Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry[1]

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Abstract: Given that fire is the most important disturbance of the boreal forest, climatically induced changes in fire frequency (i.e., area burnt per year) can have important consequences on the resulting forest mosaic age-class distribution and composition. Using archives and dendroecological data we reconstructed the fire frequency in four large sectors along a transect from eastern Ontario to central Quebec. Results showed a dramatic decrease in fire frequency that began in the mid-19th century and has been accentuated during the 20th century. Although all areas showed a similar temporal decrease in area burned, we observed a gradual increase in fire frequency from the west to Abitibi east, followed by a slight decrease in central Quebec. The global warming that has been occurring since the end of the Little Ice Age (~1850) may have created a climate less prone to large forest fires in the eastern boreal forest of North America. This interpretation is corroborated by predictions of a decrease in forest fires for that region of the boreal forest in the future. A longer fire cycle (i.e., the time needed to burn an area equivalent to the study area) has important consequences for sustainable forest management of the boreal forest of eastern Canada. When considering the important proportion of overmature and old-growth stands in the landscape resulting from the elongation of the fire cycles, it becomes difficult to justify clear-cutting practices over all the entire area as well as short rotations as a means to emulate natural disturbances. Alternative practices involving the uses of variable proportion of clear, partial, and selective cutting are discussed.

Résumé : Le feu étant la perturbation majeure dans la forêt boréale, un changement dans la fréquence (i.e., superficie brulée par année) des feux induit par le climat peut avoir des conséquences importantes sur la mosaïque forestière, la distribution des classes d'âge et la composition. Nous avons reconstitué la fréquence des feux à l'aide d'archives et de données dendrochronologiques historiques pour quatre grands secteurs localisés entre l'est ontarien et le centre du Québec. Les résultats montrent une décroissance dramatique dans la fréquence des feux depuis le milieu du 19e siècle qui s'est accentuée au 20e siècle. Bien que tous les secteurs étudiés montrent la même décroissance temporelle, nous avons observé une augmentation de la fréquence des feux de l'ouest jusqu'à l'est de l'Abitibi, puis une légère diminution vers le centre du Québec. Les changements climatiques observés depuis la fin du Petit Âge Glaciaire (ca. 1850) pourraient avoir induits un climat moins propice aux incendies forestiers de grande superficie dans la portion est de la forêt boréale canadienne. La décroissance de l'activité des incendies qui est prédite dans le futur corrobore ces résultats. L'allongement du cycle des feux (i.e., le temps nécessaire pour brûler une superficie équivalente à l'aire d'étude) a des conséquences importantes pour l'aménagement durable des forêts de l'est du Canada. Comme la proportion de forêts anciennes et surannées s'accentue suite à l'allongement du cycle des feux, il devient difficile de justifier l'utilisation généralisée de la coupe à blanc et de courtes révolutions en tant qu'approche qui imite les perturbations naturelles. Une alternative impliquant l'utilisation de proportions variables de coupes totales, partielles et sélectives est discutée.

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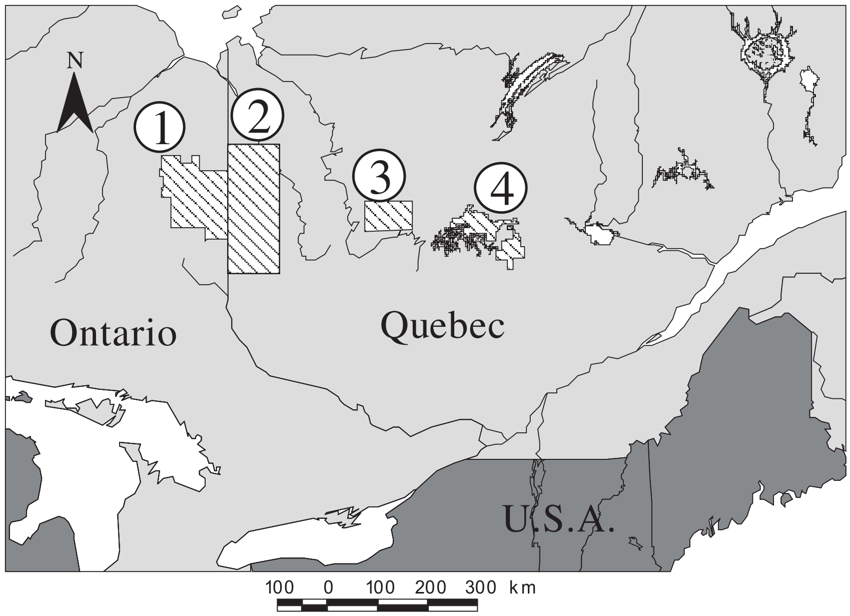
Fig. 1. Location of the four study areas: (1) Lake Abitibi model forest, (2) Abitibi west, (3) Abitibi east, and (4) central Quebec.



Introduction

Fire is the main natural disturbance of the boreal forest (Johnson 1992; Payette 1992). There is little doubt that past and predicted climate changes had caused and will cause changes in forest disturbances, including natural fire regimes (Clark 1988; Overpeck et al. 1990). Several studies both in the western and eastern part of Canada suggest that a major decrease in fire frequency (i.e., area burned per year) occurred with the last major phase of warming of the Little Ice Age around 1850 (Bergeron and Archambault 1993; Larsen 1996; Weir et al. 1999). Under a 2 × CO_2 scenario, numerical simulations predict heterogeneous changes in the Canadian Fire Weather Index (CFWI) across North America, with increased values observed in the central regions and lower values in the northeast and west (Flannigan et al. 1998).

It is generally assumed that the North American boreal forest is characterized by relatively short fire cycles (i.e., the time needed to burn an area equivalent to the study area) and by a forest mosaic mainly composed of post-fire even-aged stands (Heinselman 1981; Johnson 1992), and this generalization has often been used to justify forest management based on clear-cutting and short rotation (i.e., age at which the forest is harvested). On the other hand, long fire intervals allowing for changes in canopy dominance and development of uneven-aged forests have also been reported, particularly in the eastern boreal forests (Foster 1983; Cogbill 1985; Frelich and Reich 1995; Bergeron 2000). Moreover, the increase in fire cycle length suggested under climate change will likely accentuate this phenomenon.

The past decade has seen an increasing interest in forest ecosystem management and, in particular, in forest management strategies based on an understanding of natural disturbances (Attiwill 1994; Galindo-Leal and Bunnell 1995; MacDonald 1995; Lieffers et al. 1996; Bergeron and Harvey 1997; Angelstam 1998). Currently, there is considerable agreement that a management approach aimed at maintenance of stand composition and structures similar to those characterizing natural environments could provide a means of maintaining biodiversity and the essential functions of forest ecosystems (Franklin 1993; McKenney et al. 1994; Gauthier et al. 1996). The logic behind this assumption is that organisms are adapted to the environmental forces with which they have evolved over the millennia. In this context, background information on natural fire cycles and their control on composition and structure of the forest mosaics are pivotal to the sustainable management of the boreal forest (Johnson et al. 1998; Bergeron et al. 1999*b*). In this paper, we have reconstructed the fire frequency of a large area from the eastern boreal forest. Our objectives were threefold: (*i*) to assess whether the fire cycle has varied in the last 300 years; (*ii*) to compare the fire cycle among four regions of the eastern Canadian boreal forest, and (*iii*) to discuss the consequences of the results on forest attributes and forest management of the eastern boreal forest.

Methods

Study area

Fire history was reconstructed in four different regions that cover more than 30 000 km^2 along a 1000-km transect ranging from eastern Ontario (80°30′W) to central Quebec (73°30′W) between 48 and 50°N (Fig. 1, Table 1). All sectors are located in the southern boreal forest at the transition zone between mixedwood and conifer-dominated forests (Grondin et al. 1996). The mixedwood region has an annual average temperature of 0–1.0°C and annual precipitation between 800 and 1000 mm, while the conifer region is characterized by an average temperature between 0 and –2.5°C and 600–1000 mm of annual precipitation. There is a slight increase in precipitation from the western location towards the east, while temperatures remain relatively uniform. Lake Abitibi Model Forest (LAMF) and Abitibi west are part of a broad physiographic unit known as the clay belt, which extends across northern Quebec and Ontario. The flat topography of the Abitibi region was created by lacustrine deposits from the maximum post-Wisconsonian extension of proglacial lakes Barlow and Objibway

Table 1. Characteristics and estimated fire cycles for each region.

Region*	Area (km^2)	Mean age (years)	% over 100 years†	Fire cycles (years)‡ 1920–1999	1850–1920	<1850
Lake Abitibi model forest *a*	8 245	172	78	521 (370–733)	234 (171–321)	132 (98–178)
Abitibi west *b*	15 793	139	57	325 (248–424)	146 (114–187)	83 (65–105)
Abitibi east *c*	3 294	111	54	191 (124–294)	86 (56–131)	—§
Central Quebec *b*,*c*	3 844	127	56	273 (183–408)	123 (83–181)	69 (47–102)

*Regions marked with different letters are significantly different at $p < 0.05$ for the fire cycles of the three periods.
†Percentage of the stands that are older than 100 years in Fig. 1.
‡The three periods are significantly different at $p < 0.001$ for all regions.
§There was not enough data to allow for fire cycle computation for this period.

(Vincent and Hardy 1977). Although clay is the dominant deposit throughout these areas, shallow tills and rock outcrops are more abundant in the south, where altitude averages 300 m than in the north, which is characterized by lower altitude (250 m) and the abundance of wetlands. The Abitibi east and central Quebec regions are located on the Canadian Shield and are characterized by a rolling topography with till and glaciofluvial deposits (Robitaille and Saucier 1998). Rock outcrops and shallow tills are more abundant in Abitibi east, while deeper till deposits cover a large area in the central Quebec region. The average altitude is 450 m in central Quebec and about 400 m in Abitibi east. With the exception of the southern part of the Abitibi west region, which has been colonized for agriculture in the beginning of the 20th century, the area is essentially unpopulated and is typical of the eastern boreal forest that is currently under extensive forest management.

Fire history reconstitution

In each area, fire history was reconstructed up to the last 300 years; the length of the reconstruction was limited by tree longevity. In all sectors but central Quebec the proportion of stands originating from the different fires was based on an exhaustive stand initiation map (Johnson and Gutsell 1994) for the complete sector. In the case of central Quebec, instead of producing a time since fire map, we used a network of 157 clusters made of three permanent plots (1 cluster/25 km^2). The clusters were systematically distributed in all the studied areas from which we derived the area burned per decade from the frequency of sample in each decade. The fire maps show the distribution of forest stands as a function of time since last fire, without considering the effect of land clearing, felling, or other disturbances. For the recent past, the time of the last fire was identified using available historical documents (forest companies, protection agencies, Donnelly and Harrington 1978). For the residual area, fire limits were established using old air photographs (1920s and 1930s) when possible, and the dates of stand initiation were determined using standard dendroecological techniques (Arno and Sneck 1977). At least one site was sampled every 100 km^2.

At each site, increment cores or cross sections were taken on 5–10 fire-prone tree species, and when available snags of jack pine (*Pinus bamksiana* Lamb.) and cross sections of trees bearing fire scars were also collected. The age of the oldest tree in each site was used as an indication of the time since fire. In most of the cases (70% LAMF, 81% Abitibi west, 85% Abitibi east, and 84% central Quebec), 60% of the tree ages were within 10 years of one another, allowing for a good estimation of the fire decades. Moreover, when the ages of the trees were too far from each other, we used the oldest tree age as a minimum time since fire date. In these cases, the data were considered as censored, which was taken into account in further analysis. The area burned in each fire decade was then estimated from maps by creating Thiessen polygons around the sampled sites (Bailey and Gatrell 1995). Previous studies involving a higher resolution (Bergeron 1991; Dansereau and Bergeron 1993) have shown that most of the area burned is characterized by a few relatively large fires (>100 km^2), and consequently, we think the map adequately represents the large fires occurring over the area.

Statistical analysis

The proportion of area burned for each decade and the mean stand age were derived from the fire-history reconstruction of the four regions. Assuming that the probability of burning is independent of stand age, which is generally mentioned in studies on the boreal forest (Johnson 1992), the age-class distribution should follow a negative exponential or the reverse cumulative percentage of the area burned should follow a straight line on semilog paper (Van Wagner 1978). As a first step, the distribution was derived for all the regions pooled to evaluate whether the fire frequency was constant over time or space (Johnson and Gutsell 1994). As the distribution was not a straight line, the same procedure was applied to each region. Again, distributions did not show a constant hazard of burning, fire cycles were computed for the following predetermined periods: before 1850, 1850–1920, and after 1920. The 1850 limit between periods was selected because it corresponds to the reported end of the Little Ice Age in the area (Archambault and Bergeron 1992), while 1920 corresponds to the beginning of the intensive colonization of the region. Fire cycles were computed using PROC LIFEREG (the survival analysis procedure) in SAS (SAS Institute Inc. 1990), which is a standard maximum-likelihood estimate (MLE) procedure for analyzing survival data (Allison 1995). This type of analysis enabled the estimation and comparison of fire cycles for the three periods and the four regions simultaneously while taking into account the censored data in the data sets (minimal dates of fire).

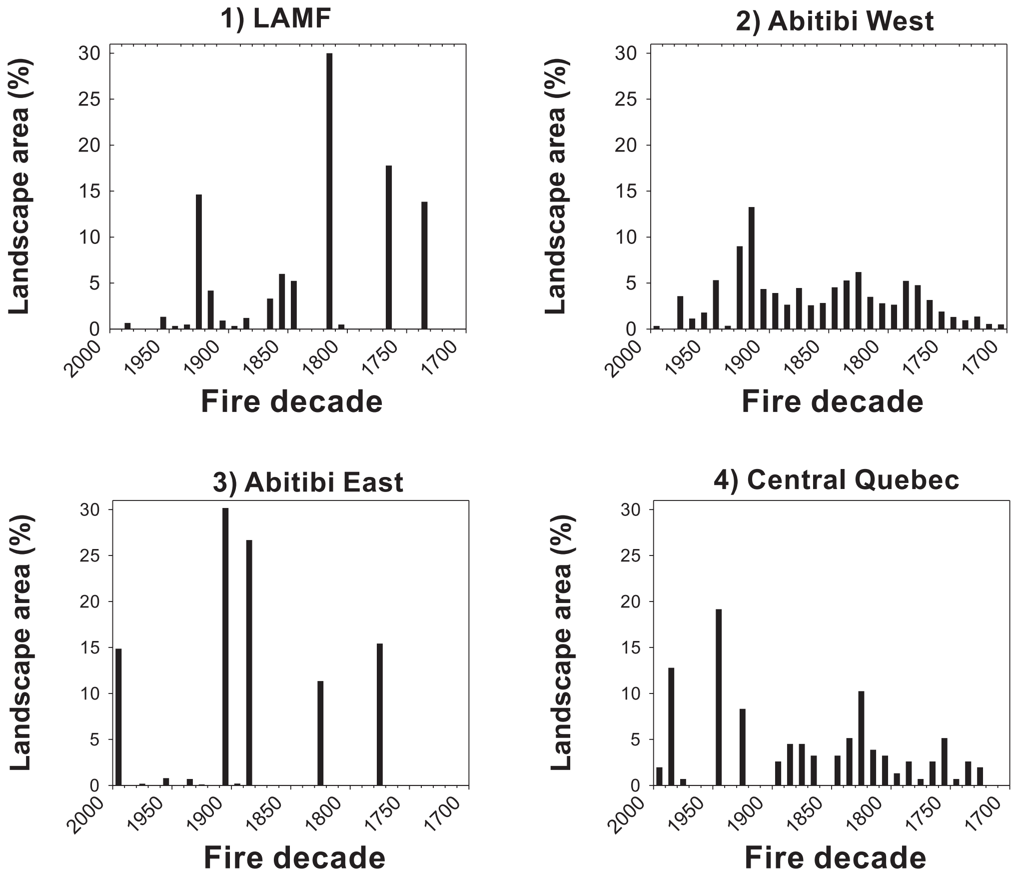
Results

Forest age distribution and fire cycles

The age distributions (Fig. 2) of the four forest regions have a very low proportion of forests that have originated from fires after 1920. These graphs also show that forest stands initiated more than 100 years ago are abundant in all sectors. The proportion of forest that is currently older than 100 years is higher than 50% in the four regions, with 78% in the LAMF and 53% in the Abitibi east region. The average stand age is decreasing from the LAMF region (172 years) to the Abitibi east (111 years) region, with a slight increase in central Quebec (127 years) (Table 1).

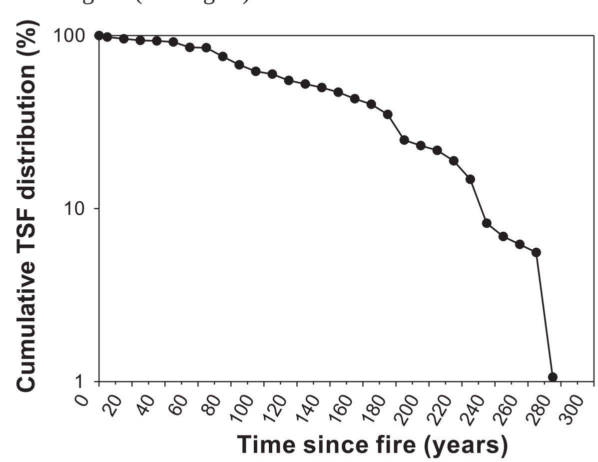
The global cumulative time since fire distribution (Fig. 3) did not show a straight line, suggesting differences in fire frequency among regions or changes over time. As the reverse cumulative area burned in each sector were not straight lines (Fig. 4), this indicates that fire frequency may have changed over time. Generally speaking, each distribution is

Fig. 2. Forest age distribution for each study areas: (1) Lake Abitibi model forest, (2) Abitibi west, (3) Abitibi east, and (4) central Quebec.



showing two changes in slopes in the early 20th century and around the mid-19th century. The fire cycles were computed for the three predefined time periods and for the four regions. The global analysis revealed that the age-class distributions followed a negative exponential and that the periods and the regions were significantly different. A significant increase in fire cycle is observed over time with shorter fire cycles (69–132 years) before 1850 increasing to cycles greater than 190 years after 1920. Although all areas show a similar significant temporal decrease in area burned, estimated fire cycles are significantly different among regions. In fact, the LAMF is characterized by a fire cycle that is significantly longer than in the other regions, whereas the shortest fire cycle length is observed in Abitibi east.

Fig. 3. Semilog cumulative time since fire (TSF) distribution for the four regions combined. As the distribution did not show a constant hazard of burning, semilog distributions were derived for each region (see Fig. 4).

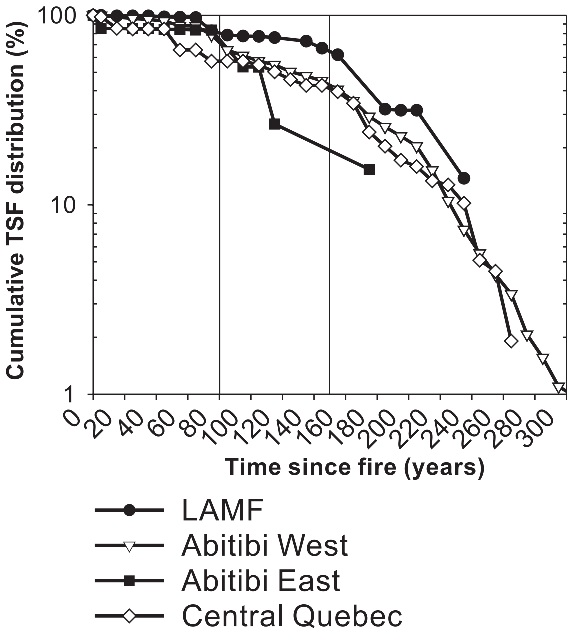


Discussion

Fire frequency

Since the areas examined were still virgin in 1850, the decreasing fire frequency observed probably was not caused by direct human activity. Although the influence of native peoples on fire frequency could not be totally ruled out, we believe that the low density of the population in this part of the boreal forest (Côté 1993), together with common knowledge of the use of fire by natives (Lewis 1982), could not explain the importance of the observed decrease. The subsequent decrease around 1920 corresponds to a period of important human settlement, especially in the southern section of the study area. Therefore, the observed decrease in fire frequency may have resulted from human activities such as passive and active suppression. However, it is difficult to explain the observed decrease only with an anthropogenic effect. Active suppression using water bomber tankers began only around 1970. Furthermore, fire danger reconstitution studies are suggesting a decrease in the extremity of the fire season in the study area for the 20th century (Lefort 1998; Lesieur 2000). Moreover, the pattern during the 300-year

Fig. 4. Semilog cumulative time since fire (TSF) distribution of each of the sectors. As distributions did not show a constant hazard of burning, fire cycles were computed for periods of relatively constant fire frequency (see Table 1 for results).



period is also similar to the decrease reported for the islands of Lake Duparquet (Bergeron 1991), where fires have never been suppressed. All these elements suggest that the decrease in fire frequency is at least partly driven by a change in climate. The increase in the fire cycle at Lake Duparquet was related to a reduction in the frequency of drought events since the end of the Little Ice Age (Bergeron and Archambault 1993). The present results suggest that the phenomenon can be extended to a larger area of the eastern boreal forest. It is hypothesized that the warming that started at the end of the Little Ice Age is associated with an important change in the circulation of air masses. This hypothesis is supported by simulations using the Canadian general atmospheric circulation model, which predicted a decrease in forest fire activity for most of the eastern boreal forest, with future warming (Flannigan et al. 1998).

On the other hand, the west–east increase in fire frequency does not seem to be explained by a similar trend in the severity of climatic conditions. In fact, precipitation (Atmospheric Environment Service 1986) and computed fire weather indices all suggest a decrease in the severity of the fire season from west to east (V. Kafka, B. Todd, and M. Flannigan, unpublished results). This suggests that other factors such as lightning occurrences could influence the fire regimes in these areas. Moreover, the longer fire cycles observed in eastern Ontario and western Quebec might be explained in part by the abundance of wetlands that characterized the clay belt region as compared with the eastern portion of the study area, which is located on the Canadian Shield. Currently, it is not possible to discriminate between the relative importance of climate or the geological characteristics that control the fire cycle reported here. Therefore, more information on fire frequency is required to explain these spatial patterns.

Consequences on forest attributes

Long fire cycles have important consequences on stand age distribution, and consequently, on the composition and structure of the forest mosaic. Using a chronosequence and a stand reconstitution approach Bergeron and Dubuc (1989) and Bergeron (2000) have shown how stand composition and structure change with long elapsed time since fire. Postfire composition is characterized by even-aged pure or mixed stands dominated by trembling aspen (*Populus tremuloides* Michx.), birch (*Betula papyrifera* Marsh.), jack pine, or black spruce (*Picea mariana* (Mill.) BSP). This first cohort of trees is replaced at maturity (>100 years after a fire) by a second cohort dominated by shade-tolerant conifers such as balsam fir (*Abies balsamea* (L.) Mill.), white cedar (*Thuja occidentalis* L.), white spruce (*Picea glauca* (Moench) Voss), and black spruce. At this stage, stands tend to be unevenaged with a more irregular canopy. In old-growth stands (>225 years after a fire), a dynamic driven by gaps or insects permits the self-maintenance of heterogeneous stands of conifers (Bergeron and Leduc 1998; Kneeshaw and Bergeron 1998).

Without fires, forest structure and composition are closely related to secondary disturbance, particularly spruce budworm (*Choristoneura fumiferana* (Clem.)) outbreaks and windthrow, which are both common in eastern Canadian boreal forest. The incidence of spruce budworm outbreaks depends on species composition, in particular the abundance of balsam fir (MacLean 1980; Bergeron and Leduc 1998; Bergeron 2000), which varies with time since fire (Bergeron et al. 1995). Windthrow can vary with stand age, composition, or structure (Ruel 1995). Both of these disturbances are becoming more abundant as forests age following fire (Bergeron et al. 1995; K. Harper, Y. Bergeron, S. Gauthier, and P. Drapeau, paper submitted) and may interact one with the other (Morin 1990).

In this context, changing the stand age distribution has important consequences on the proportion of stand types observed in the forest mosaics (Gauthier et al. 1996). This might in turn have important consequences in the maintenance of diversified habitats used by other organisms (Franklin 1993).

Forest management implications

Our results indicate that, in all regions, the current age structure has more than 50% of the area that exceeds 100 years. With a harvesting age of 100 years, this means that 50% of the stand age structure would disappear from the landscape. To take into account the possible effect of human activities on increasing the fire cycles since 1920, we have estimated the proportion of stands that were older than 100 years in 1920. The same west–east trends were observed with more than 40% of the landscapes aged at more than 100 years. Therefore, the characteristics of naturally disturbed landscapes discussed above have important implications for developing silvicultural systems that are inspired by natural ecosystem dynamics (Attiwill 1994; Bergeron and Harvey 1997). A normal harvesting rotation of about 100 years would only preserve 22–46% (Table 1) of the current forest age structure and associated composition, depending on the region under consideration. This discrepancy between the natural and managed age-class distribution would be even more important if we use contemporary (since 1920) fire cycles as a benchmark for estimating the proportion of stands that should survive over rotation age. A short industrial forest rotation would lead to a dramatic decrease in stand diversity at the landscape level (Gauthier et al. 1996) in terms of stand composition and structure, with potentially significant consequences on biological diversity (Hunter 1990).

One possibility to overcome this problem is to increase forest rotation to better mimic the natural fire cycle (Burton et al. 1999; Seymour and Hunter 1999). However, the short longevity of eastern boreal species limits the possibility of using only this option as longer rotation would imply an important decrease in allowable cut. Another option involving the use of silvicultural practices designed to maintain specific structural or compositional elements of mature to overmature stands in forests being managed may provide a means of maintaining species and ecosystem diversity while only slightly modifying allowable cut (Bergeron et al. 1999*a*; Harvey et al. 2001). Briefly, we suggest that it is possible to treat some stands with clear-cutting followed by planting or seeding to create an even-aged structure analogous to that observed after fire, other stands with partial cutting, which simulate the natural evolution of overmature stands, and still others with selective cutting as a means of emulating gap dynamics in old growth. As our results suggest, the proportion of stands that should be treated with each of these silvicultural practices should vary in relation to the natural disturbance cycle of a particular region together with the maximum harvest age. It would thus be possible to partially maintain not only the natural composition and structure of stands but also a landscape age structure that approaches the typical distribution created by fire.

If logging activities are to be viewed as a different type of disturbance that can be integrated into sustainable forest management, it is necessary to verify that these activities are able to maintain essential disturbance-related processes and dynamics in the ecosystem. Although it has been recognized that both disturbance types initiate stand replacement, comparative studies previously conducted in the boreal forest have reported important compositional differences in the vegetation observed following logging and burning (Carleton and MacLellan 1994; Johnston and Elliott 1996; Nguyen-Xuan et al. 2000). Comparable diversity and productivity were observed, however, for post-logging and post-fire stands with similar composition (Reich et al. 2001), suggesting that logging can potentially maintain ecological processes similar to fire. The challenge is, thus, not only to recreate a landscape age structure that approaches the typical distribution created by fire but also to maintain the integrity of the ecological processes at the stand level.

Conclusion

Our results have shown considerable spatial and temporal variations in the fire cycles along a large transect in the boreal forest of northeastern Canada. Our results suggest that, in the four studied regions, there is an increase in the fire cycle length since the end of the Little Ice Age. Moreover, the fire cycles reported here are longer than those generally reported for the boreal forest (Heinselman 1981; Johnson 1992). These observations imply that, with long fire intervals, species replacement is likely to occur in large areas of the eastern boreal forest. Therefore, management strategies have to be adopted or developed to take these phenomenon (abundance of mature to overmature forests and successional changes) into account.

Our results and those of other researchers indicate that fire frequency can be highly variable in time and space (Armstrong 1999). Therefore, a target toward a single fire cycle may not be appropriate in forest management. We suggest that the current average time since fire (forest stand age), derived from a 300-year fire history, can be used as a baseline in strategic planning of harvesting activities to estimate the desired proportion of even-aged, irregular, and uneven-aged stand types that can be recreated using different silvicultural treatments (Bergeron et al. 1999*b*). In fact, this value has the advantage of encapsulating the variations in the fire cycles observed here. It also provides an indication of the amount of forest that exceeds the usual rotation age, allowing for an assessment of the risk of losing this component of the landscape diversity.

Finally, our results have also shown a west–east gradient in fire cycle length. These spatial variations suggest that the boreal forest is a complex and variable system, where management strategies have to be developed on a regional basis to consider this complexity.

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