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Reconstruction of recent and Holocene fire chronologies and associated changes in forest composition: a basis for forest landscape management

by

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ABSTRACT

As some consequences of fire resemble the effects of industrial forest harvesting, forest management is often considered as a disturbance having effects similar to those of natural disturbances. Although the analogy between forest management and fire disturbance in boreal ecosystems has some merit, it is important to recognise that it has limitations. We discuss results on fire regime and stand dynamics in Quebec's boreal forest. The large fluctuations observed in fire frequency during the Holocene limit the use of a single fire cycle to characterise natural fire regimes Short fire cycles generally described for boreal ecosystems do not appear to be universal; rather, shifts between short and long fire cycles have been observed. These shifts imply important changes in forest composition and structure at the landscape and regional levels. All these factors create a natural variability in forest composition and structure that should be maintained by forest managers concerned with biodiversity conservation. On the other hand, the current forest management approach tends to decrease this variability: for example, normal forest rotations truncate the natural forest stand age distribution and eliminate over-mature forests from the landscape. In this report we suggest that the development of silvicultural techniques that maintain a spectrum of forest compositions and structures over the landscape is one avenue to maintain this variability.

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INTRODUCTION

The forest industry is heading back to nature to find a way to conciliate economic fibre production with biodiversity One of the avenues being explored is the development of silvicultural systems that are inspired by and closely resemble natural ecosystem dynamics (Attiwill 1994; Galindo-Leal and Bunnell 1995; Bergeron and Harvey 1997). In the boreal forest, fire is the disturbance agent that has the greatest impact on forest dynamics (Engelmark et al. 1993). The North American boreal forest is generally characterized by relatively short fire cycles (50 to 250 years) and stand-replacing fires (Heinselman 1981; Johnson 1992 ; Payette 1992). Because some consequences of fire resemble the effects of industrial forest harvesting, forest management is often considered as a disturbance having effects similar to those of natural disturbances.

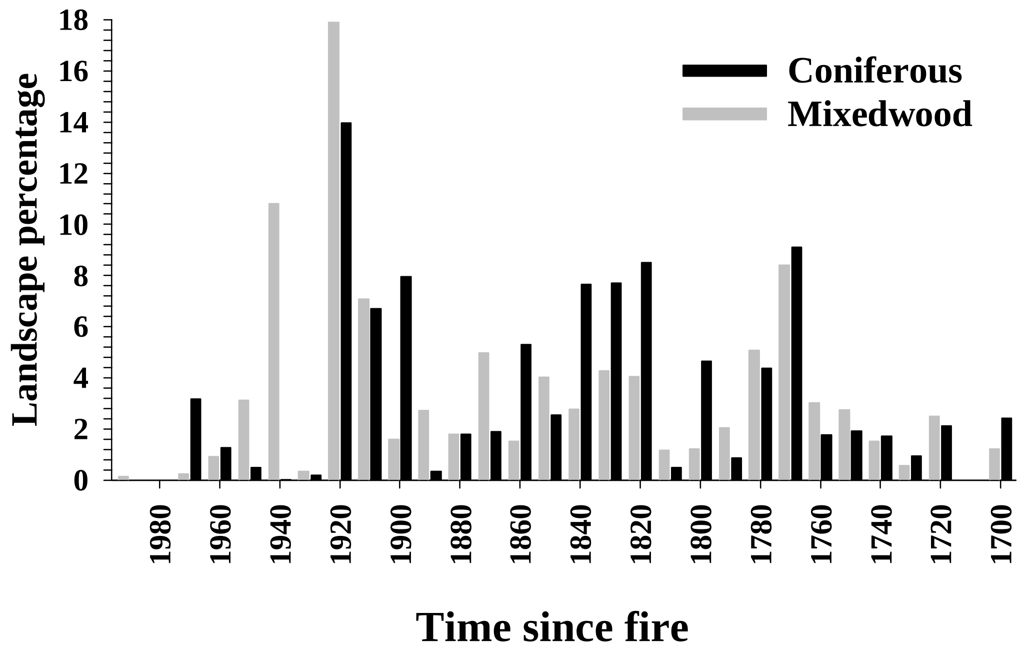
Although the analogy between forest management and fire disturbance in boreal ecosystems has some merit, it is important to recognise that it has limitations. In this report we describe, using research results on natural disturbances and forest dynamics in Quebec's boreal forests, characteristics of boreal systems controlled by fire that contribute to increase variability. We then suggest several avenues that should be explored to develop silvicultural systems that are inspired by, and closely resemble, natural ecosystem dynamics. Although the general principles presented here can be extended to the boreal forest in general, the empirical results presented apply mainly to Quebec’s Clay Belt.

VARIABILITY IN THE FIRE REGIMES

Recent Fire History

Dendrochronological reconstructions of fire events over the last 300 years in a 15,000 km^2 between 48^0 and 50^0 N along the Quebec-Ontario border. The 49th parallel constitutes the limit between the Mixedwood boreal zone and the Coniferous boreal zones. The results showed a dramatic decrease in fire frequency during the twentieth Century. The fire cycle estimated at 62 years for the period before 1850, has increased to 121 years and has continued to lengthen during the Twentieth Century. This decrease in fire frequency is responsible for the presence of large tracks of over-mature and old-growth forests in the territory (Fig. 1).

The increase in the fire cycle appears to be due to a reduction in the frequency of drought events since the end of the Little Ice Age (~1850) (Bergeron and Archambault, 1993). This climatically induced increase in the fire cycle appears to be a general phenomenon in the eastern boreal forest. A companion study comparing landscapes with different degrees of human activities (Lefort et al. submitted and Appendix 1) tend to confirm that the observed change in fire cycles is mainly related to climate and not to changes induced by human activities. Moreover, a climatically driven decrease in fire frequency is supported by simulations using



the Canadian General Atmospheric Circulation Model that predict a decrease in forest fire activity, for this region, with future warming (Flannigan et al. 1998).

Figure 1. Current age class distribution of stands in the mixedwood and coniferous boreal regions. Notice the important proportion of the landscape in over-mature and old-growth stands

Fire cycles computed for the periods during and after the end of the Little Ice Age do not vary significantly between the two forest types. This suggests that the transition between Mixedwood and Coniferous forest observed in the southern boreal forest cannot be explained by a difference in fire frequency, during at least the last 300 years. On the other hand, fire regime in the Coniferous region is characterised by few large fires whereas a high abundance of small fires is observed in the Mixedwood region (Fig.2). In the north, serotinous fire-adapted conifers such as jack pine and black spruce appears to be favored by large fires while in the south conifer species such as balsam fir and white spruce which need to re-invade from unburned areas would be favored by smaller and possibly less severe fires

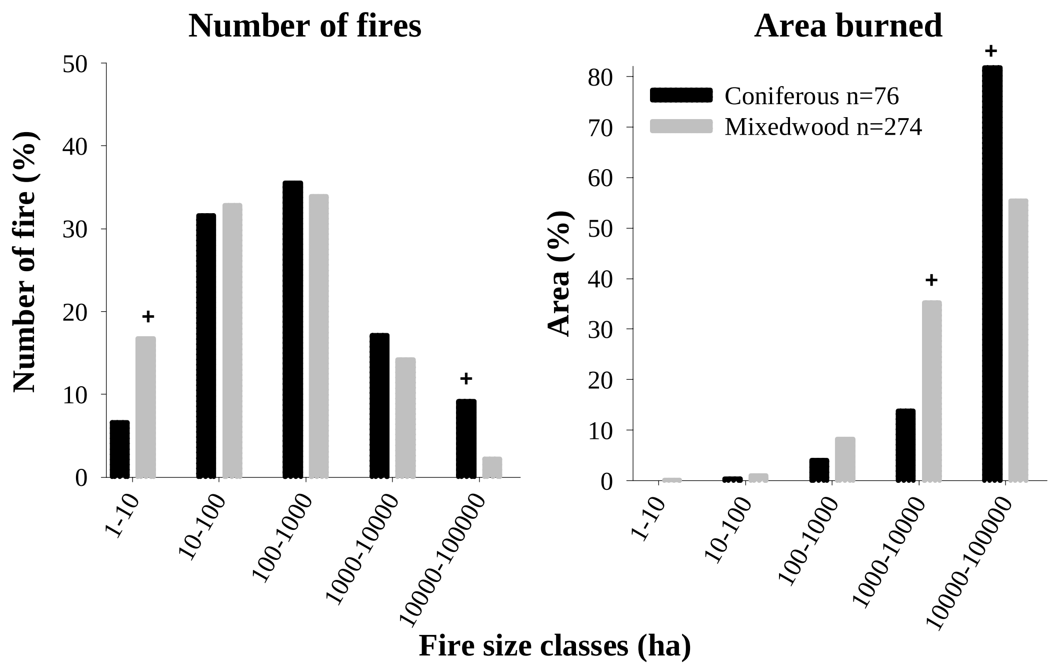


Figure 2. Comparisons of the number of fires and the area burned per class of fire size among the Coniferous and the Mixedwood regions. + indicates that significantly more fires (left) or more area burned (right) are observed.

Presence of fire of smaller sizes in the mixed-woods is congruent with results from simulations of fire sizes using the Canadian fire behavior model (Hely et al, submitted, and Appendix 2). Fires tend to be smaller in deciduous and mixed stands regardless of the fire weather indexes (Fig.3). This interpretation is supported by the observed fire behavior in at least one fire where observed fire severity was lower in deciduous and mixed stands in comparison with coniferous stands (Kafka et al. submitted and Appendix 3).

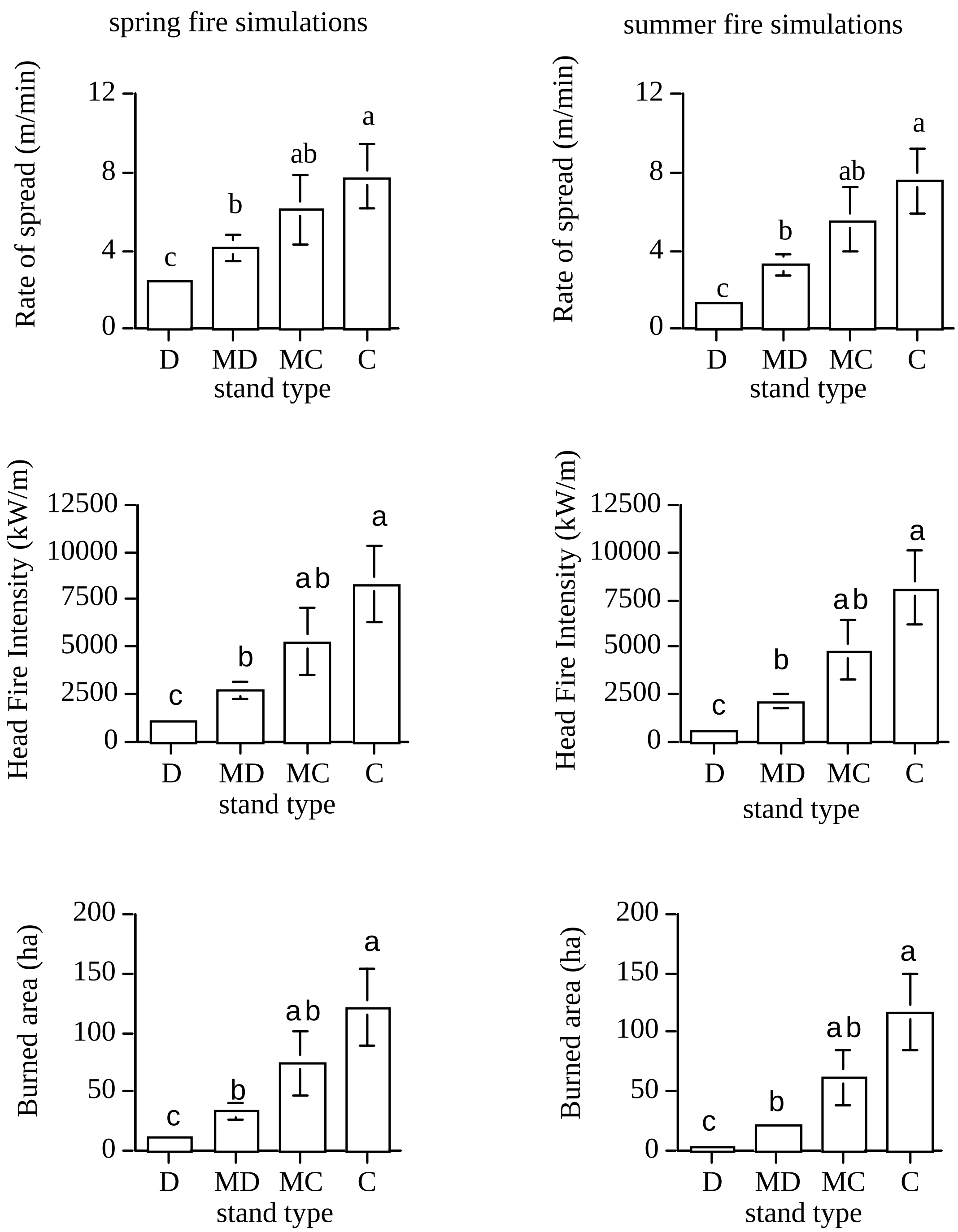


Figure 3: Differences in the simulated rate of spread, head fire intensity, and burned area according to the stand types. The simulations were computed with the Fire Behavior Prediction (FBP) system for spring and summer fires. D is for deciduous stands, MD for mixed-deciduous, MC for mixed-coniferous, and C for coniferous stands.

The same study has stressed the great variability of fire severity (Table 1) showing that a large part of the burnt area was occupied by patches of unburnt trees. This pattern might have important consequences on how clear-cut logging mimics or not the fire behavior .

Table 1. Area covered by the various burn severity classes for the Lebel-sur-Quévillon fire (from Kafka et al. submitted)

SEVERITY CLASS	Area (ha)	% of total area	Number of patches	Average area of patches (ha)
1) Blackened trees with burnt crowns and generally over 40% blowdown	525	1.1	12	44
2) Blackened trees with burnt crown and generally less than 40% blowdown	20 935	42.7	108	194
3) Trees with damaged crowns and generally less than 25% blowdown	929	1.9	41	23
4) Unburnt trees and trees with damaged crowns (more numerous)	4865	9.9	112	43
5) Unburnt trees and trees with damaged crowns (less numerous)	13 526	27.6	119	114
6) Islands of unburnt trees	1292	2.6	30	43
7)Pre-fire clearcut areas	6998	14.3	21	333
Total fire area	49 070	100.0	443	111

Holocene Fire History

At a longer time scale (6,800 yrs), the stratigraphic analysis of micro-charcoal in a laminated lake from the same area (Carcaillet *et al.*, submitted) shows that fire cycle has been variable throughout the Holocene. Starting after BC 1000, the raw data show an increase of the charcoal . Fire intervals dropped dramatically from Mid- to Late-Holocene at *ca*. BC 200, from 260±208 yrs to 85±55 yrs. This change discriminates two periods corresponding to 18 events between BC 4800-200 and 24 since BC 200. The fire intervals change is interpreted as resulting from an increase in drought frequency due to the increasing influence of Westerlies among Mid- to Late-Holocene. Climate forcing changes in fire intervals at this longer time scale appears to be convergent with what was observed following the end of the Little Ice Age at the secular time scale.

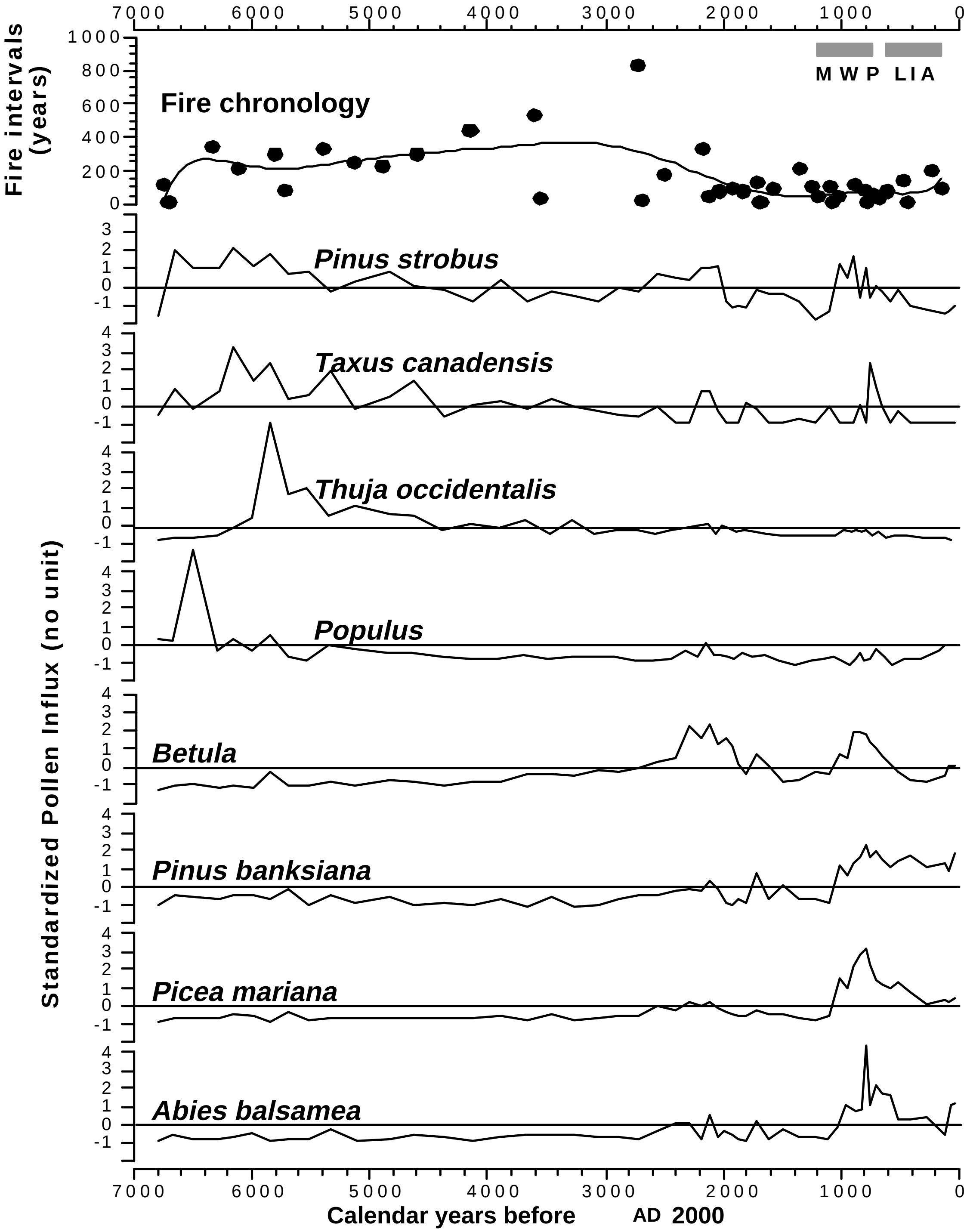


Figure 4: Fire chronology and forest plant dynamics. The fire chronology is based on a charcoal analysis over the entire length of a lacustrine sediment core from L. Francis. The raw data were initially detrended before the identification of the local fire events. The plant dynamic is based on the pollen influx data for selected taxa. Pollen influx values were initially standardized by substracting the mean for the sequence and dividing by the standard deviation for each pollen taxon to determine the significant shifts.

At 6800 yrs cal. BP, the initial woodlands were dominated by *Pinus strobus* and *Populus*. Between 6800-5800 cal. yrs BP, the pollen influx of *Thuja* and *Taxus* increased while *Populus* decline sharply. This plant dynamic occurred during a period where the fire intervals increased. At 5800 cal. yrs BP *Thuja* was the dominant species in the forest immediately surrounding L. Francis as well everywhere in the Abitibi area (Richard, 1980; Liu, 1990; Bergeron *et al*. 1998) indicating that this phenomenon correspond to regional processes triggered by the climate or the initial built-up of the forest ecosystem. The abrupt decrease of *Thuja* occurred immediately after a fire event characterized by a short interval (< 100 yrs). From 5800 to 2000 cal. yrs BP, the pollen curve of these taxa decreased slightly but remained noisy.

Betula shows two maxima, first between 2400-1900 cal. yrs BP, and second between 1100-700 cal. yrs BP (Fig. 4). The first increase in *Betula* influx matches with the occurrence of short fire intervals at 3600 and 2700 cal. yrs BP. The second change in *Betula* corresponds to the abrupt pollen influx increase of *Picea mariana*, *Pinus banksiana*, *P. strobus* and *Abies balsamea* dated of 1100 cal. yrs BP. Since 700 cal. yrs BP, most taxa show an important decrease in the pollen influx except *Pinus banksiana* which remained elevated. Currently the pollen influx of *Betula*, *Abies balsamea* and *Pinus banksiana* show an increase associated with the present day decrease in the fire frequency according to the local lacustrine charcoal data (Fig.4) and the regional dendrochronological reconstructions (Bergeron and Archambault, 1993).

The delay of response of the known fire prone coniferous species (*P. mariana*, *P. banksiana*) to the fire interval change is the main feature of these results. This lag is about 1000 yrs whereas *Betula* reacts immediately. The increase of *Abies* and *Taxus* pollen influx, which are two local pollen productors collected in a small surface lake (*ca*. 0.8 ha) indicates that the abrupt change in *P. mariana*, *P. strobus* and *P. banksiana* corresponds to a change both in the regional and local vegetation.

The local elevated pollen influx of most taxa at *ca*. 1100 cal. yrs BP until 700 cal. yrs BP closely matches with the timing of the Medieval Warm Period (MWP), while the low values between 500-200 cal. yrs BP (AD 1500-1800) correspond to the Little Ice Age (LIA) (Arsenault and Payette, 1997; Luckman *et al*. 1997). The increasing pollen influx since AD 1800-1850 matches with the change in the fire intervals trend and also with the current global warming. Thus, it appears that the long-term pollen productivity depends from climatic change more than changes in the fire regime. Indeed, we have no evidence of change in the fire intervals during the MWP and the LIA. But, we can not exclude that the repeated fire events have an influence on the long-term dynamics of trees. *Thuja* and *Taxus*, two late successional taxa, show a long-term decrease since the early afforestation period near L. Francis meanwhile fire events regularly occurred along the Holocene. These results are confirmed by local paleoecological reconstruction of fire and vegetation (Larocque et al, submitted and Appendix 4 and 5) .

VARIABILITY IN STAND COMPOSITION AND STRUCTURE

A chronosequence covering more than 230 years after fire have been reconstructed for both the Mixedwood boreal and the Coniferous boreal zones using fire areas originating in different years (Gauthier et al, submitted; Fig. 5). Figure 3 summarizes natural post-fire succession based on the relative importance of each species (dominance)without distinction among the surficial geology types. Succession in the coniferous zone is characterised by fewer changes in species composition because of the high dominance of black spruce (Fig. 4). On the other hand, succession in the Mixedwood zone is more complex and can be characterised by a transition from intolerant hardwood to a coniferous forest over time with an increasing importance of balsam fir and eastern white cedar (Fig. 5, Bergeron and Dubuc 1989; Leduc et al. 1995).

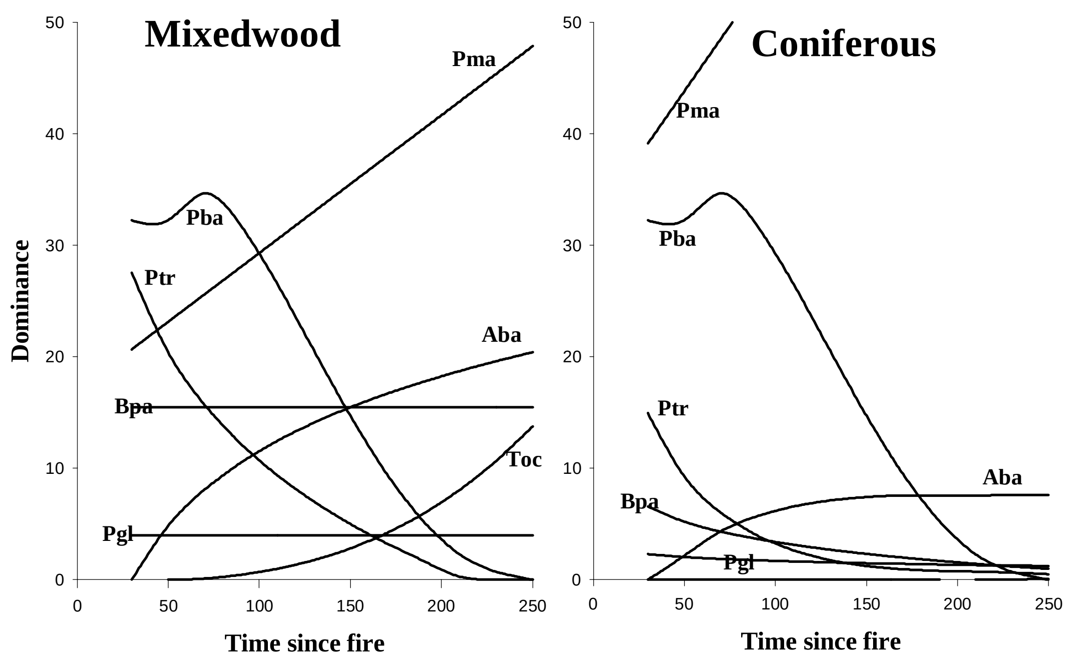


Figure 5. Comparisons of successional trends between the Mixedwood and Coniferous regions over a 250 year chronosequence. and Aba: Abies balsemea; Bpa: *Betula papyrifera*; Pma: *Picea mariana*; Pgl: *Picea glauca*; Pba: *Pinus banksiana*; Ptr: *Populus tremuloides*; Toc: *Thuya occidentalis*. Note that the dominance of black spruce is increasing linearly to attain 90% at 250 years in the coniferous zone.

IMPLICATIONS FOR FOREST MANAGEMENT

The characteristics of naturally disturbed landscapes discussed above have important implications for developing silvicultural systems that are inspired by and closely resemble natural ecosystem dynamics. First, it must be recognised that normal forest rotations dramatically change the natural forest stand age distribution. In *fact*, assuming that the probability of burning is independent of stand age (which is generally mentioned in studies on the boreal forest; see Johnson 1992), the age class distribution of the burned area will follow a negative exponential distribution (Van Wagner, 1978) with close to 37% of the stands older than the fire cycle. Fire may affect stands several times before their maturity while allowing some stands to survive beyond 100 years whereas forest harvesting will only occur at stand maturity. Assuming a 100 years rotation, proportions of over-mature stands (> 100 years), and old-growth (> 200 years) increase as the fire cycle lengthens (Fig. 6) and could cover an important proportion of the boreal forest landscape.

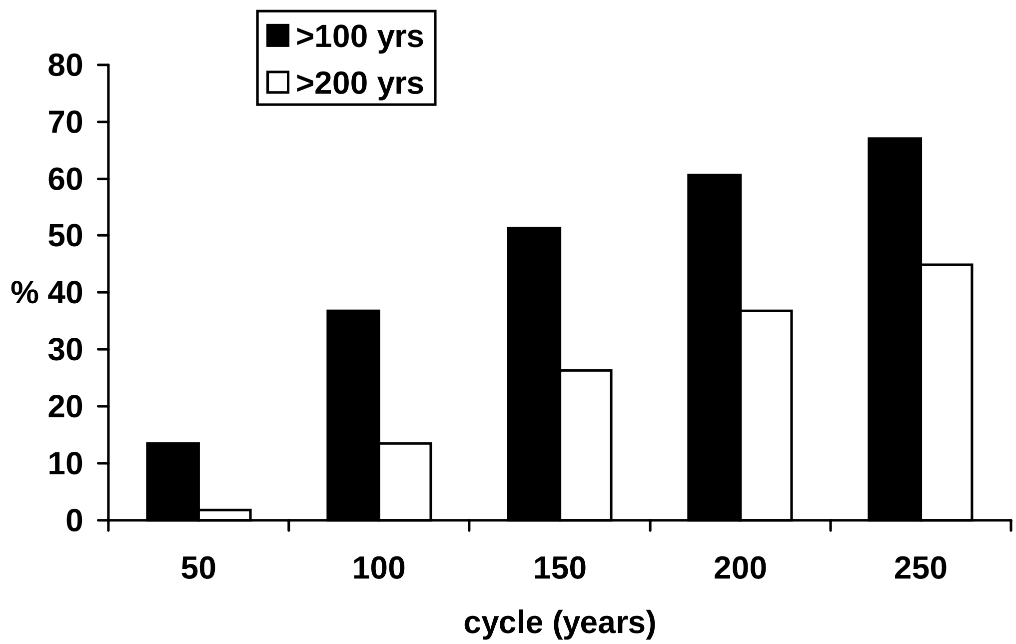


Figure 6: Percentage of stands older than 100 and 200 years increases from short to long fire cycles. With a 100 year forest rotation, none of these stands would be present.

In the Mixedwood region, on mesic sites succession towards over-mature and old-growth stands may implied a change in forest composition from deciduous towards mixed and coniferous forests (Fig. 5; Gauthier *et al. 1996*). In the coniferous forest of the north, while composition may not change, stand structure varies in relation to time since fire (Fig. 5).

These characteristics are fundamental as they imply, under fully regulated, even-aged management, the loss of over-mature forests, often judged essential to biodiversity maintenance, or a decrease in allowable cut due to longer forest rotations if the natural disturbance cycle is strictly adhered to.

TOWARDS A SOLUTION

The use of silvicultural practices designed to maintain specific structure or composition of over-mature stands in forests under management may provide a means of maintaining species and ecosystem diversity while only slightly modifying allowable cut (Bergeron et al. 1999).To this end it would be possible to treat some stands by clear-cutting followed by planting or seeding, homologous to fire, others by partial cutting or careful logging, which simulate the natural evolution of over-mature stands, and still others by selection cutting as a means of emulating gap dynamics in old growth. A simple example illustrating the natural dynamics and an ecosystem approach to managing the mixedwood and the conifer forests are presented in Figure 7. The first cohort, originating from fire, is replaced by clear-cutting and planting or seeding, the second cohort by partial cutting that emulates natural succession, and the third cohort by selection cutting that mimics the natural gap dynamics of old growth stands.

The proportion of stands that should be treated by each of these silvicultural practices should vary in relation to the natural disturbance cycle and the maximum harvest age. Just as in natural landscapes where not all stands survive to a mature or old growth stage before being burned and recommencing succession, not all stands pass through the three cohorts. Reinitiation of the first cohort may be generated by clear-cutting and planting or seeding of stands of any of the three cohorts. It would thus be possible to partially maintain not only the natural composition and structure of stands, but also a forest age structure that approaches the typical distribution produced by fire.

In Table 2, we present an abacus that allows determination of the proportion of the management cohorts as a function of fire cycle and maximum harvest age. For this exercise, the harvest age was fixed at 100 years but proportion may vary depending on commercial rotation. With a 50-year fire cycle, the great majority of the forest area is composed of the first cohort and clear-cutting is the most important silvicultural practice. This cohort is, however, relatively less important when fire cycles lengthen and thus area that should be submitted to partial or selective cutting increase.

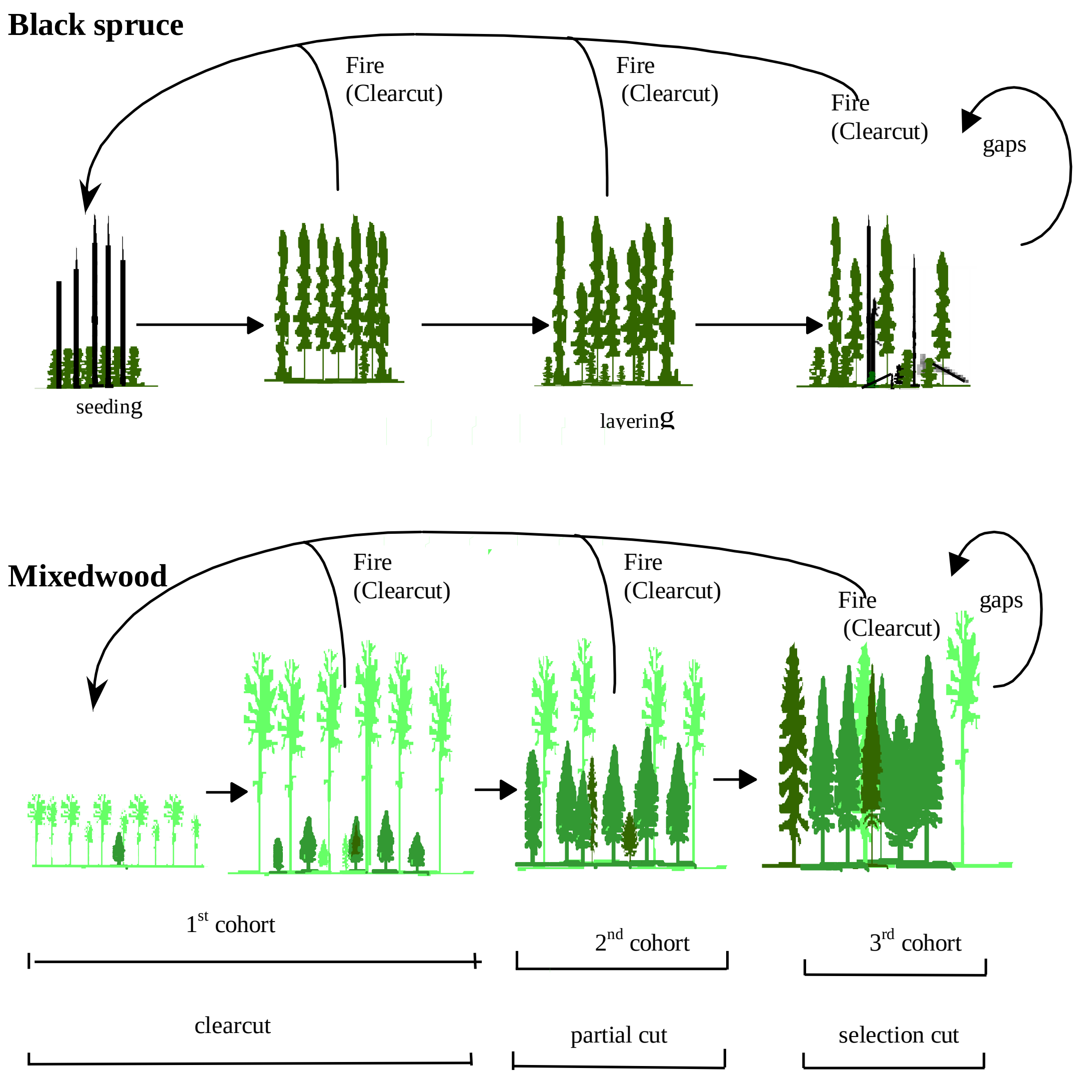


Figure7: Examples of natural dynamics and associated silvicultural treatments. For the Mixedwood and the black spruce forests. The X axis represents the time since last major disturbance (Clearcut or fire).

Table 2. Abascus for evaluating the desired proportion of the three cohorts submitted to different silvicultural treatments as a function of disturbance cycle. Harvest rotation is fixed to 100 years.

Cohort	FIRE CYCLE								
(%)	50	75	100	125	150	200	300	400	500
1st	86	74	63	55	49	39	28	22	18
2nd	12	19	23	25	25	24	20	17	15
3rd and more	2	7	14	20	26	37	51	61	67

Use of the abacus should, however, take into consideration the inherent variability in the calculation of fire cycles and the temporal fluctuations in fire cycle due to climate change. Over a period of 8,000 years, the forest in the Quebec Clay Belt has been subjected to fire cycles varying between 50 and 500 years. Because vegetation can take an extremely long time to adjust to a particular fire cycle, the current landscape contains stands that are essentially relics from past fire regimes. Moreover, predictions concerning the effects of future climate change suggest changes in fire cycle (Flannigan et al. 1998). It is therefore desirable to attempt to maintain all stand types that make up the cohorts, even if strict application of the proposed model would lead to their elimination. This management strategy 1) permits the allocation of a portion of an area to the protection of rare ecosystems; 2) maintains a certain flexibility with respect to future modifications in the wood products market; and 3) allows preservation of the resilience of the forest landscape in the context of changing disturbance regimes.

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APPENDIX 1

A 235 YEARS BOREAL FOREST FIRE HISTORY IN EASTERN CANADA: THE PART OF CLIMATE AND LAND USE

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ABSTRACT: A 235 years forest fire history reconstruction (1760 to 1995) was undertaken in eastern Canada to characterize forest fire fluctuations in an area that covers up to 600 000 ha at the southern edge of the boreal forest. The border between the provinces of Ontario and Quebec divides the whole sector into two landscapes, each of which has undergone a different land use when the area was opened up to settlement in 1912 with the completion of the transcontinental railroad. Forest management took place in Ontario (500 000 ha) whereas farming occurred on Quebec's side (130 000 ha) -the latter landscape is still dominated by a forest matrix-. Natural forest fire reconstruction was completed by studying aerial photographs and by sampling fire-origin forest stands. Forest fire history under human influence was done by compiling government records which include information on fire ignition source, fire location, burned surfaces and the date on which the fire was reported. Results indicate that between 1760 to 1853, fire years were infrequent but burned large areas. In fact, more than 50% of the fire-origin stands in 1996 originate from fires that occurred before 1854. The following period before european settlement (1854 to 1912) was characterized by a low fire occurrence: only 3% of the overall study area was burned. Natural fire regime variations were related to climatic fluctuations that undergone with the Little ice Age Period (1650 to 1850), which was a drier and cooler period than the following one. With the arrival of european man, fire occurrence increased dramatically. However, logged area (Ontario) had 7 times less fewer fires than the area devoted to agriculture (Quebec) and two times less fewer burned areas. Fire ignition and burned areas depend on many factors: type of land use, month in the fire season, period of technological development and population density. Although there was an upward trend in fire occurrence since 1912, burned areas and their mean extent have decreased. An analysis of fluctuations in the Fire Weather Index (FWI), a rating of fire danger severity, showed a significant decrease in climatic stresses since 1912. However, improved fire suppression and landscape fragmentation may also have contributed to the decrease in mean fire size. Our results indicate that the importance of old-forest has decreased in managed landscapes as a comparison to one under a natural fire regime. This decrease may have important consequences on biodiversity conservation.

APPENDIX 2

Relative importance of vegetation and climate on fire behavior in the southeastern Canadian boreal forest

Christelle Hely, Mike Flannigan, Yves Bergeron, and Douglas McRae

Abstract

Simulations were carried out in the Fire Behavior Prediction (FBP) and the BEHAVE systems for spring and summer seasons to study the importance of vegetation and climate on fire behavior in the mixedwood boreal forest. Stand were characterized as deciduous, mixed-deciduous, mixed-coniferous, or coniferous stands, if their conifer basal area was respectively less than 25%, between 25 and 50%, between 50 and 75%, or greater than 75% of stand basal area. Sampled fuel loads (litter, duff, woody debris, herbs, and shrubs), and local weather conditions around Lake Duparquet (Quebec, Canada) were input in the simulation systems. The predicted fire behavior variables were Rate of Spread (ROS), Head Fire Intensity (HFI), and burned area. Results from Anovas on ranks showed that the two simulators attribute differently the maximum explained variance to the different factors. Climate is the most important factor for all fire behavior variables with the FBP whereas BEHAVE gives the greatest part of variance to the vegetation factor. Spring values are always higher than those from summer simulations. Deciduous stands record the lowest values. Mixed stands present intermediate values while conifer stands record the highest values for all variables. These differences related to stand composition exist within each fire risk (FWI), even for extreme weather risk. This implies that the widely accepted idea that during extreme FWI days all vegetation types would burn without difference is not applicable to southeastern boreal forest. Moreover, three prescribed burnings from Ontario, used to compare both systems, revealed that BEHAVE was not adapted to the mixedwood boreal region whereas FBP predictions were close to observed prescribed values. Climate and vegetation impacts on fire behavior and forest mosaic are discussed.

APPENDIX 3

INFLUENCE OF BIOTIC AND ABIOTIC FACTORS ON THE SPATIAL STRUCTURE OF BURN SEVERITY IN THE BOREAL FOREST OF WESTERN QUÉBEC

SUGGESTED RUNNING HEAD: BURN SEVERITY IN THE BOREAL FOREST

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ABSTRACT: Within the context of studying the impact of large wildland fires in shaping boreal forest mosaics, a spatial analysis of a large wildland fire was conducted. The wildfire covered nearly 500 km^2 in the northwestern part of Québec's boreal forest in the summer of 1995. The distribution and spatial structure of burn severity on trees and the effect of major local biotic and abiotic factors on the degree of burn severity were assessed using a geographic information system. Although important islands of unburnt trees accounted for a very small area within the fire perimeter, surviving trees were found throughout the burn. Small proportions of the total disturbed area were found within a few hundreds meters from islands of unburnt trees. Fire shape and edge indices indicated a complex pattern of fire limits. Despite the extent and intensity of the wildfire created by extreme fire conditions, the burn severity was connected to some local components of the terrain and vegetation. Stepwise logistic regression and analysis by log-linear models indicated that surface material, stand composition and estimated stand age had a significant effect on burn severity. However, it appears that height and density of stand, as well as topography, did not have an influence. Our study shows the variation of burn severity and suggests that a set of local factors play an important role in the severity of burning during large fires.

KEY WORDS: Black spruce, Canada, Disturbance, Forest mosaic, Geographic information systems, GIS, Jack pine, Landscape ecology, Lebel-sur-Quévillon, Log-linear model, Québec, Stepwise logistic regression

APPENDIX 4

Distribution of *Thuja occcidentalis* in the southern Canadian boreal forest: Long-term effect of local fire disturbance

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Abstract

Thuja occidentalis has been described as a late successional species. In the boreal forest, many recent studies based on dendrochronology, seed dispersal and aerial photography have shown that *Thuja occidentalis* becomes dominant only when the fire interval is long (>250 years). When fire is more frequent, *Thuja occidentalis* does not dominate the canopy. The patchy distribution of *Thuja occidentalis* on the landscape may be related to local disturbance history; sites with long fire intervals have *Thuja occidentalis* while sites with higher fire frequency do not. To verify this hypothesis on a longer time period, we used pollen and charcoal analysis to determine the time of establishment or extinction of *Thuja occidentalis* relative to time-since-fire at 4 different sites in the Abitibi region of Canada. Our results indicate that *Thuja occidentalis* is successor to a pine-dominated coniferous forest and is dominant only where there has been no fire for 200 or more years. Extinction of *Thuja occidentalis* from some sites was not observed but our results suggest that a high fire frequency can explain its absence in the canopy.

APPENDIX 5

LATE-HOLOCENE STAND-SCALE RECORD OF FIRE HISTORY AND VEGETATION DYNAMICS FROM THE LAC DUPARQUET REGION, QUEBEC, CANADA.

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Abstract

A stand-scale record of boreal forest dynamics, in Quebec, Canada, recovered by pollen and charcoal analysis of a forest hollow on a small rock outcrop, shows that fire has been the major driving force for vegetation change over the last 4000 years. The local charcoal record changed markedly through time. There is little evidence for local burning since Euro-canadian settlement. Two major fire events prior to and at the time of settlement caused significant vegetation change. *Picea mariana,* which was dominant prehistorically, was replaced by *Pinus -Ericaceae* communities. Alhtough charcoal horizons were frequent in the prehistoric record, concentrations were generally lower. The stand-scale record reveals details about fire history and vegetation response that are not apparent in larger scale studies.