Natural Fire Regime: A Guide for Sustainable Management of the Canadian Boreal Forest

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The combination of certain features of fire disturbance, notably fire frequency, size and severity, may be used to characterize the disturbance regime in any region of the boreal forest. As some consequences of fire resemble the effects of industrial forest harvesting, conventional forest management is often considered as a disturbance that has 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 also has its limitations. Short fire cycles generally described for boreal ecosystems do not appear to be universal; rather, important spatial and temporal variations have been observed in Canada. These variations in the fire cycle have an important influence on forest composition and structure at the landscape and regional levels. Size and severity of fires also show a large range of variability. In regions where the natural matrix of the boreal forest remains relatively intact, maintenance of this natural variability should be targeted by forest managers concerned with biodiversity conservation. Current forest management tends to reduce this variability: for example, fully regulated, even-aged management will tend to truncate the natural forest age distribution and eliminate over-mature and old-growth forests from the landscape. We suggest that the development of strategic-level forest management planning approaches and silvicultural techniques designed to maintain a spectrum of forest compositions and structures at different scales in the landscape is one avenue to maintain this variability. Although we use the boreal forest of Quebec for our examples, it is possible to apply the approach to those portions of the boreal forest where the fire regime favours the development of even-aged stands in burns.

Keywords Natural disturbance, landscape patterns, coarse filter, harvest pattern, volume retention, historic variability, even-age management, biodiversity
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1 Introduction

Over the past decade, there has been an increasing interest in the development of forest management approaches that are based on an understanding of natural disturbance dynamics (Attiwill 1994, Bergeron and Harvey 1997, Angelstam 1998). The rationale, which is generally considered sound, is that management that favours the development of stand and landscape compositions and structures similar to those that characterise natural ecosystems should be favourable to the maintenance of biological diversity and essential ecological functions (Franklin 1993, McKenney et al. 1994, Gauthier et al. 1996, Hunter 1999). Despite a certain interest for natural disturbance-based management, the application of the concepts is still not well developed. In effect, most articles treating the subject are limited to providing basic principles, but few go as far as suggesting silvicultural treatments and management strategies that allow practical application of the concepts. In absence of concrete alternatives, forest industry is often hesitant to distant itself from traditional practices that have proved to be satisfactory for wood production.

Application of management approaches based on natural fire regimes has also been constrained by limited knowledge of disturbance dynamics. Understanding of the fire regimes that characterise the boreal forest is still somewhat fragmentary and it is inappropriate to generalise from regional studies to all parts of the boreal zone. This lack of understanding has often lead to abusive generalisations. For example, clear-cutting has been justified for use throughout the boreal forest based on the assumption that the fire regime is characterised by the presence of frequent and severe fires that produced even-aged stands. In fact, it has become increasingly evident that this rule applies only partially to the entire boreal forest and that the situation is considerably more complex (Bergeron et al. 2001).

As a result of historical differences between Northern Europe and the boreal zone of North America, a greater emphasis has been placed on *restoring* biodiversity to European forests that have been intensively managed for 200 years (Angelstam 1998). In Canada, where there are still vast tracts of natural forest, *maintaining existing* biodiversity is more likely to be considered a primary management objective. In this article, we explore several avenues that provide greater linkages between natural disturbances and forest management strategies applicable to regions containing a large proportion of natural and semi-natural forests. Based on our understanding of the fire regimes of the boreal forest of western Quebec, we illustrate how it is possible to use judiciously a solid understanding of natural forest dynamics in forest management. While fully aware that biological processes involved in fire disturbance and forest harvesting may differ in many regards, we limit our treatment of natural disturbance-based management to strategic forest-level planning. This does not, however, preclude the integration of more fine-scale knowledge of ecosystem processes into such an approach. Although the examples are especially applicable to the boreal forest of western Quebec, it is possible to apply the approach to those portions of the boreal forest where the fire regime favours the development of even-aged stands in burns.

2 Respecting Historic Variability of Forest Conditions

Fig. 1 conceptually illustrates on three axes the potential variability characterising a natural disturbance regime. In the boreal forest, considerable amplitude may exist on all of these axes, and variations can be expected to exist from region to region. The risk of a fire occurring is such that one site may burn two years in a row whereas another may be spared for several hundred years. Similarly, the area burned by a fire can vary from less than one hectare to 100s or even 1000s of km^2. Finally, while certain surface fires may only affect ground vegetation, an intense crown fire will kill virtually all trees in its path and may consume the forest humus layer down to the mineral soil. The combination of these characteristics – fire frequency, fire size and fire severity – and others, make up the disturbance regime that is proper to an ecosystem or a forest region. Other than the variability imposed by permanent

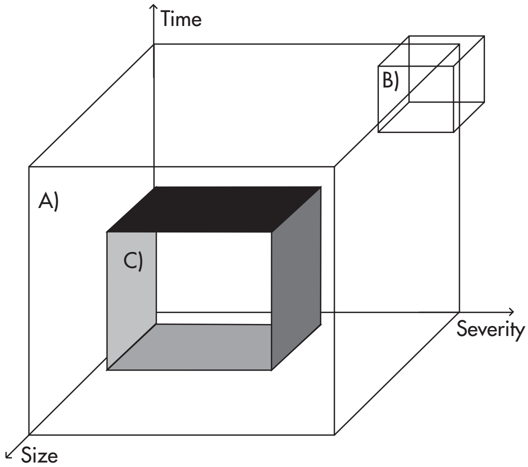

Fig. 1. Three dimensional conceptual model of fire regime variability in natural ecosystems (A) and managed ecosystems (B and C). In B, forest management produces a disturbance regime that incorporates little of the diversity of the natural regime. In C, management is illustrated as incorporating more variability than B but less than the natural disturbance regime.

site features which influence thermal, hydric and nutritional regimes, it is the disturbance regime that is responsible for the variety of forest habitats which occur in a region and thus determines the coarse filter on which maintenance of biodiversity should be based. In contrast, we can represent the variability theoretically created by an intensive forest management regime involving, for example, the wide-spread use of plantations and stand tending treatments. In this context, large-scale, intensive forestry that tends to standardise harvest interval, and produce uniform cutover size and treatment impacts constitutes a management regime whose variability is considerably narrower than that of the natural disturbance regime. It could even be situated outside of the range of historic variability of the disturbance regime (Fig. 1).

Although the objective of ecosystem or natural disturbance-based management is to respect the inherent variability of natural disturbance regimes, in practical terms it is aimed rather at defining a socially and economically acceptable compromise within the limits of historic variability that will reduce the risk of negatively affecting biodiversity. This management target is generally situated somewhere between the great variability generated by the natural regime and the homogeneity generated by a management regime aimed primarily at sustained wood production.

In the following sections we treat each of the three variability axes that characterise fire regimes in the boreal forest, that is, fire frequency, size and severity, and discuss interpretations for the development of new silvicultural and management planning practices. We will illustrate our points with concrete examples from work undertaken in the boreal forest of western Quebec.

3 Fire Frequency and Its Implications for Management Strategies and Silvicultural Practices

When forest rotation age approaches fire cycle, it may appear at first glance that even-aged management resembles the natural disturbance regime. However, full, even-age forest regulation does not produce the same age class distribution as natural disturbance, even for forest rotations that are as long as the fire cycle. In effect, in even-aged management, a forest is referred to as fully regulated when stand age classes are uniformly distributed throughout a territory. Thus, in theory, after one complete rotation in a region submitted to a 100 year rotation, no stands over the rotation age will exist (Fig. 2a).

The same region submitted to forest fires intense enough to generate even-aged stands will, at equilibrium, present a completely different forest age class distribution. Assuming that the probability of burning is independent of stand age (as is generally reported for studies in the boreal forest; Johnson 1992, Johnson et al. 1998), the forest age structure will, again theoretically, resemble a negative exponential curve, with about 37% of forests older than the fire cycle (Johnson and Van Wagner 1985; Fig. 2b). This means that for a fire cycle and a forest rotation of similar duration, forest management will not spare any forest that exceeds rotation age whereas fire will

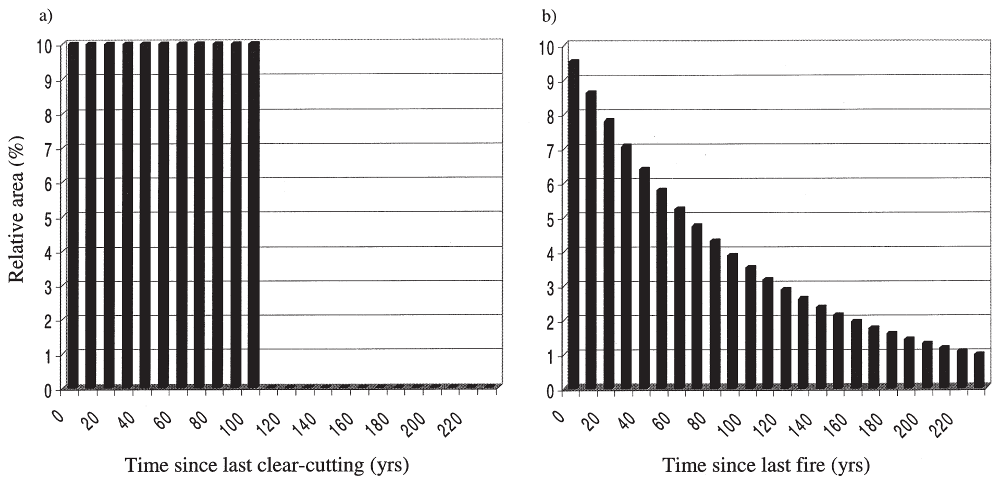

Fig. 2. Theoretical forest age class distribution based on a 100 year even-aged rotation (a) and a 100 year fire cycle (b) (adapted from VanWagner 1978).

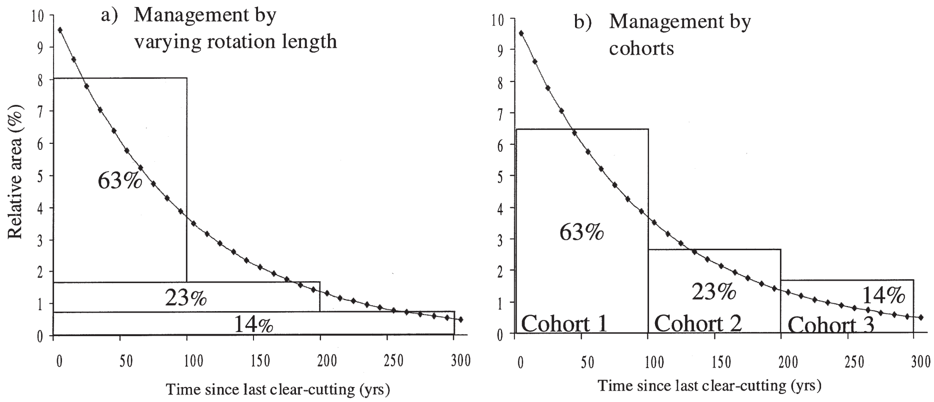

Fig. 3. Alternative strategies to full, even-aged forest regulation. In a), proposed by Seymour and Hunter (1999), the approach consists in applying different forest rotation lengths in an area under management. In b), management by cohorts consists of diversifying silvicultural practices in order to favour the development and maintenance of stands with even- and uneven-aged structures. The theoretical natural age class distribution, indicated by the inverse exponential line provides a reference for the proportion of each zone or cohort (63, 23 and 14%).

maintain over 37% of the forest in older age classes. This difference is fundamental because it implies that full regulation in an even-age management regime will result in the loss of over-mature and old-growth forests that may be essential to biodiversity maintenance at a regional level. Our studies in the forests of western Quebec show that almost 50% of the natural mosaic contains forests in these categories.

Use of rotations of variable length in proportions similar to those observed in the natural fire regime is one approach that has been proposed for maintaining natural forest age structure (Seymour and Hunter 1999, Burton et al. 1999). In the example given of this approach (Fig 3a), 63% of forest area is managed on a 100 year even-aged cycle, 23% on a 200 year cycle, and 14% on a 300 year cycle. Such a strategy is dependant

Table 1. Targeted proportions of cohorts according to fire cycle and maximum harvest age. Note: The third cohort consists of the sum of proportions of all subsequent cohorts.

Maximum harvest age	Fire cycle 50 Cohort (%) I	II	III	100 Cohort (%) I	II	III	200 Cohort (%) I	II	III	400 Cohort (%) I	II	III	500 Cohort (%) I	II	III
50	63	23	14	39	24	37	22	17	61	12	10	78	10	09	82
100	86	12	2	63	23	14	39	24	37	22	17	61	18	15	67
150	95	5	0	78	17	5	53	25	22	31	21	47	26	19	55
200	98	2	0	86	12	2	63	23	14	39	24	37	33	22	45

on the existence of forest types containing tree species that have commercial rotations of 200 and 300 years. However, this is not the case in the boreal forest and would probably lead to a loss in wood production and allowable cut.

Another approach that is applicable to the boreal forest involves the use of silvicultural practices designed to maintain structural and compositional characteristics of older, uneven-age stands in treated stands. The objective is to maintain habitat diversity without necessarily affecting allowable cut. In Fig. 3b, a forest age structure similar to that of Fig. 3a is attained by using "stand-initiating" harvesting to recruit even-aged stands on 63% of the land base (cohort 1), partial cutting to move even-aged stands into an uneven or irregular structure, and often into a mixed composition (cohort 2), and selection cutting to reflect gap dynamics in over-mature and old growth stands (cohort3). Depending on their structure and composition, when stands reach maturity, they are either treated by even-aged silviculture to recruit into the first cohort or treated by partial or selection cutting to move them into the second or third cohorts. Thus, varying silvicultural practices is intended to recreate a composition and structure comparable to natural stands at different development stages. While recognising differences in the residual stand structure and some ecosystem processes resulting from fire and forest harvesting, the *even-aged structure* of the first cohort issued from fire can be generated by clear-cutting (or other even-aged harvesting treatment) followed by natural or artificial regeneration. Similarly, partial and selection cutting may not perfectly mimic mortality and recruitment processes that occur through stand development, but they do serve the intended purpose of creating the changes in stand structure and composition that produce older stands. The proportion of stands submitted to each of these treatments and the proportion of forest areas to be maintained in each cohort are a function of the natural disturbance cycle and maximum harvest age (Table 1). The latter corresponds to the age at which stand break-up begins to occur (i.e., when tree mortality represents significant merchantable volume loss). However, under even-aged management, commercial rotation is generally shorter than maximum harvest age.

A simple example illustrating natural dynamics and management of the boreal forest of eastern Canada is presented in Fig. 4. The first case (Fig. 4a) illustrates natural succession in the mixedwood forest located in the southern portion of the eastern boreal forest. Following fire, we generally observe an invasion of shade-intolerant hardwoods such as white birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) that are gradually replaced in the canopy by shade-tolerant conifers (Bergeron and Dubuc 1989, Bergeron 2000). Over a period of 200 years or so, successive replacement of hardwood stands by mixed stands then by softwood stands occurs. Further north, in the coniferous boreal forest dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) (Fig. 4b), stand establishment following fire is often dominated by an initial cohort of spruce which gives rise to a dense, even-aged forest issued principally from seed. After attaining maturity, this stand structure is gradually replaced by a more open forest containing stems originating from the fire and regeneration partly of layer origin. In the prolonged absence of fire, these stands develop into uneven-aged stands maintained by layering and

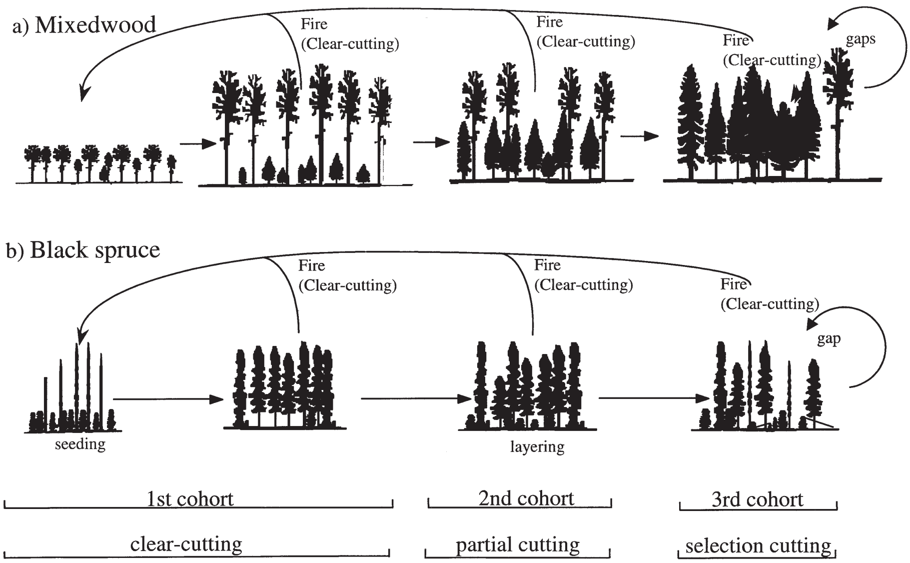

Fig. 4. Natural stand dynamics and silviculture proposed for a) the boreal mixedwood and b) the black spruce boreal zones. The arrows going from left to right represent time since the last fire or clear-cut.

characterised by an even more open and heterogeneous structure. In comparison to the mixedwood forest, tree species composition remains relatively stable in the black spruce forest but the structure is very different between mature, over-mature and old growth stands (Harper et al., this issue). In a forest system under a natural fire regime, not all stands survive to a mature or old growth stage before again succumbing to fire. In the same way, in the proposed strategy, not all stands should develop to the latter, advanced cohorts. Thus, the reinitiation to a first cohort forest type can occur when forest types in any of the three cohorts are clear-cut and either naturally or artificially regenerated. Fig. 3b provides an example of a possible forest age structure where maximum harvest age and fire cycle are both 100 years. The approach provides a means of covering a forest management area with zones of regulated, even-aged forests with proportions of each varying in relation with time since the last stand-initiating clear-cut or fire. It should be noted here that the third cohort includes all age classes greater than 200 years. In the case where more time is required to attain a state of quasi-equilibrium, more than three cohorts could be necessary to simulate forest dynamics. In contrast, in regions where fire cycle is short relative to harvest age, probably only two cohorts will be necessary (Table 1). It would thus be possible to partially recreate not only the natural composition and structure of stands, but also to reproduce a forest age structure (proportion in each cohort) that approaches the distribution produced by the fire regime (Fig.2b). While this distribution is theoretical, it does reflect the real tendency of natural landscapes to contain a portion of over mature and old growth forest, albeit in decreasing proportions relative to younger forests.

In regions where particular site or forest cover conditions generate variable fire frequencies, the model should be applied to homogeneous forest types. This is the case of the ASIO model (Angelstam 1998) for European boreal forests. In the Canadian boreal forest, however, with the exception of situations that are clearly very humid or very dry, it appears that fire is only slightly influenced by the quantity and type of fuel, and that the model can be applied directly to most areas (Johnson 1992, Johnson et al. 1998).

Although controlling stand composition and structure by using different silvicultural treatments to varying degrees may contribute to maintaining biodiversity at the forest level, it must be stressed that, at the stand level, the role of attributes such as tree age or size, coarse woody debris etc. need to be assessed. For example, Boudreault et al. (in-press) have shown that while maintaining stand structure and composition might be a good strategy for maintaining terricolous lichens and mosses, old or large trees are essential to the maintenance of epiphytic lichens.

4 Fire Size and Its Implications for Size and Spatial Distribution of Cutovers

It may appear socially unacceptable to want to use fire size as a basis for developing management directives for cutover size and mean buffer size for even-aged harvesting in the boreal forest. In some countries, regulations limit the size of clear-cuts in any continuous block to under 150 ha, whereas lightening-caused fires can easily spread over thousands of hectares. However, while individual cut blocks are clearly much smaller than the mean size of natural burns, they are normally distributed in a continuous progression and tend to be clustered in a given area. The proximity of numerous blocks over time usually results in the creation of vast areas in regeneration within which remain only fragments of mature forest, essentially in the form of cut block separators, buffer strips and unproductive or inaccessible forest. The spatial and temporal scales at which questions concerning clear-cut size and spacing should be addressed correspond to those scales at which these "regeneration areas" are established.

Establishment time for a regeneration area and, consequently its size, will depend on the time required for plants and animals indigenous to the mature forest to be reintroduced into the young forest following harvest, or the time required for the young forest to acquire structural and compositional attributes of the mature forest. Depending on the forest type and specific habitat requirements of wildlife species, it may take 35 to 70 years before vital habitat attributes present in the surrounding mature forest appear in the oldest portion of a regeneration area. Over such long periods, the forest industry has created regeneration areas that exceed tens of thousands of hectares and it is certainly questionable whether these expansive areas of young even-aged forests are situated within the historical limits of variability of burn sizes characteristic of the natural fire regime.

There are relatively few studies documenting the size of past lightening-ignited forest fires. Although human land occupation appears to have an effect on fire size (Niklasson and Granstrom 2000), greater control of fire size by direct intervention has yet to be demonstrated in Canada (Johnson et al. 1999). In Quebec, the oldest fire records are provided by the Ministry of Natural Resources. These records document forest fire events that have occurred in Quebec since the 1940s and provide information concerning their location, origin, ignition date and size. From these records we have analysed only lightening fires to document forest fire size distribution. The majority of this fires occurred in remote forests that were not accessible by road. One of the first things that becomes evident when illustrating frequency of fire occurrence by different size classes is that, whereas most fires are smaller than 1000 ha, these fires are generally responsible for less than 10% of the total area burned in western Quebec (Figs. 5a, b). Consequently, it is primarily the large fires (those over 1000 ha) that are responsible for the natural regeneration of the forest and that permeate a given forest age structure and configuration (Johnson et al. 1998). At the high end of fire size distribution are fires that cover very large areas. Among fires over 1000 ha, the 10% that are over 20 000 ha are alone responsible for 40% of total area burned. There is little evidence that human intervention aimed at limiting fire extension has had a real impact on these fire events. In fact, mean fire size is greater for the period following the beginning of fire suppression activities than the previous period without intervention (Chabot et al. 1997). This assertion is supported by the fact that, of the 20 fires greater than 20 000 ha registered since 1940, 18 have occurred during the period of fire

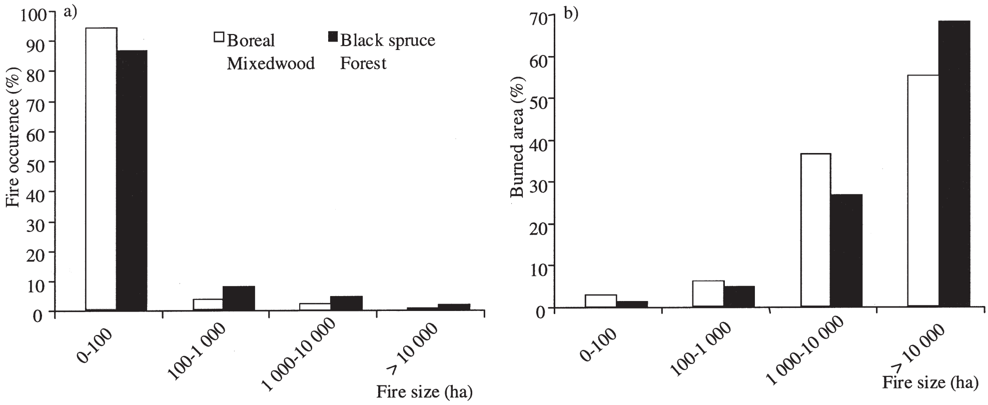

Fig. 5. Size distribution of fires in the boreal forest of western Quebec for the period 1940–1998. a) shows the relative frequency of fires and b) shows the relative area burned, both according to fire size class.

suppression. Considering that these extremely large fires reflect exceptional events (a fire occurring during a particularly dry season, for example), of which we have little effective control, it would appear prudent to exclude these fires from those that should be emulated by forest management.

Perhaps the most important point of this analysis of fire size distribution is that, over the last 60 years, almost 55% of area burned in the balsam fir (*Abies balsamea* (L.) Mill.) mixedwood forest of western Quebec occurred from fires varying in size from 265 to 15 000 ha. In the black spruce zone of western Quebec for the same period, fires ranging from 950 to 20 000 ha could be considered characteristic. In newly accessed areas of mature and over-mature forests, analysis of fire size distribution suggests that regeneration areas should be limited within these intervals.

With respect to the spatial distribution of these regeneration areas, or a minimal distance to be maintained between these areas, there is very little existing evidence that fires tend to be clustered in the landscape within a region. A cautious approach would be to maximise the dispersion of regeneration areas in order to limit the cumulative effects that may occur from their juxtaposition. In such a case, guidelines for minimum spacing between regeneration areas could be developed based primarily on fire cycle and its influence on the ratio of even-aged to uneven-aged forest to be maintained in the forest mosaic under management.

To this effect, a fire history map of the boreal forest of western Quebec illustrates the spatial organisation between recent fires (less than 100 years) and older fires (over 200 years) in a region where the average age of the forest is about 150 years (Fig. 6a). The overlapping of recent and older fires suggests the application of a fairly complex juxtaposition of clear-cuts (to be favoured in even-aged forests issued from recent fires) with partial and/or selection cuts to be practised in older, uneven-aged forests. In fact, there exists a gradient of heterogeneity of forest mosaics according to the natural disturbance regimes that generated them. At one extremity of this gradient are found mosaics driven by short fire cycles approaching maximum harvest age of stands. These mosaics are relatively homogeneous in terms of composition and distribution of the cohorts because they are largely dominated by even-aged stands (Fig. 6b). Old stands, originating from fragments of the oldest fires that have not been effectively erased by more recent fires, are generally sparse and may present a more or less elongated form (Johnson et al. 1998). The use of clear-cutting (or other even-aged harvesting practices) as the main harvesting regime should be favoured in the case of these mosaics.

At the other extremity of the gradient are forest mosaics in which fires are very infrequent and,

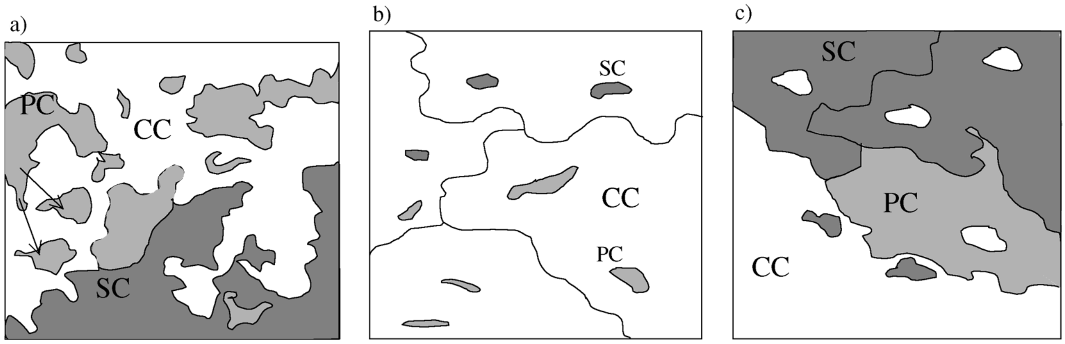

Fig. 6. Time-since-fire maps illustrating the relative importance of different silvicultural treatments (CC = clear-cut, PC = partial cut, SC = selection cut) in relation to regional fire cycle. The treatments correspond roughly to the following time period since fire: CC: < 100 years, PC: 100–200 years, SC: > 200 years. a) shows a real forest mosaic created under an intermediate fire cycle in the Abitibi region of north-western Quebec (see Gauthier et al. 1996); b) shows a hypothetical mosaic under a fire cycle (50–80 years) that is shorter than average maximum harvest age; c) shows a hypothetical mosaic under a long fire cycle (300–500 years) which greatly exceeds the life expectancy of the first cohort.

consequently, fire cycle greatly exceeds the life span of the first cohort. Here again the forest is relatively homogeneous because it is dominated by large tracts of uneven-aged and irregular stands characteristic of old age structures (Fig. 6c). Management of these forests should favour the use of partial and selection cuts, practices that should more closely resemble natural disturbances (ex. windthrow, stem breakage, gap dynamics) that occur in the absence of fire.

These two examples of contrasting fire cycles and corresponding management regimes (Fig. 6b, 6c) characterise extreme situations in which one management strategy, either even-aged or uneven-aged, dominates over the other. In any case there is always place for preharvest inventory and silvicultural prescriptions to ensure that treatments to be applied are appropriate to specific stand and site conditions.

5 Fire Severity and Its Implications for Cutting Patterns

One of the most tenacious beliefs shared by many foresters in North America is that fires in the boreal forest are generally severe; that is, that they induce the mortality of most trees within their perimeter. Moreover, several studies have shown that only about 5% of burns generally subsists as interior forest islands, untouched by a fire (Eberhart and Woodard 1987), a figure which may approach the proportion of residual forest left by the forest industry within a cutover. As a corollary, even-aged harvesting is often presented as being no more or no less severe than a fire and, as such, contributes in a similar manner to natural regeneration processes of the forest, even though differences in biological and soil processes clearly exist.

In fact, a forest fire, especially if it extends over very large areas and burns for longer than a day, will present considerable variation in severity in its path, leaving green trees following its passage (Kafka et al. 2001, Turner and Romme 1994, Van Wagner 1983). Fire severity mapping in Quebec recognises *de facto* the existence of this phenomenon by including the class “mixture of green crowns and reddened crowns with green-crown dominance” in order to designate zones where fire has had a low impact. Far from being a marginal phenomenon, these “low severity zones” may occupy up to 50% of a burn area, depending on the type of forest burned and, especially, the prevailing weather conditions prior to (Fire weather index) and during the fire. Not only do those trees that survive the passage of a fire

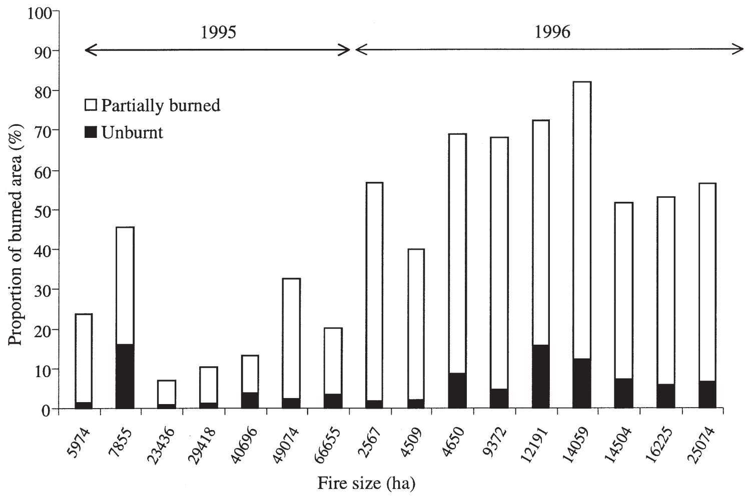

Fig. 7. Relative area of unburnt zones, partially burned and severely burned portions of 16 fires that occurred in 1995 and 1996 in the boreal forest of western Quebec.

appear to play a determining role in regenerating burns (Greene and Johnson 2000), but they also constitute habitat refuges or shelter in the regenerating forest and contribute to the spatial heterogeneity of the forest mosaic resulting from fire.

Again, there exist few empirical studies based on detailed mapping of fire severity in the Canadian boreal forest. Nonetheless, existing studies tend to attest to the variability of fire severity and would advise caution in drawing similarities between forest conditions created by even-aged harvesting and those prevailing after fire (Nguyen-Xuan et al. 2000). The following example illustrates this variability and the importance of low impact zones within burns. In recent years the Quebec government has encouraged salvage cutting in burns to limit losses of wood volumes following fires. This practice has given rise to a systematic procedure of mapping fire zones in order to guide salvage operations. Although the collection of fire impact maps is limited, it does provide a means of estimating spatial heterogeneity of recent fires.

Fig. 7 presents internal composition profiles of 16 fires that occurred during 1995 and 1996. In comparing these profiles, it can quickly be inferred that one of the principal sources of variability in fire severity is year of fire occurrence. In this example, it is clear that 1995 was particularly favourable for the development of large, severe fires, and in fact, during this year the largest fire in 60 years, the Parent Fire, burned almost 67 000 ha. In contrast, the fire weather index during 1996 generally remained within normal historical values. Consequently, fires in 1996 generally burned smaller areas and contained more area of lightly burned forest, roughly 30 to 50% of their area (Fig. 7). It should be noted that this variability primarily represents areas slightly affected by the fires, rather than areas that escaped burns altogether (preserved islands) which remained around 5% (Fig. 7). The sustained presence of these lightly burned zones suggests that the mortality pattern generated by fire is notably distinct from that produced by conventional forest harvesting.

In order to reduce the difference between these two disturbance types, variable retention strategies for cutovers have been increasingly proposed in North America (Cissel et al. 1999).The quantity of stems to be left on site raises questions of both an ecological and economic nature. For example, in their article aimed at defining forest ecosystem management targets, Cissel et al. (1999) propose maintaining almost 30% (on average) of forest

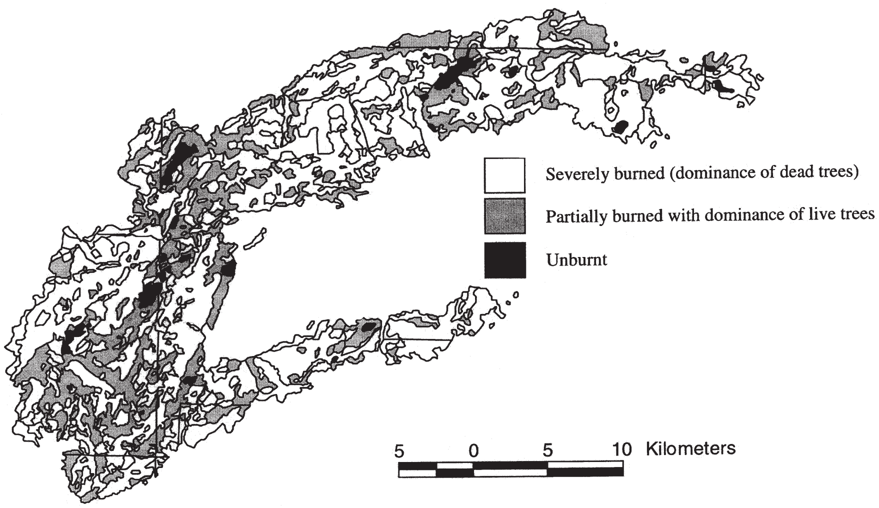

Fig. 8. Map showing the variability of fire severity in the Lac Crochet Fire.

cover after harvesting in the Blue River region of Oregon. The impact of this strategy would result in a decrease in wood supply of approximately 17%. Another example is provided by the company Alberta Pacific, operating in north-eastern Alberta, Canada, which applies a mix of clumped and single tree retention of an average of 5% of deciduous merchantable volume in cutovers (A. Desrochers, pers. comm.). There are currently no regulations concerning the maintenance of a proportion of green trees in cutovers in the boreal region of Quebec. Our example, however, suggests that almost 5% of regeneration areas should be dedicated to integral preservation in addition to up to 30–50% of the area in which variable volume retention should be practised.

Detailed impact mapping of the Lac Crochet Fire, undertaken by Kafka et al. (2001), provides further illustration of the kind of spatial configuration that retention areas could occupy. This 49 070 ha fire that burned in 1995 left a number of zones lightly burned in its passage. These low impact zones appear distributed over the entire burn rather than confined to any particular sector (Fig. 8). Moreover, the preserved (unburned) parcels, averaging 52 ha in size, appear frequently surrounded by low impact zones (Fig. 8). An analysis of their form shows that these islands display a relatively regular form and thus would be expected to incorporate less edge effect than more linear forms. Almost 75% of their area may be considered as interior habitat (value calculated for an edge effect to 50 m). As a comparison, residual areas left following forest harvesting are most often linear (ex. 100 m cut block separator strips) and thus do not generally preserve interior habitat. Finally, Kafka et al. (2001) calculated that almost 50% of severely burned zones are found less than 200 m (maximum distance judged adequate for seed dispersal by wind) from a potential seed source in unburned or low impact zones.

In order to minimise economic losses due to the application of retention measures, questions regarding the permanence of retention volumes need to be addressed. Even if we have little data concerning this subject, preliminary data from one fire in Quebec indicate that the mortality rate of residual stems in lightly burned zones can vary from 30–50% two years after fire. Moreover, the dominance of even-aged structures in post-fire boreal stands forest suggests that a portion of residual stems will die over a number of years following the fire. Resistance to retention of large volumes for economic reasons would probably diminish if most of these volumes could be salvaged a number of years following harvesting. In all instances however, a part of retention trees should be left in cutovers to provide senescent and dead trees as key foraging and habitat structures for many species.

In summary, what we know of fire severity in the eastern Canadian boreal forest should prompt the development of measures aimed at volume retention within even-aged regeneration areas. Between 3–5% of total regeneration areas should be dedicated to preservation (Fig. 7). These preserve islands, varying in size from 50–200 ha, should be surrounded by a buffer zone (of which the dimensions remain to be determined) where volume retention would be in the order of 30 to 50%. In total, retention volumes, outside of preserves, should represent 15–20% of initial standing volume and could be harvested at a latter period. If natural inseeding is an objective, composition of these volumes should be made up of forest species known for regenerating from protected seed-trees (ex. balsam fir, white pine (*Pinus strobus* L.) and white spruce (*Picea glauca* [Moench] Voss)). Distribution of residual volumes should be such that no part of a regeneration area is farther than 150 m from a potential seed source, a distance, according to Greene et al. (in press), that can still provide moderate stocking. While perhaps not fully compatible with this guideline, as a practical measure, retention trees intended to be eventually salvaged should be located as close as possible to existing road systems. Moreover, given the importance of snags for certain species, a number of stems of a variety of species, but especially those that are of large diameter and wind-firm should be left on site.

6 Flexibility in Applying the Approach to Different Regional Realities

Existing work in the Canadian boreal forest has demonstrated the high regional variability in fire regime characteristics and empirical data is still missing to cover all of this variability. Moreover, it is now well established that following future climatic changes, as in the past, fire regime will continue to change (Flannigan et al. 1998). Given this context, it might appear imprudent to want to fix precise management objectives that are inspired from fire regime. While remaining cautious concerning the precision of potential guidelines, it is possible to offer targets for forest managers that are sufficiently wide and allow some flexibility. These targets have the advantage of offering concrete alternatives to current practices, alternatives that move the composition and age structure of managed forest mosaics closer toward their natural state.

In the following section, the applicability and flexibility of the approach described above is illustrated using three regions of Canada that are submitted to contrasting fire regimes. In the boreal forest of western Canada, historically fire cycles have been relatively short (50–75 years) and, as a result, the forest mosaic is principally composed of even-aged (first cohort) stands issued from the last fire; a very small area is occupied by over-mature or old growth stands (Johnson et al. 1998). Referring to Table 1, it can be seen that the proportion of first cohort stands should increase in a landscape as maximum harvest age increases relative to fire cycle. In such situations, clear-cutting (and other even-aged silvicultural systems) are to be favoured. Fires affecting forest age structure in western Canada generally cover large areas over 1000 ha. Almost 50% of total burned area originates from fires over 10 000 ha (Johnson et al. 1998). Regeneration areas created by forest industry could therefore cover over 10 000 ha, with maximum spacing between areas. Finally, fires that are normally severe will nonetheless preserve some sparsely distributed green trees, either individually or in small groups in the burn (Greene and Johnson 2000). This heterogeneity in the mortality pattern within burns should prompt some volume retention within cut blocks. (See section on severity.)

In contrast, the situation of the mixed or coniferous forest regions of western Quebec shows, historically, an intermediate fire cycle of around 150 years. In this context, forest managers should rely on even-aged management for about 50% of the region, whereas variable intensities of removal of stand volume (partial and selection cutting) should be applied to the rest of the region (Table 1). As fire size and severity are similar to those in Alberta, management strategies concerning size of regeneration areas as well as quantities of retention could resemble the preceding prescriptions.

Finally, in the more humid climate of eastern Canada, for example in the Quebec North Shore or Labrador, where fire cycles can reach 500 years (Foster 1983), stands are most often irregular or uneven-aged. Consequently, the use of clear-cutting should be considerably diminished and greater use should be made of partial and selective harvesting. In this case, it is less the fire regime that offers the most important information for forest management but rather other secondary disturbances, such as windthrow and insect outbreaks, that are largely responsible for the make up of the forest mosaic. These disturbances justify the use of other silvicultural approaches (Bergeron et al. 1999).

7 Conclusion

These examples clearly demonstrate that, for the boreal forest of eastern North America, the universal presence of a disturbance regime characterised solely by frequent and severe fires that produce only even-aged stands – as is often used to justify even-aged management – is a myth. In the context of sustainable forestry, this basic understanding has significant implications for management practices, notably in the recognition that uneven-aged silviculture should assume a much greater place in boreal forest management. Although some of the solutions presented in this paper still remain somewhat theoretical, they do attempt to provide concrete measures for application in forest-level planning. Furthermore, while there are still knowledge gaps in our understanding of how natural disturbance and forest management interventions differ in their effects on ecosystem processes and organisms, this forest-level framework provides a reference for the development and evaluation of stand-level silvicultural practices based on natural disturbance.

Rather than merely attempting to *mimic Nature*, ecosystem management should be *based on our understanding of natural systems* in order to maintain their essential functions (ex. productivity, resilience) and their biological diversity. In this sense, the use of so-called “hard practices” such as site preparation and plantations can be justified if they are aimed at reproducing the processes that are essential to assuring forest regeneration and productivity. At the same time, it is important to recognise that there are numerous constraints related to forest operations and that it is probably easier to adapt proven forest practices than to invent totally new treatments. In this respect, projects aimed at testing new silvicultural approaches inspired by natural dynamics (Harvey et al. 2002, Spence et al. 1999) should be initiated throughout the boreal forest. However, we can not wait for the results of these studies in order to change forest practices. In effect, natural forests are disappearing rapidly and we have the responsibility *now* to maintain forest ecosystem diversity in Canada and elsewhere. Moreover it is probably operationally easier and less costly in the long term to activate natural disturbance-based forestry over large areas than to attempt to restore biodiversity to biologically impoverished forests resulting from past forest practices. There are lessons to be learned from northern European countries that currently have to invest in the restoration of their natural forests (Kuuluvainen, this issue).

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References

Angelstam, P.K. 1998. Maintaining and restoring biodiversity in European boreal forests by developing natural disturbance regimes. Journal of Vegetation Science 9: 593–602.

Attiwill, P.M. 1994. The disturbance of forest ecosystems: the ecological basis for conservation management. Forest Ecology and Management 63: 247–300.

Bergeron, Y. 2000. Species and stand dynamics in the mixed-woods of Quebec's southern boreal forest. Ecology 81: 1200–1516.

— & Dubuc, M. 1989. Forest succession in the southern part of the boreal forest, Canada. Vegetatio 79: 51–63.

— & Harvey, B. 1997. Basing silviculture on natural ecosystem dynamics: an approach applied to the southern boreal mixedwoods of Québec. Forest Ecology and Management 92: 235–242.

— , Harvey, B., Leduc, A. & Gauthier, S. 1999. Basing forest management on natural disturbance: Stand- and landscape-level considerations. Forestry Chronicle 75(1): 49–54.

— , Gauthier, S., Kafka, V., Lefort, P. & Lesieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Canadian Journal of Forest Research 31: 384–391.

Boudreault, C., Bergeron, Y., Gauthier, S. & Drapeau, P. Bryophyte and lichen communities in mature to old-growth stands in eastern boreal forests of Canada. Canadian Journal of Forest Research (in press).

Burton, P.J., Kneeshaw, D.D. & Coates, K.D. 1999. Managing forest harvesting to maintain old-growth forest in the Sub-Boreal Spruce zone of British Columbia. Forestry Chronicle 75: 623–631.

Chabot, M., Gagnon, R., Gaboriault, L. & Giguere, R. 1997. Analyse du régime de protection des forêts. Ministry of natural resources, Quebec.

Cissel, J.H., Swanson, F.J. & Weisberg, P.J. 1999. Landscape management using historical fire regimes: Blues Rives, Oregon. Ecological Applications 9: 1217–1231.

Eberhart, K.E. & Woodard, P.M. 1987. Distribution of residual vegetation associated with large fires in Alberta. Canadian Journal of Forest Research 17: 1207–1212.

Flannigan, M., Bergeron, Y., Engelmark, O. & Wotton, M. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9: 469–476.

Foster, D.R. 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. Canadian Journal of Botany 61: 2459–2471.

Franklin, J.F. 1993. Preserving biodiversity: species, ecosystems or landscapes. Ecological Applications 3: 202–205.

Gauthier, S., Leduc, A. & Bergeron, Y. 1996. Forest dynamics modelling under a natural fire cycle: A tool to define natural mosaic diversity in forest management. Environmental Monitoring and Assessment 39: 417–434.

Greene, D.F. & Johnson, E.A. 2000. Post-fire recruitment of Picea glauca and Abies balsamea from burn edges. Canadian Journal of Forest Research 30: 1264–1274.

— , Kneeshaw, D.D., Messier, C., Lieffers, V., Cormier, D., Doucet, R., Coates, K.D., Groot, A., Grover, G. & Calogeropoulos, C. Modelling silvicultural alternatives for conifer regeneration in boreal mixedwood stands (aspen/white spruce/balsam fir). Forestry Chronicle (in press).

Harper, K.A., Bergeron, Y., Gauthier, S. & Drapeau, P. 2002. Post-fire development of canopy structure and composition in black spruce forests of Abitibi, Québec: a landscape scale study. Silva Fennica 36(1): 249–263. (This issue)

Harvey, B., Leduc, A., Gauthier, S. & Bergeron, Y. 2002. Stand-landscape integration in natural disturbance-based management of the southern boreal forest. Forest Ecology and Management 155: 371–388.

Hunter, M.L. Jr. (Ed.). 1999. Maintaining biodiversity in forest ecosystems. Cambridge University Press, Cambridge, UK, 698 p.

Johnson, E.A. 1992. Fire and vegetation dynamics-studies from the North American boreal forest. Cambridge Studies in Ecology, Cambridge University Press, Cambridge, 129 p.

— & Van Wagner, C.E. 1985. The theory and use of two fire history models. Canadian Journal of Forest Research 15: 214–220.

— , Miyanishi, K. & Weir, J.M.H. 1998. Wildfires in western Canadian boreal forest: Landscape patterns and ecosystem management. Journal of Vegetation Science 9: 603–610.

— , Miyanishi, K. & O'Brien, N. 1999. Long-term reconstruction of the fire season in the mixedwood boreal forest of Western Canada. Canadian Journal of Botany 77: 1185–1188.

Kafka, V., Gauthier, S. & Bergeron, Y. 2001. Fire impacts and crowning in the boreal forest: study of a large wildfire in western Quebec. International Journal of Wildland Fire 10: 119–127.

Kuuluvainen, T. 2002. Natural variability of forests as a reference for restoring and managing biological diversity in boreal Fennoscandia. Silva Fennica 36(1): 97–125. (This issue)

McKenney, D.W., Sims, R.A., Soulé, F.E., Mackey, B.G. & Campbell, K.L. (Eds). 1994. Towards a set of biodiversity indicators for Canadian Forests: Proceedings of a forest biodiversity indicators workshop. Sault Ste. Marie, Ontario, Nov. 29–Dec.1, 1993, 133 p.

Nguyen-Xuan, T., Bergeron, Y., Simard, D., Fyles, J.W. & Paré, D. 2000. The importance of forest floor disturbance in the early regeneration patterns of the boreal forest of western an central Quebec: a wildfire versus logging comparison. Canadian Journal of Forest Research 30: 1353–1364.

Niklassson, M. & Granstrom, A. 2000. Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81: 1484–1499.

Seymour, R.S. & Hunter, M.L. Jr. 1999. Principles of ecological forestry. In: Hunter, M.L. Jr. (Ed.), Maintaining biodiversity in forest ecosystems. Cambridge University Press. Cambridge, UK. p. 22–61.

Spence, J.R., Volney, W.J.A., Lieffers, V.J., Weber, M.G., Luchkow, S.A. & Vinge, T.W. 1999. The Alberta EMEND project: Recipe and Cooks' argument. p. 583–590. In: Veeman, T.S., Smith, D.W., Purdy, B.G., Salkie, F.J. & Larkin, G.A. (Eds.), Proceedings of the 1999 Sustainable Forest Management Network Conference, Science and Practice: Sustaining the Boreal Forest. Edmonton, Alberta, Canada, 14–17 February 1999. 816 p.

Turner, M.G. & Romme, H.W. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9: 59–77.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8: 220–227.

— 1983. Fire behaviour in northern conifer forests and shrublands. In: Wein, R.W. & MacLean, D.A. (Eds.), The role of fire in northern circumpolar ecosystems. John Wiley & Sons, New York. p. 65–80.

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