scale climate patterns synchronizing fire occurrence across large areas (Swetnam and Betancourt 1990; Johnson and Wowchuck 1993; Swetnam and Baisan 1996; Kitzberger et al. 1997; Flannigan et al. 2000). Climate will thus contribute in defin-

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ing spatially explicit fire regimes over large areas (Payette et al. 1989). Temporal changes in global climate also control fire regimes. For example, in the eastern (Bergeron et al. 2001) and western (Larsen 1996; Weir et al. 2000) boreal forests of North America, a reduction in fire frequency has been identified and attributed to large-scale climate change following the end of the Little Ice Age (approx. AD 1850).

Factors other than climate are also believed to be important in controlling fire regimes. Deviations from regional fire regimes have been attributed to variations in microclimate and fuel load controlled by local site factors (Barton et al. 2001; Brown et al. 2001; Heyerdahl et al. 2001; Turner and Romme 1994). Steep gradients in elevation, changes in aspect, and other physiographic features have been shown to drive spatial variation in fire regimes by influencing fuel moisture, humidity, and interaction with the wind, thereby affecting the probability of fire (Whelan 1995; Rowe and Scotter 1973). Waterbodies have also been found to function as natural firebreaks affecting fire spread (Larsen 1997; Bergeron 1991; Romme and Knight 1981; Heinselman 1973).

Humans also strongly influence fire regimes. Colonization leads to improved access to once-remote areas, providing an increased potential for fire ignitions (Weber and Stocks 1998). In fact, national statistics show that human-induced fires make up the majority of the ignition sources in Canada (Anonymous 2002). Studies have also shown that activities associated with the colonization process (i.e., using fire to clear forested land for agriculture and other human use) significantly increase the annual area burned (Lefort et al. 2003; Niklasson and Granström 2000). However, other studies have found human impacts to lead to a decrease in area burned as a result of fire suppression (Brown et al. 2001; Everett et al. 2000; Barrett et al. 1991; Tande 1979). It seems no consensus has been reached as to the overall effect humans have played on the fire regime.

In comparison with the northern boreal forest, the temperate forest is characterized by a low fire frequency. Fire-history studies in the temperate forests of North America have documented fire cycles >1100 years (Zhang et al. 1999; Lorimer 1977; Wein and Moore 1979; Wein and Moore 1977; Whitney 1986), while in contrast the closed-crown boreal forests are described by a much shorter natural mean fire cycle <150 years (Payette 1992). Comparisons of fire studies in the temperate zone have also shown fire cycles in forests dominated by deciduous species (Whitney 1986; Frelich and Lorimer 1991) to be much longer than those in pine-dominated stands (Heinselman 1973; Whitney 1987; Cwynar 1976). A greater mixed or deciduous composition in temperate forests is thus thought to play a role in the lower fire frequency in this biome. Historical documentation additionally shows human influence and major alterations of temperate forests since European colonization in North America (Whitney 1994; Cronon 1983), while these effects are relatively recent in boreal forests.

The Timiskaming region of southwestern Quebec is located at the transition between the temperate and boreal biomes. The forest is mixed in vegetation composition, with both boreal and temperate elements. The first harvesting efforts in this region began as early as 1800, though exploitation on a regular basis did not begin until the 1860s (Vincent 1995). Settlement began in the 1870s, with most major municipalities being established after 1890 (Vincent 1995). However, little information is known regarding the role of fire for this transitional region between a boreal forest system controlled by many fires and a temperate forest system affected by comparatively few fires. The relative importance of natural fires in shaping natural forest mosaics for this region could therefore have important implications on decisions forest managers make about silvicultural systems (even age vs. uneven age) that should be implemented (Bergeron et al. 1999). There is also speculation as to the naturalness of the 20th-century fire regime, given possible human influence; consequently, to improve our knowledge and comprehension of the function fire has in this relatively unstudied area, we worked in the transition between these biomes. Our objectives were to (1) document fire frequency in the context of stand-replacing events in this temperate–boreal transitional area and (2) identify spatial or temporal influences that may have caused variation in the fire cycle. The latter is defined as the time required for an area equal in size to the study area to burn over once (Johnson and Gutsell 1994).

Materials and methods

Study area

The study site is located within the Timiskaming region of southwestern Quebec, Canada, bordering eastern Ontario along the Ottawa River (approx. 47°30′N, 79°00′W; Fig. 1). The region is found within the Northern Temperate Zone, located just below and adjacent to the boreal forests of southwestern Quebec (Saucier et al. 1998). The surface area of the study area measures approximately 2500 km^2. Average altitude is about 350 m, with moderate relief composed of hills and depressions with intermediate slopes throughout and rock escarpments in the western portion of the region. Surface deposits are composed mainly of glacial till and lacustrine deposits; 20% of the surface area is made up of water bodies (Robitaille and Saucier 1998). Average annual temperature is 2.5–5.0 °C, and average precipitation measures 800–900 mm/year, with 25% falling as snow.

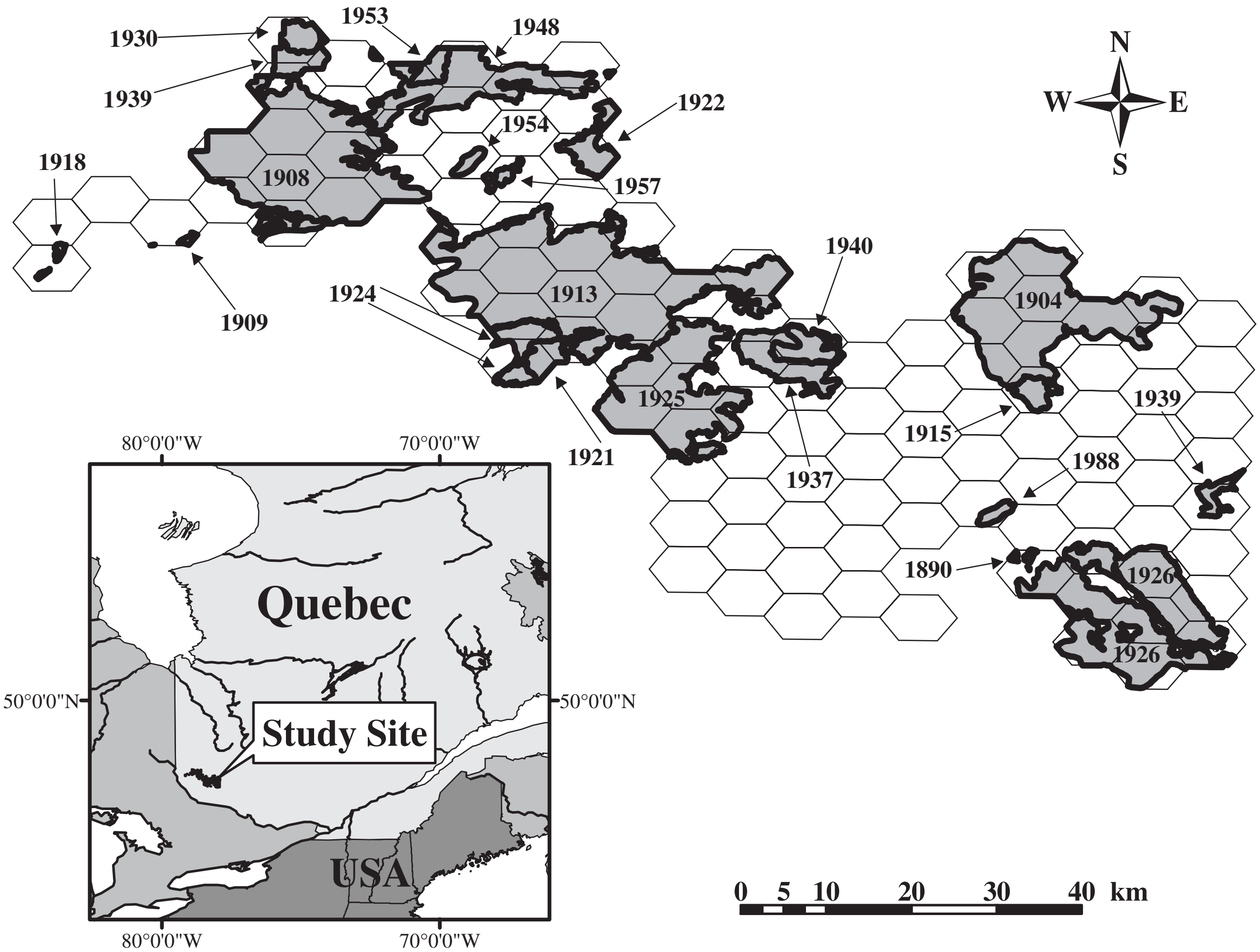
The study area lies within the fir – yellow birch bioclimatic domain for western Quebec (Saucier et al. 1998), which is of a mixed-forest type dominated by balsam fir (*Abies balsamea* (L.) Mill.) and yellow birch (*Betula alleghaniensis* Britt.) accompanied by white spruce (*Picea glauca* (Moench) Voss), sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), and white birch (*Betula papyrifera* Marsh.). Fire-associated species such as red pine (*Pinus resinosa* Ait.), white pine (*Pinus strobus* L.), and jack pine (*Pinus banksiana* Lamb.) are represented on xeric sites (Grondin 1996).

Human influence on the landscape through widespread forestry activities and extensive agricultural land use is documented for the northern and western portions of the study area since the late 1800s (Vincent 1995). The towns of Béarn, Ville Marie, Belleterre, Angiliers, Laverlochère, and Latulipe are found along the western edges of the territory. Road networks are laid out primarily along the northern and western margins.

Fire-history reconstruction and mapping

We reconstructed the fire history of the study area using both archival and field-collected data to produce a stand-initiation map (Johnson and Gutsell 1994). Georeferenced

Fig. 1. Maps of the study area. The inset panel shows the location of the study area in a regional context: the Timiskaming region of southwestern Quebec, Canada. The large panel shows a magnification of the study site. An initial time-since-fire map for the most recent fires of the last 111 years was created using archival data and air photos, with a hexagonal grid system overlaid onto the map to aid in our sampling design.



archival information (Arc/View/Info format) dating from 1945 to 1998 from the Ministry of Natural Resources of Quebec (MNRQ) on stand history, composition, fire years, areas burned, and site conditions was gathered to obtain preliminary information on the recent fire history of the study area. Given that almost no major fires occurred during this period (<5000 ha burned for the whole study site from 1950 to 1998), aerial photographs from the Canadian National Air Photo Library dating from the 1930s, 1940s, and 1950s were acquired to supplement these data. Fire boundaries on these photos were identified, digitized, and dated using the photographs. Small residual islands less than 5 km^2 were excluded from the reconstruction. Additional past fire boundaries were also recognized using variation in forest stand tones and textures in the photos to identify even-aged stands of early-seral tree species typically found growing immediately after fire. These boundaries were then dated using trees that were aged within these areas during an MNRQ forest survey on the study site (Anonymous 2000*a*, 2000*b*). All fire data were then entered into a Geographic Information System (GIS, Arc/View GIS, version 3.1) to create an archival fire dataset linked to an initial time-since-fire map (Fig. 1). The map shows the fire dates for the last 111 years and stand distribution for time since last fire (TSLF), not accounting for other disturbance types such as insect outbreaks and windthrow. Finally, to verify the fire map and GIS accuracy, fire dates were again compared with age data (i.e., ages of trees) from the MNRQ forest survey of the area (Anonymous 2000*a*, 2000*b*).

Field sampling and dendrochronological analysis

When the time of the last fire could not be determined from the archives or air photos, the date was determined using a standard dendroecological approach (Arno and Sneck 1977; Bergeron 1991; see following text for details). To facilitate this, a grid system composed of 114 polygons (approx. 22 km^2 per polygon) was overlaid onto the map of the study area (Fig. 1) to stratify the territory for sampling. Fire dates from the GIS were assigned to the 52 polygons that fell within the boundaries of the burns on the initial time-since-fire map. Polygons positioned outside of the mapped burn areas were visited for dendrochronological sampling to date stands (Johnson and Gutsell 1994). For 41 polygons, a set of paired plots (approx. 500 m apart) from the MNRQ survey assessment of the study area was randomly selected for on-site visiting. For the 21 polygons without archival data or air photo fire dates and not containing MNRQ survey plots, a location among areas deemed accessible was randomly selected. Paired plots 500 m apart were then established at these locations for sampling.

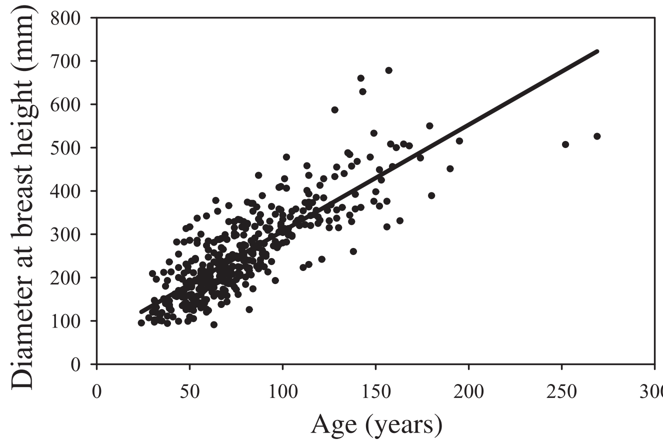
At each visited polygon, efforts were made to identify evidence of past fire by searching for fire-scarred trees and by examining the mineral soil for bits of charcoal. While fire-scarred trees were observed at only one site, the nearly universal occurrence of charcoal observed at the base of the humus layer at sampling sites confirmed the widespread extent of past fires in these areas. TSLF for visited polygons was estimated by using a cohort of trees, taking the age of the oldest tree when at least three of the sampled individuals had an establishment date within a range of 10 years for jack pine and 20 years for all other species (Lesieur et al. 2002). When samples did not allow for determination of the TSLF event by cohort, the polygon was characterized by the age of the oldest individual sampled (Bergeron and Dubuc 1989; Johnson and Gutsell 1994; Lesieur et al. 2002). Data of this sort were considered a minimum estimate of TSLF, with the date regarded as censored in further statistical analyses (see following text for details). Censorship is a statistical method of handling data when the exact survival time of an individual is unknown as a result of loss of an individual during the study period or from the study period ending before all individuals fail (i.e., the study period is too brief for all individuals to experience the event; Allison 1995). Data are also presented in 10-year age-classes to reduce bias due to the lack of precision in the estimation of the real fire date.

At each visited polygon, increment cores or cross-sections were collected from 5 to 10 trees having the largest diameter, preferably from pioneer species (n = 443 cores, n = 120 cross-sections, average of 9.23 samples per polygon; Kipfumueller and Baker 1998). Selection priority (from first choice to last) was *Pinus banksiana* (jack pine), *B. papyrifera* (white birch) – *B. alleghaniensis* (yellow birch), *Populus tremuloides* (trembling aspen), *Picea mariana* (black spruce), and *Picea glauca* (white spruce). Increment core samples were extracted from the base of the trunk as low as possible (i.e., high enough to allow the increment borer to turn), with attempts made to core through the pith so as to minimize aging problems (Phipps 1986).

Sampled cores were mounted, sanded, and aged by the direct counting of the annual rings on the cores using a dissecting microscope (Phipps 1986). For cores that missed the pith, pith locators were used to estimate the number of missing years from ring curvature and growth rate (average of 6.1 rings to pith when missed; Applequist 1958). Cross-sections were prepared similarly, with rings counted on two axes (Arno and Sneck 1977). To confirm ages, cross-dating was visually performed using identified diagnostic rings (i.e., narrow, light, and frost rings; Yamaguchi 1991). We then measured annual ring widths using a Velmex measuring system to the nearest 0.01 mm and validated our cross-dating with COFECHA, a computer program that constructs a long homogeneous tree ring-width master series to which individual tree ring-width series can be compared (Holmes 1999).

Yellow birch was the exception to the aforementioned aging procedure. Because heart rot was prevalent in yellow

Fig. 2. Diameter–age relationship ($y = 0.2733x + 9.265$, $R^2 = 0.671$, $n = 409$) for yellow birch (*Betula alleghaniensis*) used in age estimation of field-measured individuals.



birch trees, accurately aging individuals through annual rings was often impossible; consequently, diameter at breast height (DBH = 1.4 m) for individuals encountered was recorded for age estimation attempts for those individuals with rot. A diameter–age regression curve was created using data gathered for yellow birch within the study area from the MNRQ forest survey ($y = 0.2733x + 9.265$, $R^2 = 0.671$, $n = 409$; Fig. 2). The derived diameter–age relationship was then used to estimate the ages of the field-measured yellow birch individuals (Lorimer 1980).

Fire frequency estimation

The proportion of area burned for each decade, derived from the time-since-fire map, provided us with a time-since-fire distribution. The time-since-fire distribution can be described using the Weibull model (Johnson and Gusell 1994):

$$A(t) = \exp[-(t/b)^c]$$

where $A(t)$ is the cumulative proportion of the landscape that survived to time t, b is the scale parameter, and c is the shape parameter. The negative exponential distribution is a special case of the Weibull where $c = 1$, indicating that the hazard of burning remains constant in time (Johnson and Gutsell 1994). Under a negative exponential distribution the cycle is equal to b, the mean of the distribution (Johnson and Gutsell 1994). When a cumulative time-since-fire distribution fits a negative exponential, it will appear as a straight line on a semilog scale. When the parameter $c \neq 1$, it implies that the risk of burning changes with time. When $c \neq 1$, the fire cycle is equal to $b\Gamma(1/c + 1)$.

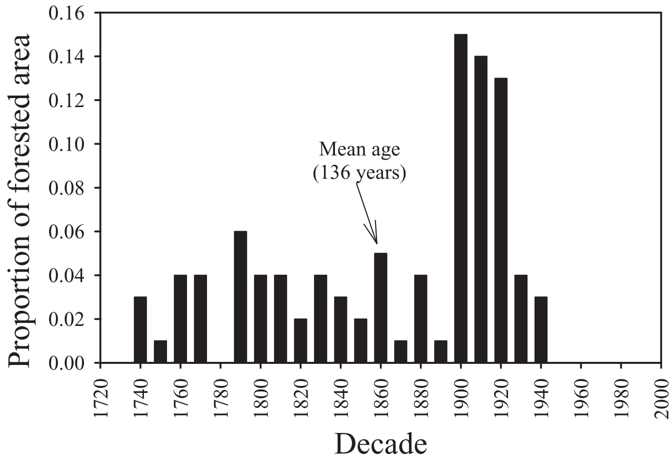
Fire cycles were assessed using survival analysis, a statistical method for studying the occurrence and timing of events (Johnson and Gutsell 1994; Allison 1995). This method has been long used in other fields but has only recently been applied to vegetation ecology (Pyke and Thompson 1986; Muenchow 1986; Johnson and Gutsell 1994; He and Alfaro 2000). It is well suited for time-series data and allows for the use of data that contain censored information. The 114 TSLF observations were fit using the exponential model in the PROC LIFEREG procedure of SAS (SAS Institute Inc. 1990). This log-likelihood-based survival analysis also made it possible to compare cumulative TSLF distributions and assess whether the fire cycle was constant as a function of spatial and temporal influences. A χ^2 test evaluated whether the survival estimates of different covariates or classes of a covariate were significantly different. In addition, survival models using the temporal and spatial covariates individually found to statistically have an influence on fire frequency were explored in conjunction to identify their relative importance. For each survival model, a Lagrange multiplier χ^2 test was performed to see whether each hazard function was constant over time. This is a one degree of freedom test for the null hypothesis that the scale term in the negative exponential model equals one. Additionally, we used the partial information provided from stands where we had only a minimum estimate of time since fire (i.e., the data were censored, meaning that we know the stand had survived for at least a certain time.) in this process. Thirty-seven percent of the data were categorized as censored in this study.

Because we had reason to suspect temporal changes in the fire cycle related to human influence, we evaluated fire cycles before versus after 1890, the date corresponding to the start of colonization of the settlements adjacent to the northwestern part of the study area. The fire cycle was also compared before and after 1850; the end of the period known as the Little Ice Age. Research in boreal forests has shown variation in fire frequency before versus after this time point related to a sharp transition in climate (Bergeron and Archambault 1993; Larsen 1997; Hofgaard et al. 1999; Weir et al. 2000; Bergeron et al. 2001; Girardin 2004).

We also thought it probable that human land use and influence could have caused spatial variation in the fire cycle due to human concentration in the north and west of the study site. Consequently, we equally divided the territory in half (north vs. south, and then west vs. east) and compared time-since-fire distributions and fire cycles to determine whether distributions and cycles for areas closest to settlements were different from areas further away. The influence of relief on the fire cycle was tested, given that this factor is also thought to have an important spatial effect on fire regimes (Hemstrom and Franklin 1982; Turner and Romme 1994; Heyerdahl et al. 2001). Given the topography of the Timiskaming region, the study site was divided into one of two relief classes (plain or hill). Fire cycles and time-since-fire distributions were then estimated and compared for the relief classes. Firebreaks may also affect fire spread (Larsen 1997). Accordingly, we tested their potential impact on the cycle by comparing distributions and cycles by coarse classes for the study site by identifying for each plot the mean distance to firebreaks (lake, river, stream, and bog) measured along each of the eight cardinal directions on topographics maps with a scale of 1 : 50 000. In addition, we tested whether the fire cycle remained spatially constant as a function of superficial deposit. The study area was divided into one of two coarse soil classes (glacial and fluvioglacial), and time-since-fire distributions and fire cycles for each class were identified and compared.

Finally, post hoc likelihood-ratio tests were performed to evaluate survival model goodness of fit. Results showed that the Weibull model did not provide a better fit than that obtained with the negative exponential model in all cases except when analyzing the aforementioned temporal influences and temporal and spatial influences in combination. It is possible that the natural fire regime was altered on the study site to the point that the negative exponential model may not provide the best fit for the data. However, considering the coarse-scale resolution obtained with our sampling strategy, the testing of more complex nonlinear models may not be justified. Consequently, we felt that the negative exponential model provided adequate fire cycle estimations.

Fig. 3. Forest age distribution for the complete study area.



Results

Forest age distribution

Mean stand age (±SD) was 136 ± 60 years, not accounting for censorship (i.e., minimum estimate of stand initiation), and approximately 52% of the forest was older than 100 years (Fig. 3). The proportion of stand recruitment per decade appeared relatively constant and stable (approx. 3%–4% per decade) from the mid-1700s until 1900, at which point fire-caused stand recruitment tripled for the next three decades (early 1900s). From the 1950s to the present, no large-scale fire events were observed (<5000 ha burned for the entire study site since 1950–2000). Forest stands were generally younger in the north and west (Fig. 4), areas more subject to human effects, than in the south and east (Fig. 5). Mean ages (±SD) were 115 ± 47 years for the north, 156 ± 65 years for the south, 113 ± 48 years for the west, and 153 ± 63 years for the east, not accounting for censorship (i.e., minimum estimate of stand initiation).

Cumulative time-since-fire distribution and survival analyses

Significant temporal differences in the fire cycle were detected before and after colonization in 1890 (Table 1). The fire cycle was much shorter in the period immediately after colonization (1890–1948) when compared with the period before this event (Table 2). Significantly different fire cycles were also seen before and after 1850 (Table 1). The fire cycle for the period before the end of the Little Ice Age (approx. 1850) was found to be longer than the period directly after, while no large fires occurred from 1949 to the present (Table 2).

Survival analysis detected significant differences in fire cycles when spatially dividing the territory into north versus south and then west versus east (i.e., human land use; Table 1, Fig. 6), with shorter fire cycle estimates observed in the northern and western sections of the study site than in

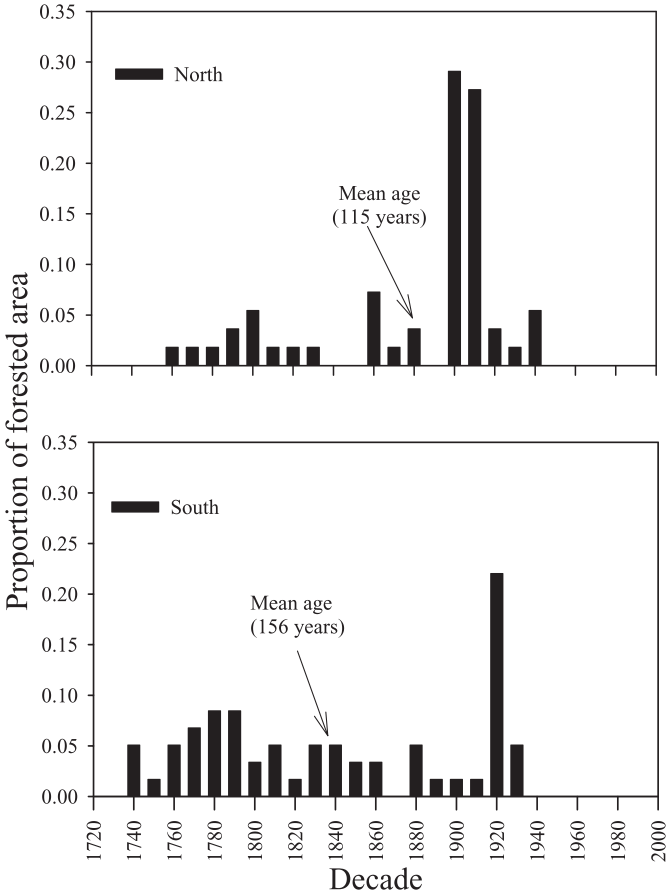


Fig. 4. Forest age distribution for the northern and southern halves of the study site (study area divided into north vs. south).

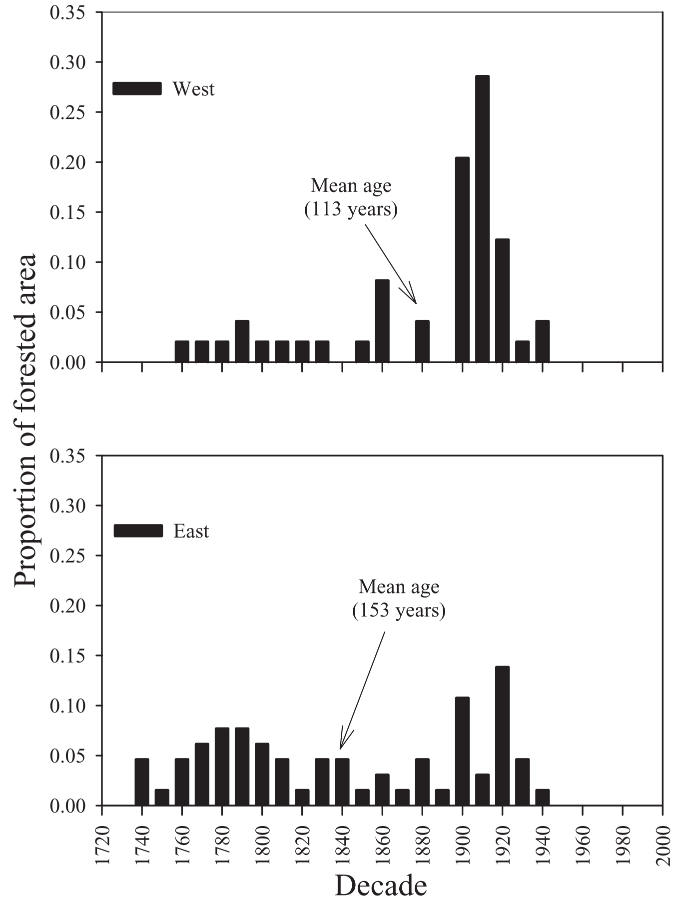


Fig. 5. Forest age distribution for the western and eastern halves of the study site (study area divided into west vs. east).

Table 1. Survival analyses and Lagrange probability results validating spatial and temporal influences on fire frequency while testing whether the hazard of burning was constant with time.

Factors tested for differences in cumulative time-since-fire distribution	Survival analysis ($p > \chi^2$)	Lagrange coefficient ($p > \chi^2$)
Time period		
Colonization (1890–1948, before 1890)	0.0003	<0.0001
Little Ice Age (1850–1948, before 1850)	0.0188	0.0102
Human land use		
North vs. south	0.0019	0.4772
West vs. east	0.0008	0.4746
Relief (plain, hill)	0.4917	0.9397
Mean distance to firebreak (near, medium, far)	0.3002	0.8739
Soil deposits (glacial, fluvioglacial)	0.4599	0.9506
Land use and time period		
North vs. south	0.0188	<0.0001
Time period (1890 break)	0.0020	<0.0001
Land use and time period		
West vs. east	0.0081	<0.0001
Time period (1890 break)	0.0018	<0.0001

the southern and eastern portions (Table 2). However, no statistical spatial relationships between the fire cycle and relief, soil deposits, or distance to fire breaks were found through survival analysis (Table 1, Fig. 6).

When including both time period and the spatial land-use variables (dividing the territory into halves) in the survival analysis model, both factors proved to be statistically significant, although p values suggested that time period might have greater importance (Table 1). The estimated cycles when including both spatial land-use variables and time period in the model did not vary largely from those observed while testing each factor individually (Table 2).

Table 2. Fire cycle estimates for spatial classes and temporal periods.

Spatial and (or) temporal influence	Time period investigated	Estimated fire cycle length[a] (years)
Time period		
Colonization	1890–1948	96 (73–126)
Precolonization	Before 1890	262 (163–422)
Post Little Ice Age	1850–1948	117 (91–150)
Little Ice Age	Before 1850	270 (141–519)
Northern part of study area	—	91 (66–124)
Southern part of study area	—	191 (135–270)
Western part of study area	—	85 (61–118)
Eastern part of study area	—	188(135–262)
Temporal and spatial effects of colonization		
Land use (N vs. S) and time (1890)	N, 1890–1948	73 (53–102)
	N, before 1890	176 (101–309)
	S, 1890–1948	130 (88–193)
	S, before 1890	313 (189–521)
Land use (W vs. E) and time (1890)	W, 1890–1948	68 (48–96)
	W, before 1890	165 (94–291)
	E, 1890–1948	130 (89–189)
	E, before 1890	314 (190–519)

[a]Average length of fire cycle, with 95% confidence interval in parentheses.

Discussion

Factors controlling fire frequency

Physiography

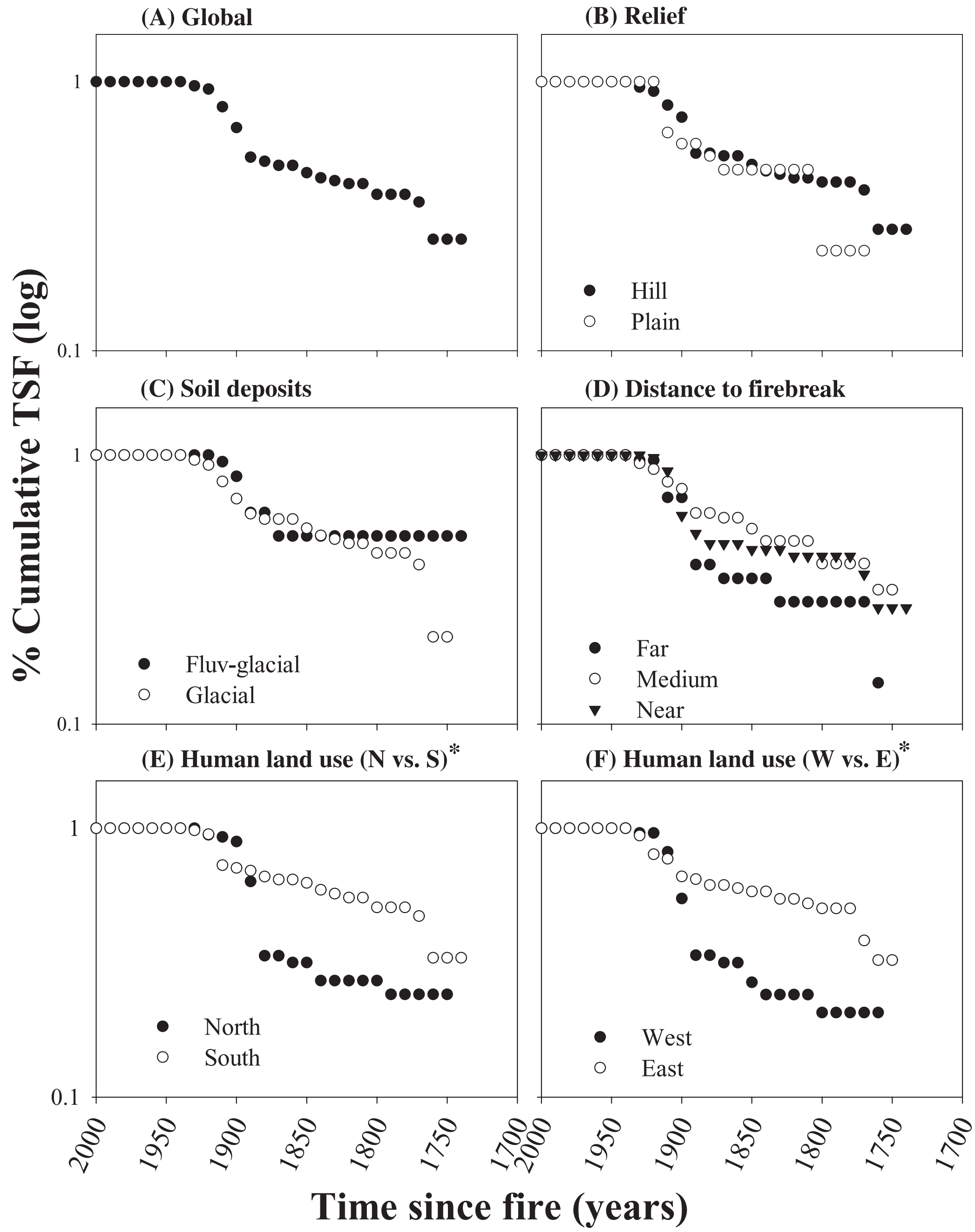
Topographically complex landscapes, fire breaks (such as lakes), and other site-specific environments have been identified as hindering fire spread and promoting local-level deviations from regional fire patterns (Bergeron 1991; Brown and Sieg 1996; Larsen 1997; Barton et al. 2001; Brown et al. 2001; Heyerdahl et al. 2001). However, no differences in fire cycles owing to relief, distance to water bodies, and surface deposits were detected in the area studied. Although topographic elements in Timiskaming are generally considered to be variable and irregular when compared with the more homogeneous landscape found in the adjoining boreal zone (Saucier et al. 1998; Robitaille and Saucier 1998), these features do not appear to have functioned as obstacles to fire spread as reported for other studies. Though no studies have sought direct verification, it is generally assumed that certain surficial soil deposits, such as fluvioglacial types, may also create changes in fire frequency. It seems that changes in soil types across the study area were also not sufficiently diverse to create significant spatial differences in fire frequency. This lack of a clear relationship between surficial deposits and fire frequency is also reported for the adjacent boreal forest (Bergeron et al. 2004). However, the lack of relationship may stem from the large grid size that we used (approx. 22 km^2 per hexagon) to ensure that we primarily sampled large stand-replacing events (i.e., those that control fire frequency), while excluding small and (or) less lethal fires that may be more connected to abiotic factors.

Climate

Numerous studies have shown regional climatic signals synchronizing fire timing across large areas (Swetnam and Betancourt 1990; Johnson and Wowchuck 1993; Wotton and Flannigan 1993; Swetnam and Betancourt 1998; Flannigan et al. 2000). Throughout the boreal forest, researchers have independently shown a decrease in fire frequency associated with warming and increased precipitation since the end of the Little Ice Age (Bergeron 1991; Engelmark et al. 1994; Larsen 1997; Weir et al. 1999; Bergeron et al. 2001; Lesieur et al. 2002). However, shorter fire cycles were identified in Timiskaming after 1850. This climatic signal may have been masked by increased fire activity associated with the colonization process and an extreme dry period throughout Quebec in the early 1900s (Lesieur 2000; Lefort et al. 2003). The fire-free period identified from 1950 to 2000 could partially be attributed to the warming trend and reduction in droughts observed after the Little Ice Age, though more efficient fire suppression measures since the 1970s may also have played a role (Bergeron 1991; Lefort et al. 2003).

Nonetheless, the period after the Little Ice Age might have produced an increase rather than a decrease in fire frequency in this mixed transitional forest. Fire frequency in the temperate forests of the Great Lakes region apparently increased at least 25% in the 20th century as a result of warm, dry conditions and the absence of fire suppression (Clark 1988). This is, however, in contrast with fire weather modeling results from Flannigan et al. (2001) using high-resolution daily weather data under a 2× CO_2 scenario. Their results suggest a decrease in severe fire weather for much of eastern Canada for this period related to increases in precipitation and humidity offsetting the warmer temperatures. To complicate matters, for this model, the Timiskaming region straddles two areas, one with no changes and another with a slight increase in severe fire weather. Therefore, there is uncertainty about the effects of global climate change on fire frequency and vegetation patterns at this temperate–boreal transitional area; in the absence of large changes in fire patterns, the most likely scenario is an increase in species that currently inhabit temperate forests and a decrease in species that currently inhabit boreal forests.

Fig. 6. Cumulative time-since-fire distributions using logarithmic scale comparing (A) global distribution, (B) relief, (C) surficial deposits, (D) mean distance to firebreak, (E) land-use patterns (north vs. south), and (F) land-use patterns (west vs. east). Statistically significant differences in distributions are denoted by asterisks.



Colonization

Humans have exerted profound effects on fire regimes, and our results suggest that the Temiskaming region of Quebec is not an exception. Colonization and its associated logging and agricultural activities in conjunction with an extreme dry period in the early 1900s in Quebec (see Lesieur 2000; and also Lefort et al. 2003) appear to have contributed to spatially mixed fire frequencies, with shorter fire cycles in areas adjacent to the developed sections of the north and west. Moreover, the observed temporal shift in fire frequency to a shorter cycle immediately after 1890 provides further support for the importance of human impact through settlement on the fire regime. Webber and Stocks (1998) suggest that an increase in fire ignitions may be due to greater access to the landscape through the settlement process, while other studies have identified an increase in the area burned during the postsettlement period due to the many fires ignited by human activities (Cwynar 1977; Hemstrom and Franklin 1982; Niklasson and Granström 2000; Lefort et al. 2003).

Natural fire cycle for the Timiskaming region

Given the aforementioned spatial and temporal influences, an accurate natural fire cycle is difficult to estimate. However, the notably longer fire cycles detected in the south and east in the earliest time period may be a result of fewer anthropogenic influences on the landscape, and thus they most likely better represent the natural cycles. The complex nature of this transitional area sometimes affected by fire and sometimes by other disturbance types consequently becomes apparent given fire cycle estimates ranging between 188 and 314 years. Long fire cycles have important consequences on stand composition, structure, and ultimately the forest mosaic (Bergeron and Dubuc 1989; Bergeron et al. 2001; Lesieur et al. 2002). Because of the presence of large tracts of old-growth forest with less frequent fires, patch (i.e., insect perturbation and windthrow) and gap (i.e., small-scale single-tree and small-group mortality) dynamics are also significant. The presence of multiple disturbance types due to the long fire cycle in this transition zone may in part explain the particularly high diversity of tree species observed at different scales in the landscape (Frelich and Reich 1995), especially when compared with the lower diversity levels observed in the boreal zone.

Implications for sustainable forest management

It is apparent from our results that when establishing forest management plans based on historical disturbance patterns it is necessary to conduct individual baseline studies to understand the natural processes unique to a management area. Yet on a larger scale, our findings and others show that humans (Hemstrom and Franklin 1982; Niklasson and Granström 2000; Lefort et al. 2003) and climate (Bergeron 1991; Engelmark et al. 1994; Larsen 1997; Weir et al. 1999; Bergeron et al. 2001; Lesieur et al. 2002) have interacted to affect the fire regime, which is something that researchers and forest managers should consider regionally and across Canada. When time intervals between fires lengthen and exceed the mean tree longevity for the postfire cohort, mechanisms of succession become important (Frelich and Reich 1995; Lesieur et al. 2002). Without fires, forest structure and composition become closely related to secondary disturbance such as spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks and windthrow, which are common in eastern Canadian forests (Bergeron et al. 2001). New studies identifying species-replacement mechanisms in the presence and absence of fire and fine-scale disturbances then become necessary, functioning as a key component in guiding forest management practices inspired by natural ecosystem dynamics.

Fire affects the pattern and structure of forests even in this transition zone between northern hardwood forests and boreal coniferous forests. However, if management objectives are to be based on natural disturbance patterns in this area, our results call into question the use of large-scale even-aged management systems with short rotations and suggest more diversified silvicultural practices. With longer fire cycles, alternatives to clearcuts are required. By the superimposition of the effects of secondar disturbance (i.e., effects of insect outbreaks and other gap-type dynamics) through partial cutting onto the mosaic created by large fires, simulated through even-aged techniques, natural stand dynamics may be emulated to a greater extent, thus advancing the goal of maintaining biodversity and natural ecological processes.

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