Past, current, and future fire frequencies in Quebec's commercial forests: implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management[1,2]

Yves Bergeron, Dominic Cyr, C. Ronnie Drever, Mike Flannigan, Sylvie Gauthier, Daniel Kneeshaw, Ève Lauzon, Alain Leduc, Héloïse Le Goff, Daniel Lesieur, and Kimberley Logan

Abstract: The past decade has seen an increasing interest in forest management based on historical or natural disturbance dynamics. The rationale is that management that favours landscape compositions and stand structures similar to those found historically should also maintain biodiversity and essential ecological functions. In fire-dominated landscapes, this approach is feasible only if current and future fire frequencies are sufficiently low compared with the preindustrial fire frequency, so a substitution of fire by forest management can occur without elevating the overall frequency of disturbance. We address this question by comparing current and simulated future fire frequency based on $2 \times CO_2$ and $3 \times CO_2$ scenarios to historical reconstructions of fire frequency in the commercial forests of Quebec. For most regions, current and simulated future fire frequencies are lower than the historical fire frequency, suggesting that forest management could potentially be used to maintain or recreate the age-class distribution of fire-dominated preindustrial landscapes. Current even-aged management, however, tends to reduce forest variability by, for example, truncating the natural age-class distribution and eliminating mature and old-growth forests from the landscape. Therefore, in the context of sustainable forest management, silvicultural techniques that retain a spectrum of forest compositions and structures at different scales are necessary to maintain this variability and thereby allow a substitution of fire by harvesting.

Résumé : Au cours de la dernière décennie, un intérêt grandissant pour le développement d'approches d'aménagement basées sur notre compréhension de la dynamique historique des perturbations naturelles s'est manifesté. Ces approches reposent sur l'idée qu'un aménagement favorisant une composition des paysages et une structure des peuplements similaires à celles créées dans les forêts passées devrait aussi maintenir la diversité biologique et les fonctions écologiques essentielles de ces mêmes paysages et peuplements. Dans les paysages contrôlés par les feux, cette approche est possible seulement si les fréquences de feux actuelles et futures sont suffisamment faibles lorsque comparées aux fréquences pré-industrielles, cela afin de permettre de substituer le feu par la coupe forestière. Nous évaluons cette possibilité en comparant les fréquences de feux actuelles et futures aux fréquences historiques à partir d'études réalisées dans la forêt commerciale québécoise. Les fréquences actuelles et futures des feux, simulées en utilisant deux scénarios de concentration de CO_2 ($2 \times$ et $3 \times$ la concentration actuelle), sont plus faibles que les fréquences passées pour la majorité du territoire, suggérant que l'aménagement forestier pourrait potentiellement être utilisé afin de recréer la structure d'âge de la forêt soumise à un régime de feux sévères. Les aménagements équiennes actuels tendent toutefois à réduire

Y. Bergeron.[3] Chaire industrielle CRSNG-UQAT-UQAM en aménagement forestier durable, Université du Québec en Abitibi-Témiscamingue, C.P. 700, Rouyn-Noranda, QC J9X 5E4, Canada.
D. Cyr, C.R. Drever, D. Kneeshaw, È. Lauzon, A. Leduc, H. Le Goff, and D. Lesieur. Centre d'Étude de la Forêt (CEF), Université du Québec à Montréal, C.P. 8888, Succursale Centre-Ville, Montréal, QC H3C 3P8, Canada.
M. Flannigan and K. Logan. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, ON P6A 2E5, Canada.
S. Gauthier. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., P.O. Box 10380, Station Sainte-Foy, Quebec, QC G1V 4C7, Canada.

[1]This article is one of a selection of papers published in the Special Issue on the North American Forest Ecology Workshop.
[2]Much of this article was presented as a keynote address at the 2005 North American Forest Ecology Workshop during the session entitled "Revisiting the natural disturbance paradigm: Should it be recycled?".
[3]Corresponding author (e-mail: bergeron.yves@uqam.ca).

la variabilité naturelle du système: par exemple, un aménagement équienne amputera, à terme, la structure d'âge de la forêt naturelle éliminant ainsi les forêts surannées et anciennes du paysage. Le développement de techniques de sylviculture permettant le maintien d'un spectre de compositions et structures forestières à différentes échelles de paysage est une des avenues proposées afin de maintenir cette variabilité.

Introduction

Over the past decade, there has been an increasing interest in forest-management approaches based on natural disturbance dynamics (Attiwill 1994; Angelstam 1998). The rationale is that management favouring development of stand and landscape compositions and structures similar to those in natural ecosystems should maintain biodiversity and essential ecological functions (Franklin 1993; Hunter 1999). In other words, the conservation of native flora and fauna may be possible by emulating the size, frequency, pattern, and severity of disturbances to which forest species have adapted over thousands of years (Hunter et al. 1988; Hunter 1993).

Understanding of the fire regimes that burn forests throughout Quebec is still fragmentary, making it inappropriate to generalize from landscape studies to an entire region. This lack of understanding has often led to false generalizations. For example, it has often been assumed that large-scale fires that produce even-aged stands are not only omnipresent but frequent in boreal and mixedwood forests However, it has become increasingly evident that short fire cycles apply only partially to the boreal forest and that the regional situation is considerably more complex (Bergeron et al. 2001). Nonetheless, the assumption of frequent large-scale fires has been used to justify the use of clear-cut harvesting. Although differences between the effects of harvesting and fire have been amply documented (see reviews by McRae et al. 2001; Haeussler and Kneeshaw 2003), the belief remains that modifications of the clear-cut harvesting system can be used to recreate even-aged stand conditions and, with some planning, an age-class structure that resembles that found in fire-dominated landscapes (Burton et al. 1999).

Focusing only on the portion of the landscape dominated by even-aged stands that were created following burns, a substitution of fire by forest management may be appropriate for the creation of some even-aged conditions. Extended rotations of even-aged management (Burton et al. 1999) or uneven-aged management (Bergeron et al. 2001) could be used to retain or create some of the structural elements found in overmature and old-growth stands (Kneeshaw and Gauthier 2003) in sections of these areas. Other old-growth stands could be maintained through careful planning of reserves and other conservation areas. The proportion of the forest under even- and uneven-aged management could be determined by the historical fire cycle of a specific area (Bergeron et al. 1999).

However, in areas where fires are still frequent, harvesting is cumulative to fire, meaning that even-aged, short-rotation management systems may be unable to maintain the historical age-class structure (Armstrong 1999). Most productive areas in the North American boreal and mixed forests lie between this situation and one where a fire-harvesting substitution is possible. The situation also depends on climate change because model predictions for fire frequency vary significantly from region to region and may influence whether a substitution is possible (Flannigan et al. 1998).

Here, we present historical, current, and projected future frequencies of stand-replacing fires for the different bioclimatic regions of commercial forests in Quebec. We characterize the extent to which the use of conventional even-aged management (i.e., clear-cutting under short rotation) or low-retention systems (e.g., 5%–30% of within-treatment area retained as mature green trees) could potentially be used to recreate the forest age structure of preindustrial landscapes that were previously disturbed by fire. We discuss the limitations of such an approach in the context of sustainable harvest levels and forest management.

Methods

Study area

Fire-history studies used in the analysis (Table 1) represent different bioclimatic subregions in Quebec's commercial forests (Fig. 1; see Saucier et al. (1998) for detailed descriptions of the bioclimatic subregions). Only a few studies exist for several of the bioclimatic subregions, making it difficult to generalize across the entire province. In most cases, however, the fire-history studies cover very large areas (Table 1). Although most studies pertain to the boreal forest, we also included studies from mixed forests in southern Quebec where fire was historically an important disturbance.

Model

We developed a simple graphical model based on the comparison of historical and current burn rates to evaluate whether even-aged management (i.e., low-retention systems under short rotation) may be appropriate for the emulation of forest age structures associated with historical fire regimes in different regions, given biodiversity and yield constraints (Fig. 2a). The x axis of this graphical model corresponds to the current burn rate; it also represents increasing yield constraints because as burn rate increases, fires increasingly compete with harvesting for timberland. In other words, yield constraints are high when current fire frequency is equal to or higher than the desired annual harvest level. The y axis corresponds to the historical burn rate; it reflects biodiversity constraints as our ability to maintain the full range of age-classes (and thereby the suite of native species and stand structures) is restricted when the combined rates of fire and harvesting are so high that a low diversity of stand ages is entrained across the landscape.

The 1:1 line in Fig. 2a represents the situation when current and historical burn rates are equal, whereas the 1% line on both axes indicates an arbitrary harvesting rate commonly applied in boreal forests. The area below the 1:1 line characterizes the situation where current burn rates are sufficiently high to resemble historical burn rates, leaving no room for

Table 1. Geographic coordinates and other details for each of the study areas.

| Site No.	Study area	Bioclimatic subdomain	Reference	Latitude (°N)	Longitude (°W)	Area (km²)
1	Abitibi northwest	Western black spruce – moss	Bergeron et al. 2004	49.50	79.00	7 942
2	Abitibi southwest	Western fir – white birch	Bergeron et al. 2004	48.50	79.00	7 777
3	Abitibi east	Western black spruce – moss	Kafka et al. 2001	48.88	76.29	3 294
4	Abitibi southeast	Western fir – yellow birch	Lesieur et al.*	48.55	77.28	13 156
5	Temiscamingue north	Western fir – yellow birch	Grenier et al. 2005	47.19	78.52	2 850
6	Temiscamingue south	Western sugar maple – yellow birch	Drever et al. 2006	46.37	78.45	1 793
7	Waswanipi	Western black spruce – moss	Le Goff et al.[†]	49.99	75.73	10 950
8	Central Quebec	Western fir – white birch	Lesieur et al. 2002	48.55	74.31	3 844
9	North shore	Eastern black spruce – moss	Cyr et al.[‡]	49.63	68.00	14 135
10	Gaspésia	Eastern fir – white birch	Lauzon 2004	48.52	65.79	6 480

Note: Study area locations are shown in Fig. 1.

*Lesieur, D., Gauthier, S., and Bergeron, Y. Unpublished data.

[†]Le Goff, H., Bergeron, Y., Flannigan, M., and Girardin, M. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. Submitted for publication.

[‡]Cyr, D., Gauthier, S., and Bergeron, Y. Manuscript in preparation.

Fig. 1. Location of the study areas throughout the bioclimatic regions of Quebec's commercial forests. See Table 1 for names and other details of the study areas.
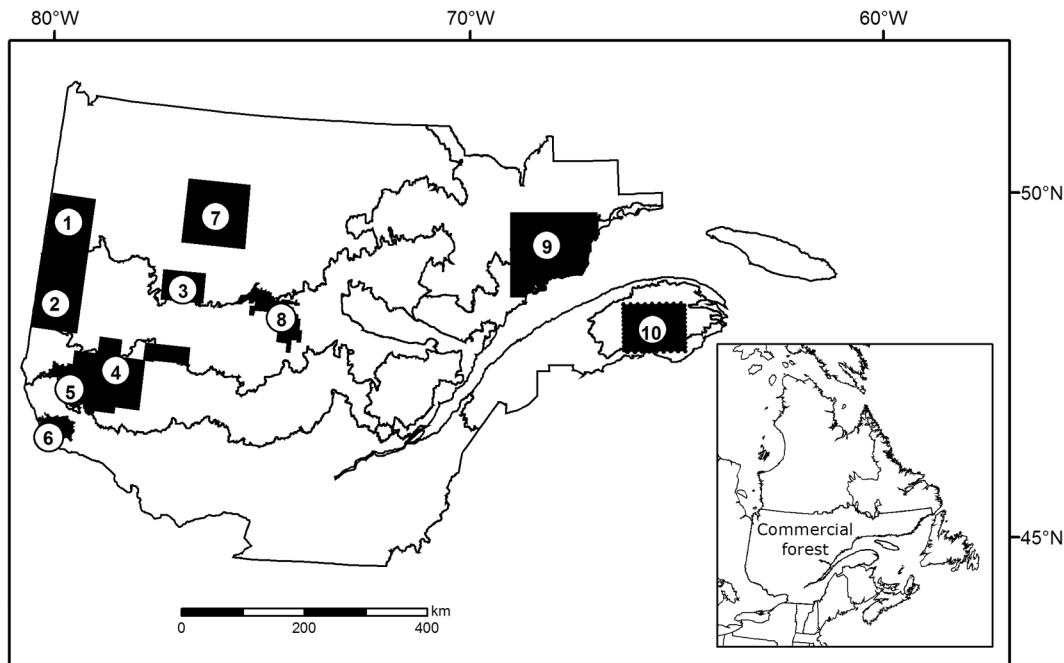
using even-aged management as a means to emulate natural disturbances. On the other hand, in the area above the 1:1 line, the current burn rate is lower than the historical burn rate, thereby allowing for the use of even-aged management to make up the difference. In this model, the amount of even-aged management that would be allowed increases according to the distance that a given region is located above the 1:1 line.

Therefore, the four quadrants in Fig. 2a represent different types of constraints. Briefly, the lower right quadrant (biodiversity and yield constraints) is the least desirable scenario: a low historical fire frequency means that the preindustrial landscape was composed principally of mature and old-growth forests; however, because of climate change, land use changes, and other factors, the current burn rate is

relatively high (Fig. 2a). This scenario entails great pressure on the ecosystem's biodiversity. In addition, harvesting at the current rate competes with forest fires, thus accelerating changes in the forest age structure. Conversely, the upper left quadrant (low constraint) is the best scenario: although historical fire frequency was high, climate change, land use, or fire suppression has decreased the current fire frequency. In such a situation, even-aged management may therefore be desirable to preserve the historical forest age structure. The lower left quadrant indicates a biodiversity constraint, as both historical and current burn rates are lower than the 1% desirable annual harvesting level. In this case, the amount of old forest present in the past would not be maintained by an even-aged management approach (Kneeshaw and Gauthier 2003). The upper right quadrant implies a yield constraint,

Fig. 2. (*a*) Graphical model to assess biodiversity and yield constraints based on past and current annual burn rates. Above the 1:1 line, current burn rate is lower than past burn rate and a real substitution of fire by harvesting is possible. As one moves up the 1:1 line, the constraints on the fire-harvesting substitutions change from principally biodiversity to yield. (*b*) Historical, current, $2 \times CO_2$, and $3 \times CO_2$ burn rates of the study areas. E, east; N, north; NW, northwest; S, south; SE, southeast; SW, southwest; Temis, Temiscamingue.
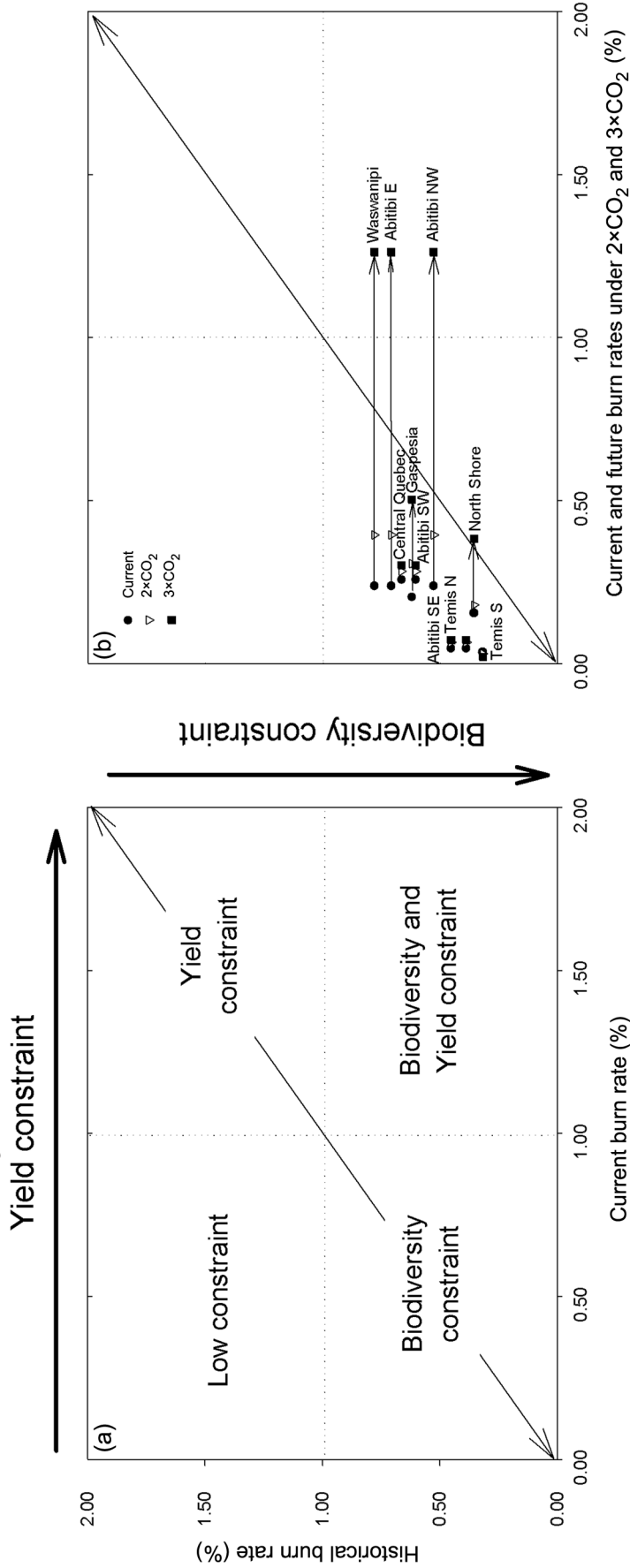
Table 2. Burn rate for each study area.

Site No.	Study area	Bioclimatic subdomain	Time period	Historical burn rate (%)*	Current burn rate (%) (since 1940)	$2 \times CO_2$ burn rate (%)	$3 \times CO_2$ burn rate (%)
1	Abitibi northwest	Western black spruce – moss	1680–1997	0.528	0.239	0.394	1.262
2	Abitibi southwest	Western fir – white birch	1530–1996	0.604	0.258	0.282	0.302
3	Abitibi east	Western black spruce – moss	1770–1995	0.708	0.239	0.394	1.262
4	Abitibi southeast	Western fir – yellow birch	1800–2004	0.389	0.048	0.064	0.072
5	Temiscamingue north	Western fir – yellow birch	1740–2003	0.454	0.048	0.064	0.072
6	Temiscamingue south	Western sugar maple – yellow birch	1580–2004	0.319	0.036	0.030	0.020
7	Waswanipi	Western black spruce – moss	1720–2003	0.781	0.239	0.394	1.262
8	Central Quebec	Western fir – white birch	1720–1998	0.665	0.258	0.282	0.302
9	North shore	Eastern black spruce – moss	1640–2003	0.356	0.155	0.179	0.384
10	Gaspésia	Eastern fir – white birch	1680–2003	0.621	0.205	0.306	0.503

as historical and current burn rates are higher than the desired 1% annual harvesting level; thus, even-aged management would compete with forest fires.
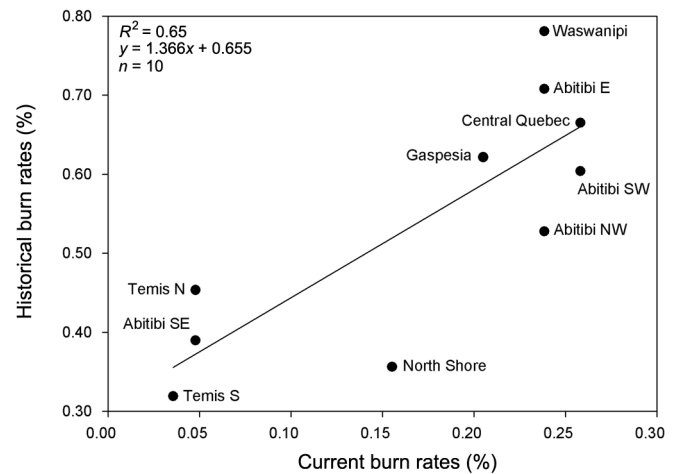
Burn rates

Historical burn rates (percentage of area per year) were determined from the literature and ongoing studies in Quebec's commercial forests (Table 2). Mean age of the forest (time since fire) before extensive clear-cutting activities began was used to estimate historic burn rates. Mean age of the forest was preferred to the historic fire cycle because it integrates climatically induced changes in fire frequency over a long period and because it is easier to evaluate than a specific fire cycle (Bergeron et al. 2001; Gauthier et al. 2002). The inverse of mean age was used to estimate the annual historic burn rate.

Current burn rates were estimated from the Quebec forest fire archives for the period 1940–2003 (ministère des Ressources naturelles et de la Faune du Québec (MRNFQ) 2005). The fire database includes all fires 50 ha and larger and represents over 98% of the area burned. Mean annual area burned was computed for each bioclimatic subregion following the Saucier et al. (1998) classification.

We estimated future burn rates using linear regression relationships developed between monthly area burned and observed weather and components of the Canadian Fire Weather Index (FWI) System (Van Wagner 1987) for each bioclimatic subregion during the 1959–1999 period. The observed weather data included temperature, relative humidity, wind speed, and 24 h precipitation at 12:00 Local Standard Time (LST) for the fire season. These data were obtained from the most appropriate Environment Canada weather station for each bioclimatic subregion. These weather variables are also input variables for the calculation of the Canadian FWI system; this system represents fuel moisture of three layers, rate of fire spread, total fuel available, and the intensity of a spreading fire. Using the $2 \times CO_2$ and $3 \times CO_2$ scenarios from the Canadian first-generation coupled general circulation model (GCM–CGCM1) (Flato et al. 2000), we calculated the components of the FWI system. This model included forcings from both greenhouse gases and sulphate aerosols that contribute to a 1% increase in CO_2 per year. At this rate, the time periods 2040–2060 and 2080–2100

Fig. 3. Linear regression between historical and current burn rates of the study areas. See Table 1 and Fig. 2 for study areas and abbreviations, respectively.

roughly correspond to a $2 \times CO_2$ and $3 \times CO_2$ scenario, respectively. The grid spacing for GCM predictions was for areas approximately 3.75° longitude × 3.75° latitude. Estimates of future burn rates for each bioclimatic subregion were calculated using the appropriate linear regression (see Table 3). Additional methodological details can be found in Flannigan et al. (2005).

Results

All the areas studied showed current burn rates significantly lower than their associated historical burn rates (Table 2; see also Figs. 2b and 3). Depending on the area, fire frequencies decreased 2 to 10 times. The relationship between historical and current burn rates among the study areas is illustrated by a significant linear regression with R^2 = 0.65 (Fig. 2). Current burn rates for all bioclimatic subregions are relatively low (Table 2). There is a trend for an increase in burn rate with latitude, with the western sugar maple – yellow birch bioclimatic subregion having the lowest frequency (0.036%/year), and the western black spruce subregion (0.239%/year) and the balsam fir – white birch (0.258%/year) showing higher frequency.

Table 3. Empirical relationships used to describe current and future burn rates for Quebec bioclimatic subregions.

Subdomain	Area (km^2)	Linear model*	N (months)	R^2
Western black spruce – moss	181 361	$Y = 0.58\,705\text{FFMCX} + 0.056\,55\text{DMCX} + 0.167\,87\text{MTEMP} - 55.116\,68$	205	0.2894
Eastern black spruce – moss	215 055	$Y = 0.125\,88\text{MDMC} - 0.924\,52$	205	0.1713
Western fir – white birch	83 813	$Y = -0.14\,568\text{MRH} + 0.050\,45\text{DMCX} + 8.465\,41$	205	0.2914
Eastern fir – white birch	55 244	$Y = 0.788\,52\text{MDSR} - 0.378\,53$	205	0.1995
Western fir – yellow birch	57 182	$Y = 0.336\,53\text{MISI} - 0.8961$	205	0.0973
Eastern fir – yellow birch	41 409	$Y = 0.449\,17\text{MISI} - 1.046\,03$	205	0.1047
Sugar maple – Yellow birch	110 161	$Y = -0.054\,12\text{RHN} + 0.056\,48\text{WINDX} + 0.000\,031\,45\text{WLRH} + 0.455\,07$	205	0.1296

*Variables are as follows: MDMC, mean duff moisture code; DMCX, duff moisture code maximum; MDSR, mean daily severity rating; FFMCX, fine fuel moisture code maximum; MISI, mean initial spread index; MRH, mean relative humidity; MTEMP, mean temperature; Rhn, minimum relative humidity; WINDX, wind speed maximum; WLRH, wind-weighted low relative humidity days.

In terms of future burn rates, the $2 \times CO_2$ simulations (Tables 2 and 3) showed a potential increase in mean fire frequency. This increase was highest for the western black spruce and moss bioclimatic subregion, an increase of 65%. The exception was the western sugar maple – yellow birch subregion where a decrease of 17% was observed. Despite strong increases in burn rate for the $2 \times CO_2$ scenarios, future fire frequencies are expected to lower than historical burn rates (Fig. 2b). In fact, the difference in current and (projected) future fire frequencies from their historical counterparts places all cases in the biodiversity constraint quadrant of Fig. 2a. Higher fire frequencies due to climate change would also significantly increase the constraint on yield. However, with a $3 \times CO_2$ scenario, the estimates of burn rate for the western black spruce – moss bioclimatic subregion lie over the 1% threshold and such that both biodiversity and yield constraints are expected.

Discussion

Changes in fire frequency

The observed shift from shorter fire cycles in the past to longer cycles over the last 63 years is likely due to a combination of climate change and improved fire suppression. Although area burned in Canada has been increasing in recent decades (Gillett et al. 2004), many studies from the Canadian boreal forest report a general decrease in fire frequency since the mid-19th century (Bergeron et al. 2001; Larsen 1997; Weir et al. 2000). Because most of the forest was still commercially unexploited at that time, it seems probable that the decrease in fire frequency was driven by climatic changes, a notion supported by the general decrease observed for all regions and the maintenance of their relative differences (Fig. 3). In northwestern Quebec, the decrease in fire frequency relates to a reduction in the frequency of drought events since the end of the Little Ice Age (Bergeron and Archambault 1993) and an important change in the circulation of global air masses that regulate climate in this region (Girardin et al. 2004).

While the fire-fighting tools available during the first part of the 20th century were likely insufficient to effectively deal with large fires, active fire suppression in this region increased during the last 63 years. The introduction of water bombers, enhanced fire detection, and improved initial response systems has meant an important improvement in firefighting (cf. Cumming 2005). Moreover, the efficacy of fire suppression likely increased because of landscape fragmentation by land clearing and the development of an extensive road system that augmented the number of firebreaks and improved firefighting access (Lefort et al. 2003). Differences in efficacy of passive or active fire suppression could account for part of the unexplained variance in the regression between past and current fire frequencies (Fig. 3).

The simulation results suggest a general increase in fire frequency in the future, especially for the latter part of this century. However, these results have to be interpreted with caution. Simulations based on different GCM scenarios often give a range of results (Flato et al. 2000). Moreover, no changes or decreases in fire frequencies have been inferred from simulation of future fire weather indices (Flannigan et al. 1998, 2001) as opposed to the current regression method that uses area burned as a predictor (Flannigan et al. 2005). In any case, the important conclusion to retain here is that, except for the western black spruce – moss subregion under a $3 \times CO_2$ scenario, the predicted increases in fire frequency are less than the historical fire frequencies observed over the last 300 years.

Implications for age-class structure, harvest rates, and sustainability

The recent decrease in fire frequency relative to the past means that even-aged or low-retention silvicultural systems could be used to create forest age structures that would exist under shorter fire-return intervals. Moreover, simulation results presented in this paper and elsewhere (Flannigan et al. 1998) show that, even if this trend is reversed in the future, predicted increases in fire frequency would probably fall short of the shortest fire intervals observed in the past. Under these circumstances, the use of even-aged or low-retention management would still be feasible to make up differences between historical and predicted burn rates (Fig. 2b).

We emphasize that clear-cutting and fire are not the same process nor do they have the same ecological effects (see McRae et al. 2001 for a review). In Quebec in particular, and in boreal forests in general, clear-cutting does not reproduce the spatial pattern observed naturally among and within individual fires. Such practices can lead to intense forest fragmentation and large losses of old and mature forest (Delong and Tanner 1996) as well as a lack of residual dead and liv-

ing tree stems inside cutblocks. Furthermore, the lack of soil disturbance and rejuvenation typically associated with fire can contribute to decreased stand productivity and can be detrimental to fire-adapted species (McRae et al. 2001; Haeussler et al. 2002). This latter phenomenon is particularly acute in the Claybelt of northwestern Quebec and northeastern Ontario, where organic matter rapidly accumulates after fire; this process is not reversed after logging and can lead to decreased postlogging stand productivity (Fenton et al. 2005; Lavoie et al. 2005). Therefore, only continued and careful examination of fire and harvesting effects on ecological patterns and processes can help define clear-cutting guidelines in the context of sustainable forest management (Ontario Ministry of Natural Resources (OMNR) 2001; Bergeron et al. 2002).

Even if current or future fire frequencies remain low, logging will continue to compete with forest fires for timber. In this circumstance, without a large investment in fire suppression (active and passive) and extensive use of salvage logging, with its associated negative effects on biodiversity, the current harvesting rate may be unsustainable if losses due to current and future fire frequencies are not included in timber supply models (Le Goff et al. 2005). Extreme changes similar to those expected in the western black spruce – moss subregion might not allow for any forestry at all.

Fire suppression has limitations; it is increasingly recognized that it is not really efficient in large tracts of natural forest where access is limited and when fire season conditions are particularly severe. The use of salvage logging is also limited by road access, especially in cases where the postfire timber quality is affected by insects. Furthermore, as the abundance and extent of mature and old-growth forest diminishes, fire will increasingly burn immature stands where salvage logging may be impossible or uneconomical. Moreover, extensive use of salvage logging may also be detrimental to biodiversity, because many plant and animal species depend upon or become periodically concentrated in recently burned stands (Nappi et al. 2003; 2004; Purdon et al. 2004). Brais et al. (2000) also reported that, in the case of poor soils, the additive effects of fire and logging can decrease nutrient pools and affect stand productivity.

Although differences among past, current, and future fire frequencies may be used to justify the use of clear-cutting or low-retention systems to emulate the historical proportion of postfire stands in the landscape, the exclusive use of these systems cannot be justified by historical fire frequencies. In most cases, reported historical fire frequencies are less than 1% (implying at least a 100 year rotation, see Fig. 2a); this low frequency means a large proportion of the preindustrial landscape was composed of forests older than the 100 year commercial forest rotation. This proportion is even higher if one considers that fire is a random process, whereas forest management is systematic: with a 1% burn rate, 37% of the stands are in fact older than 100 years in a landscape subject only to fires, whereas no stands are older than 100 years in a fully regulated managed landscape (Van Wagner 1978). Alternative silvicultural systems that include extended rotations and a variety of retention treatments have been proposed to conserve in-block forest structure and maintain mature and old-growth forests in the managed landscape (Bergeron et al. 1999, 2001). However, we may also need to fundamentally review thinking that suggests we can optimize timber supply through regulating the forest landscape. This may, under many scenarios, put us into direct conflict with biodiversity objectives and a changing fire regime. In this vein, the design and implementation of alternative silvicultural systems for the mixed and boreal forests remain urgent tasks that must be accomplished.

Acknowledgements

References

Angelstam, P.K. 1998. Maintaining and restoring biodiversity in European boreal forests by developing natural disturbance regimes. J. Veg. Sci. **9**: 593–602.

Armstrong, G.W. 1999. A stochastic characterisation of the natural disturbance regime of the boreal mixedwood forest with implications for sustainable forest management. Can. J. For. Res. **29**: 424–433.

Attiwill, P.M. 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. For. Ecol. Manage. **63**: 247–300.

Bergeron, Y., and Archambault, S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Québec and its relation to global warming since the end of the 'Little Ice Age.' Holocene, **3**: 255–259.

Bergeron, Y., Harvey, B., Leduc, A., and Gauthier, S. 1999. Forest management guidelines based on natural disturbance dynamics: stand- and forest-level considerations. For. Chron. **75**: 49–54.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., and Lesieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Can. J. For. Res. **31**: 384–391.

Bergeron, Y., Leduc, A., Harvey, B.D., and Gauthier, S. 2002. Natural fire regime: a guide for sustainable management of the Canadian boreal forest. Silva Fenn. **36**: 81–95.

Bergeron, Y., Gauthier, S., Flannigan, M., and Kafka, V. 2004. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. Ecology, **85**: 1916–1932.

Brais, S., Paré, D., and Ouimet, R. 2000. Impacts of wild fire severity and salvage harvesting on the nutrient balance of jack pine and black spruce boreal stands. For. Ecol. Manage. **137**: 231–243.

Burton, P.J., Kneeshaw, D.D., and Coates, K.D. 1999. Managing forest harvesting to maintain old growth in boreal and subboreal forests. For. Chron. **75**: 623–631.

Cumming, S.G. 2005. Effective fire suppression in boreal forests. Can. J. For. Res. **35**(4): 772–786.

Delong, S.C., and Tanner, D. 1996. Managing the pattern of forest harvest: lessons from wildfire. Biodivers. Conserv. **5**: 1191–1205.

Drever, C.R., Messier, C., Bergeron, Y., and Doyon, F. 2006. Large severe fires and canopy composition in a northern hardwood landscape in Témiscamingue, Québec. For. Ecol. Manage. **231**: 27–37.

Fenton, N., Lecomte, N., Légaré, S., and Bergeron, Y. 2005. Paludification in black spruce (*Picea mariana*) forests of eastern Canada: potential factors and management implications. For. Ecol. Manage. **213**(1–3): 151–159.

Flannigan, M.D., Bergeron, Y., Engelmark, O., and Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. J. Veg. Sci. **9**: 469–476.

Flannigan, M., Campbell, I., Wotton, M., Carcaillet, C., Richard, P., and Bergeron, Y. 2001. Future fire in Canada's boreal forest: paleoecology results and general circulation model – regional climate model simulations. Can. J. For. Res. **31**: 854–864.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., and Stocks, B.J. 2005. Future area burned in Canada. Clim. Change, **72**(1–2): 1–16.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C., and Weaver, A.J. 2000. The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate. Clim. Dynam. **16**: 451–467.

Franklin, J.F. 1993. Preserving biodiversity: species, ecosystems or landscapes? Ecol. Appl. **3**: 202–205.

Gauthier, S., Lefort, P., Bergeron, Y., and Drapeau, P. 2002. Time since fire map, age-class distribution and forest dynamics in the Lake Abitibi Model Forest. Can. For. Serv. Laurentian For. Cent. Inf. Rep. LAU-X-125.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., and Flannigan, M.D. 2004. Detecting the effect of climate change on Canadian forest fires. Geophys. Res. Lett. **31**(18): L18211. doi:10.1029/2004GL020876.

Girardin, M.-P., Tardif, J., Flannigan, MD., and Bergeron, Y. 2004. Multicentury reconstruction of the Canadian Drought Code from eastern Canada and its relationship with paleoclimatic indices of atmospheric circulation. Clim. Dynam. **23**: 99–115.

Grenier, D.J., Bergeron, Y., Kneeshaw, D., and Gauthier, S. 2005. Fire frequency for the transitional mixedwood forest of Timiskaming, Quebec, Canada. Can. J. For. Res. **35**(3): 656–666.

Haeussler, S., and Kneeshaw, D.D. 2003. Comparing forest management to natural processes. *In* Towards sustainable management of the boreal forest. *Edited by* P.J. Burton, C. Messier, D.W. Smith, and W.L. Adamovicz. NRC Research Press, Ottawa, Ont. pp. 307–368.

Haeussler, S., Bedford, L., Leduc, A., Bergeron, Y., and Kranabetter, J.M. 2002. Silvicultural disturbance severity and plant communities of the southern Canadian boreal forest. Silva Fenn. **36**: 307–327.

Hunter, M.L., Jr. 1993. Natural fire regimes as spatial models for managing boreal forests. Biol. Conserv. **65**: 115–120.

Hunter, M.L., Jr. (*Editor*). 1999. Maintaining biodiversity in forest ecosystems. Cambridge University Press, Cambridge, UK.

Hunter, M.L., Jr., Jacobson, G.L., and Webb, T., III. 1988. Paleoecology and the coarse filter approach to maintaining biological diversity. Conserv. Biol. **2**: 375–385.

Kafka, V., Gauthier, S., and Bergeron, Y. 2001. Fire impacts and crowning in the boreal forest: study of a large wildfire in western Quebec. Int. J. Wildl. Fire, **10**: 119–127.

Kneeshaw, D., and Gauthier, S. 2003. Old growth in the boreal forest: a dynamic perspective at the stand and landscape level. Environ. Rev. **11**: S99–S114.

Larsen, C.P.S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. J. Biogeogr. **24**: 663–673.

Lauzon, È. 2004. Reconstitution de l'historique des feux de forêt (1680–2003) dans la région de la Gaspésie, de l'Est canadien. Mémoire de maîtrise en biologie, Université du Québec à Montréal, Montréal, Que.

Lavoie, M., Paré, D., Fenton, N., Groot, A., and Taylor, K. 2005. Paludification and management of forested peatlands in Canada: a literature review. Environ. Rev. **13**(2): 21–50.

Lefort, P., Gauthier, S., and Bergeron, Y. 2003. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, eastern Canada. For. Sci. **49**: 509–521.

Le Goff, H., Leduc, A., Bergeron, Y., and Flannigan, M. 2005. The adaptive capacity of forest management to changing fire regimes in the boreal forest of Quebec. For. Chron. **81**(4): 582–592.

Lesieur, D., Gauthier, S., and Bergeron, Y. 2002. Fire frequency and vegetation dynamics for the south-central boreal forest of Quebec, Canada. Can. J. For. Res. **32**: 1996–2009.

McRae, D.J., Duchesne, L.C., Freedman, B., Lynham, T.J., and Woodley, S. 2001. Comparisons between wildfire and forest harvesting and their implications in forest management. Environ. Rev. **9**: 223–260.

Ministère des Ressources naturelles et de la Faune du Québec (MRNFQ). 2005. Système d'information sur les incendies forestiers (FIMAQ-FEU) de la Direction de la conservation des forêts du ministère des Ressources naturelles et de la Faune. Ministère des Ressources naturelles et de la Faune du Québec, Québec, Que.

Nappi, A., Drapeau, P., Giroux, J.-F., and Savard, J.-P.L. 2003. Snag use by foraging black-backed woodpeckers (*Picoides arcticus*) in a recently burned eastern boreal forest. Auk, **120**: 505–511.

Nappi, A., Drapeau, P., and Savard, J.-P.L. 2004. Salvage logging after wildfire in the boreal forest: is it becoming a hot issue for wildlife ? For. Chron. **80**: 67–74.

Ontario Ministry of Natural Resources (OMNR). 2001. Forest management guide for natural disturbance pattern emulation. Version 3.1. Ontario Ministry of Natural Resources, Toronto, Ont.

Purdon, M., Brais, S., and Bergeron, Y. 2004. Initial response of understorey vegetation to fire severity and salvage-logging in the southern boreal forest of Québec. Appl. Veg. Sci. **7**: 49–60.

Saucier, J.-P., Bergeron, J.-F., Grondin, P., and Robitaille, A. 1998. The land regions of southern Québec. 3rd ed. One element in the hierarchical land classification system developed by the ministère des Ressources naturelles du Québec. Internal report. Ministère des Ressources naturelles du Québec, Québec, Que.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. Can. J. For. Res. **8**: 220–227.

Van Wagner, C.E. 1987. The development and structure of the Canadian forest fire weather index system. Canadian Forest Service, Ottawa, Ont. For. Tech. Rep. No. 35.

Weir, J.M.H., Johnson, E.A., and Miyanishi, K. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. Ecol. Appl. **10**: 1162–1177.