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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.

ACKNOWLEDGEMENT

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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 49^{th} 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 53 years for the period before 1850, has increased to 143 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).

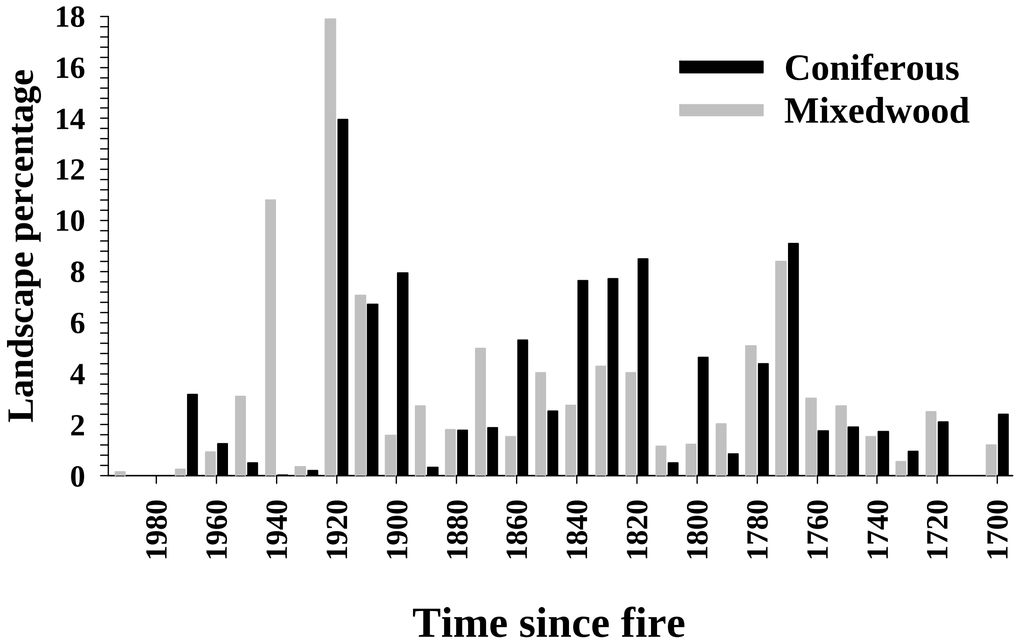

Figure 1. Current age class distribution of stands in the Mixedwood and Coniferous boreal regions. Notice the important proportion of the landscape in over-mature and old-growth stands.

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. Companion studies (Lefort *et al*., in prepar. and appendix 1; Kafka *et al*., 2000 and appendix 2; Lesieur, 2000 and appendix 3) comparing landscapes with different degrees of human activities tend to confirm that the observed change in fire cycles is mainly related to climate and not to changes induced by human activities (Table 1). 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).

Table 1. Characteristics and estimated fire cycles for each region

	Area (km^2)	Mean age (yr)	% over 100 yr[1]	Fire cycles (yr)[2]		
Region[3]				1920-1999	1850-1920	<1850
Lake Abitibi Model Forest[a]	8,245	172	78	465 (339-637)	201(151-267)	74 (58-95)
Abitibi (West)[b]	15,793	139	57	326 (251-424)	141 (111-179)	53 (43-64)
Abitibi (East)[c]	3,294	111	54	194 (126-299)	84 (55-128)	-----
Central Québec[bc]	3,844	127	56	283 (193-415)	122 (85-176)	47 (33-64)

[1] Percentage of the stands that are older than 100 years on figure 1.
[2] The three periods are significantly different at p< 0,001.
[3] Regions marked with different letters are significantly different at p< 0,05.

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; Flannigan *et al*., submitted and appendix 4).

Fire cycles computed for the periods during and after the end of the Little Ice Age do not vary significantly between Mixedwoods and Coniferous bioclimatic units. 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

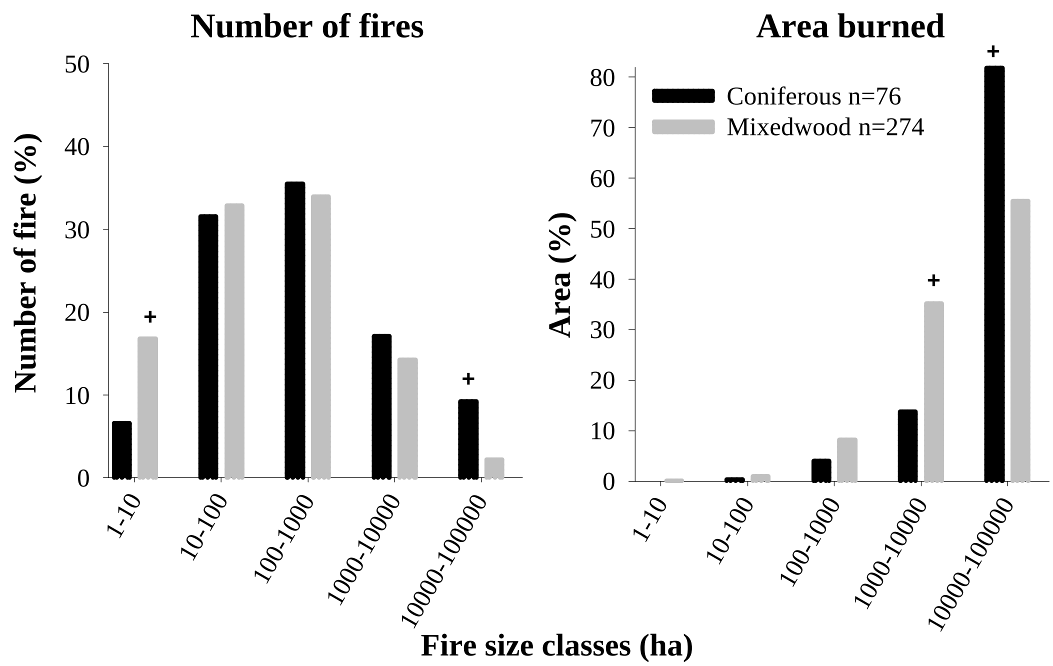

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Figure 2. Comparisons of the number of fires and the area burned per class of fire size among the Coniferous and the Mixedwood regions. + indicates that significantly more fires (left) or more area burned (right) are observed.

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*., 2000; Hely *et al.*, submitted and appendix 5). 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 the Val-Paradis fire in 1997 (Hely, 2000 and appendix 6) and Crochet fire in 1995 (Kafka *et al.*, 2000) where observed fire severity was lower in deciduous and mixed stands in comparison with coniferous stands.

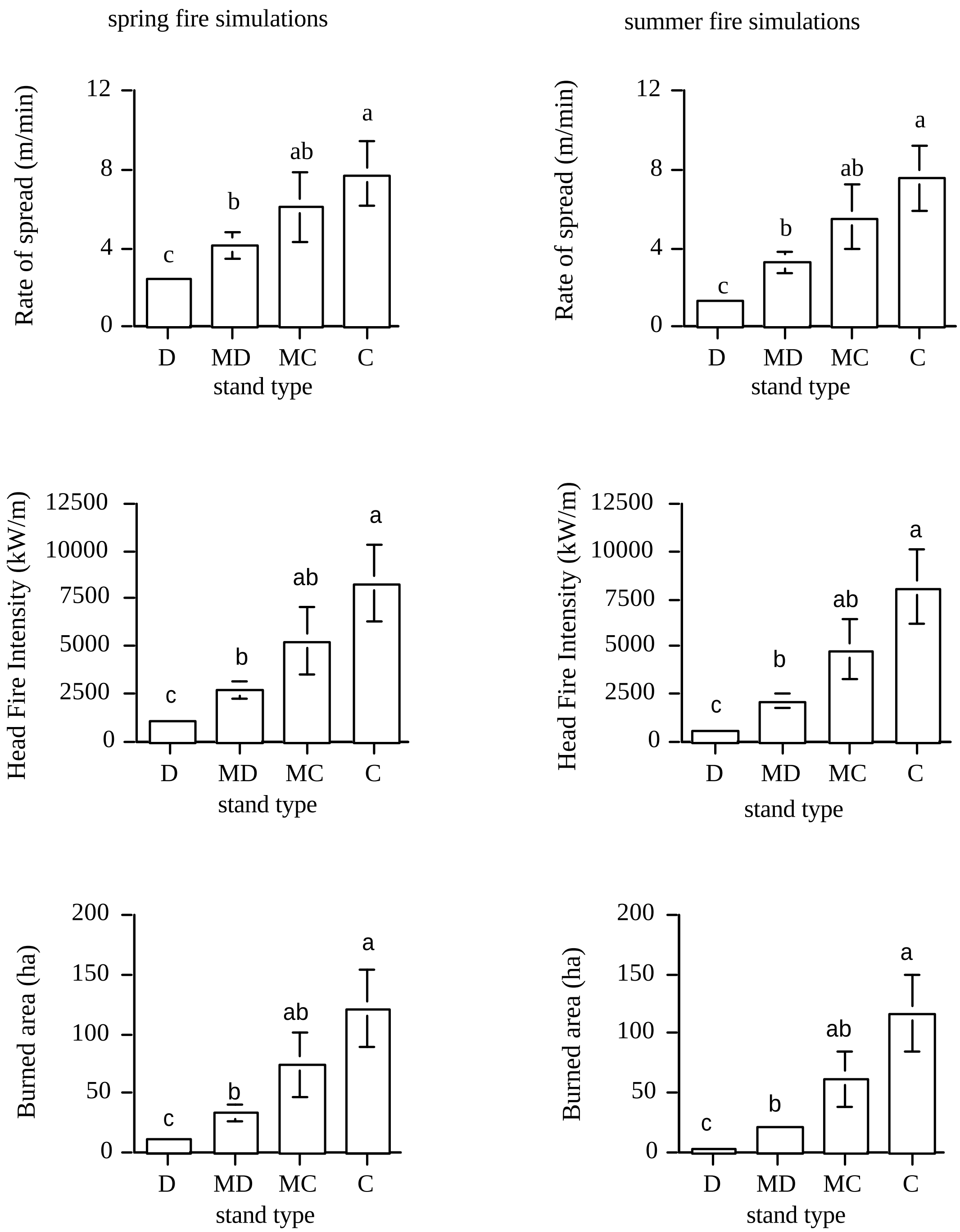

Figure 3. Differences in the simulated rate of spread, head fire intensity, and burned area according to the stand types. The simulations were computed with the Fire Behavior Prediction (FBP) system for spring and summer fires. D is for deciduous stands, MD for mixed-deciduous, MC for mixed-coniferous,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

Kafka *et al*. (2000) has also stressed the great variability of fire severity (Table 2) 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 2. Area covered by the various burn severity classes for the Lebel-sur-Quévillon fire (from Kafka *et al*., 2000)

SEVERITY CLASS	Area (ha)	% of total area	Numbe r 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 (7,650 yrs), the stratigraphic analysis of micro-charcoal in 3 laminated lake from the same area (Table 3; Carcaillet *et al*., submitted and appendix 7) shows that fire cycle has been variable throughout the Holocene. Two distinct periods of fire regime are evidenced. Between *ca*. 7000-3000 cal. yr BP, fire intervals were double than since 2000 years. The phase between 3000 and 2000 is transitory. The fire intervals history matches well the fire status in eastern Canada calculated on anomalies of charcoal accumulation rate (Carcaillet and Richard, 2000 and appendix 8).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.

Table 3. Mean fire intervals, ± standard deviation (standard error) for Lac à la Pessière (PESSIERE), Lac Pas-de-Fond (PFOND) and Lac Francis (FRANCIS). The means fire intervals have been calculated for the series of equally time-spaced intervals based on the mean deposition time for each lake (14, 24, 35 years), and for the coarsest equally time-spaced interval, *i.e*. 35 years.

Site	Middle Holocene		Late Holocene	
PESSIERE	7650-7100 BP	7100-3300 BP	3300-1200 BP	1200-0 BP
14 yr	56±19 (7) yr	210±167 (38) yr	64±55 (10) yr	439±115 (199) yr
PESSIERE	7650-7300 BP	7300-3400 BP	3400-1400 BP	1400-0 BP
35 yr	127±73 (42) yr	420±225 (75) yr	200±80 (24) yr	No peak
PFOND	7450-2000 BP		2000-0 BP	
24 yr	269±266 (59) yr		88±42 (9) yr	
PFOND	7450-2000 BP		2000-0 BP	
35 yr	337±275 (69) yr		154±60 (17) yr	
FRANCIS	680-2200 BP		2200-1000 BP	1000-0 BP
35 yr	502±466 (155) yr		115±45 (13) yr	203±83 (37) yr

Pollen analysis does not disclose vegetation changes that could explain the fire frequency transition by shift of flammability or combustibility due to change of species composition. (Fig. 4).

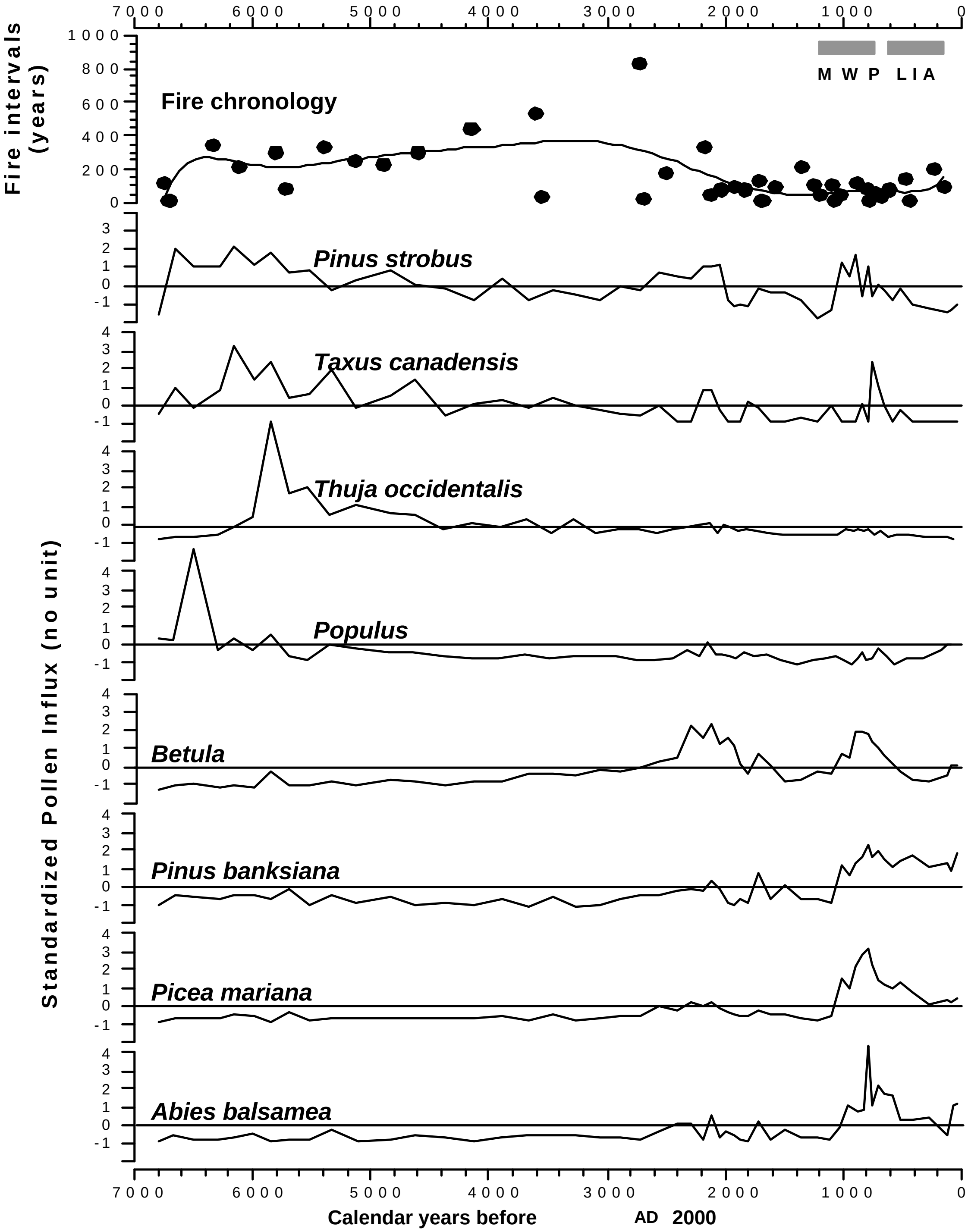

Figure 4. Fire chronology and forest plant dynamics. The fire chronology is based on a charcoal analysis over the entire length of a lacustrine sediment core from L. Francis. The raw data were initially detrended before the identification of the local fire events. The plant dynamic is based on the pollen 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 and appendix 9) 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*, *Pinus 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*., 2000a; Larocque *et al*., 2000b; Larocque *et al*., submitted and appendix 10) .

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 and appendix 11; Fig. 5). Figure 5 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. 5). 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; Bergeron, 2000).

Without fires, forest structure and composition are closely related to secondary disturbance, particularly spruce budworm 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 *Abies balsamea* (Bergeron and Leduc, 1998 and appendix 12), which varies with time since fire. Windthrow can vary due to stand age, composition or structure (Ruel, 1995). Both of these disturbances are becoming more abundant as forests age following fire.

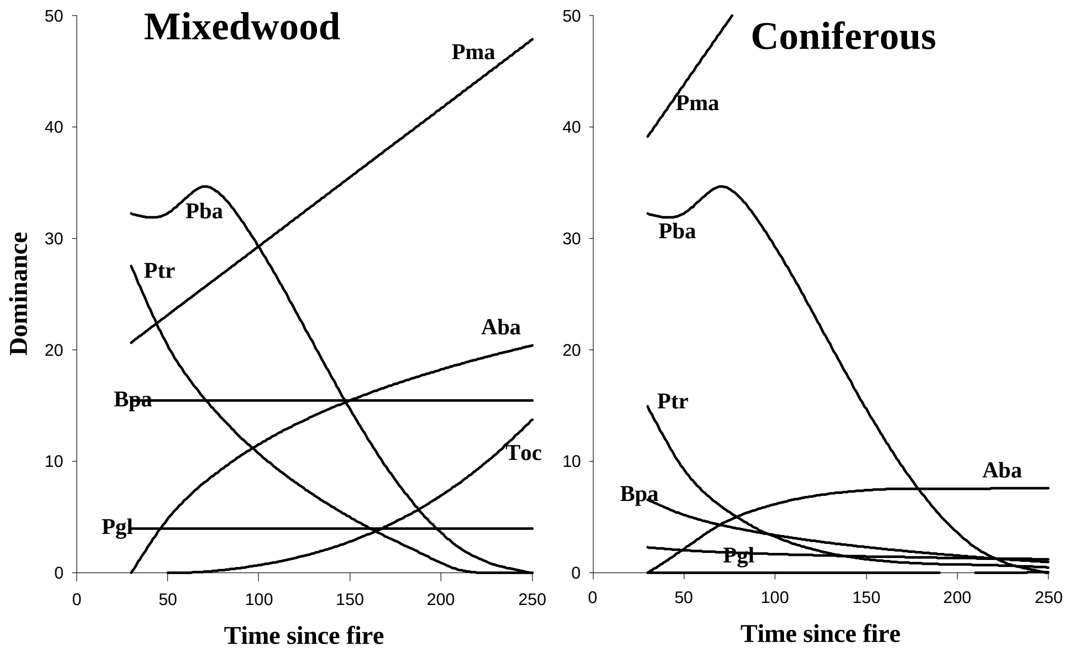

Figure 5. Comparisons of successional trends between the Mixedwood and Coniferous regions over a 250 year chronosequence. and Aba: Abies balsemea; Bpa: *Betula papyrifera*; Pma: *Picea mariana*; Pgl: *Picea glauca*; Pba: *Pinus banksiana*; Ptr: *Populus tremuloides*; Toc: *Thuya occidentalis*. Note that 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.

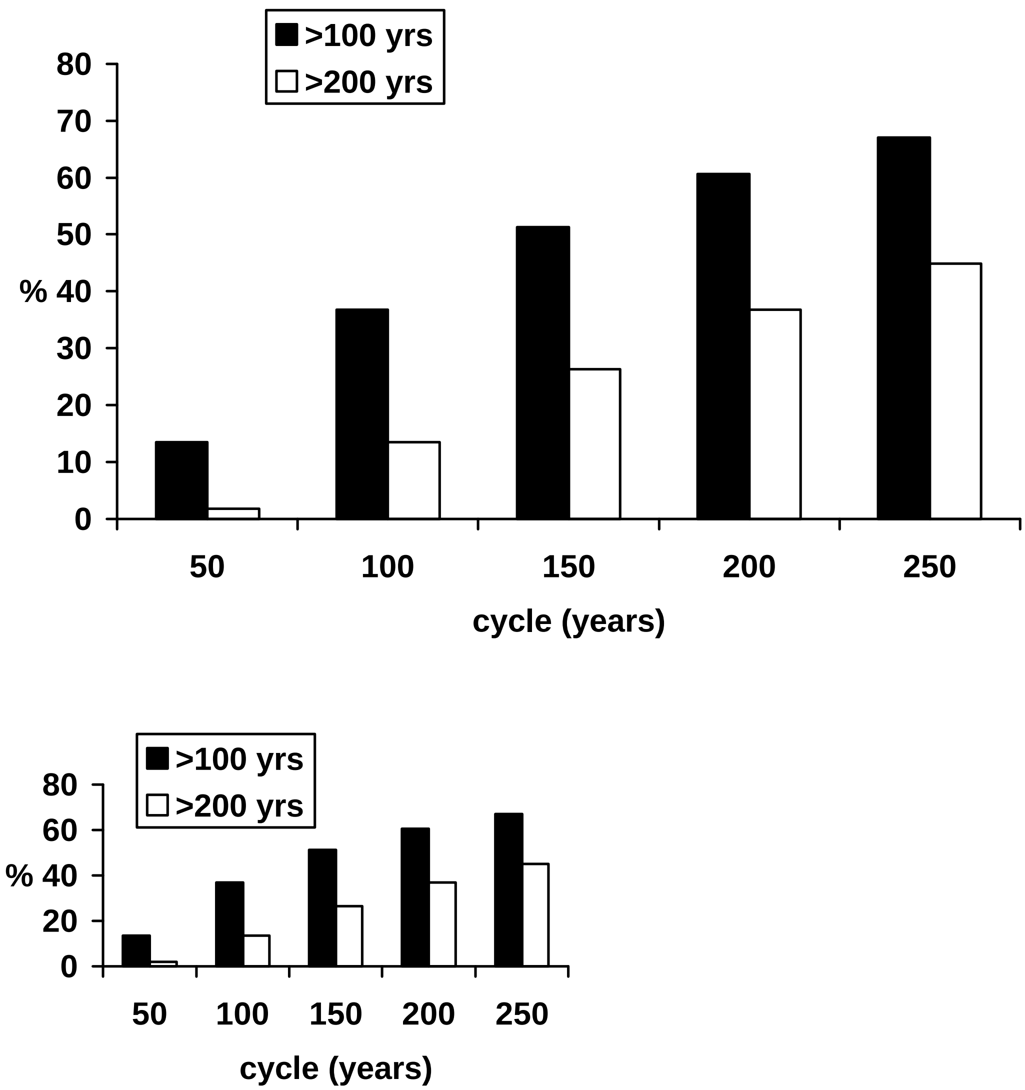

Figure 6. Percentage of stands older than 100 and 200 years increases from short to long fire cycles. With a 100 year forest rotation, none of these stands would be present.

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 and appendix 13).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 4, 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.

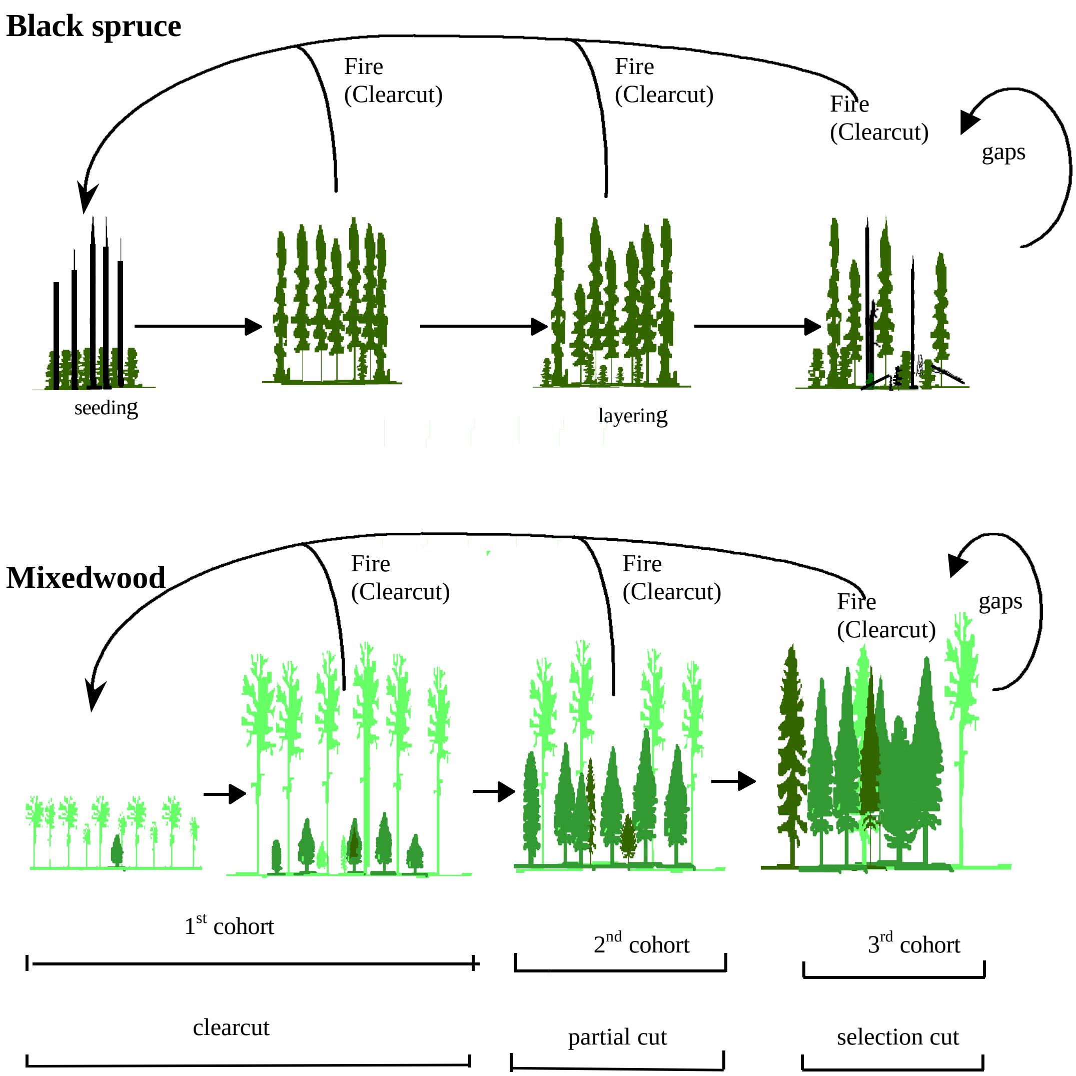

Figure 7. Examples of natural dynamics and associated silvicultural treatments for the Mixedwood and the black spruce forests. The X axis represents the time since last major disturbance (clearcut or fire).

Table 4. 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.

Harvey *et al*. (2000, in-press and appendix 14) have recently demonstrate how this approach can be implemented in using the lake Duparquet research and teaching forest as an example. Based on natural fire regime similar guidelines are currently under development for emulating clear-cut dispersion and pattern inside clear-cuts (Bergeron *et al*., 2000, accepted and appendix 15)

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