# Using spatially explicit simulations to explore size distribution and spacing of regenerating areas produced by wildfires: recommendations for designing harvest agglomerations for the Canadian boreal forest

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**ABSTRACT**

It is now recognized that in the Canadian boreal forest, timber harvesting activities have replaced wildfires as the main stand-replacing disturbance. Differences in landscape patterns derived from these two sources of disturbance have, however, raised concerns that the way forest harvesting has been dispersed is potentially shifting patterns away from the natural range. In the context of natural disturbance-based management, we used a spatially explicit model designed to capture general fire regimes in order to quantify temporal variability associated with regenerating areas (burnt areas of 25 years or younger), and to develop strategic objectives for harvest agglomeration sizes and dispersion. We first evaluated temporal variability in the proportion of stands younger than 100 years (assumed to be even-aged stands) for various fire regimes (seven fire cycles: 50 to 400 years, and three mean fires sizes: 3000, 15 000 and 60 000 ha). Secondly, we quantified the size distribution and dispersion of regenerating areas for each fire regime. As expected by theoretical fire frequencies and size distributions, the importance of even-aged stands at the forest management unit level was found to decrease with longer fire cycles. However, the temporal variability associated with these proportions is shown to increase with mean fire size. It was also observed that the size distribution and dispersion of regenerating areas was primarily influenced by mean fire size. Based on these observations, natural disturbance-based management objectives were formulated, providing guidelines on harvest agglomeration size and dispersion.

**Key words:** temporal variability, boreal forest, fire regime, forest management, age distribution, fire size distribution, clearcut agglomeration size distribution

**RÉSUMÉ**

Le rajeunissement de la forêt boréale canadienne est maintenant d'avantage lié aux activités forestières qu'à l'action des feux de forêt. Les différences majeures dans les patrons spatiaux créés par ces régimes de perturbations suscitent donc des inquiétudes quant aux pratiques forestières actuelles. Dans le cadre d'une approche d'aménagement écosystémique qui s'inspire des perturbations naturelles, nous proposons d'analyser la variation temporelle des patrons d'aire en régénération créés par le feu (brûlis de 25 ans ou moins) et d'élaborer des objectifs stratégiques d'espacement et de taille des chantiers de coupe. Les variations dans la proportion de forêt équienne (peuplements de moins de 100 ans) ont d'abord été évaluées et comparées à des valeurs attendues pour plusieurs régimes de feu (sept cycles de feux : 50 à 400 ans, et trois tailles moyennes : 3000, 15 000 et 60 000 ha). Ensuite, la variabilité temporelle liée à la distribution de taille et à la dispersion des aires en régénération a été évaluée. Telle qu'attendue la proportion de forêt de moins de 100 ans est inversement proportionnelle à la longueur du cycle de feu. Cependant, la variabilité temporelle associée à cette proportion serait davantage influencée par la taille moyenne des feux. La taille moyenne des feux serait aussi le principal agent qui influence la taille et l'espacement des aires en régénération. Suite à ces observations nous proposons des lignes directrices d'aménagement qui précisent les proportions de forêt aménagée de façon équienne, leur distribution quant à la superficie des chantiers de coupe et leur dispersion ou espacement minimal.

**Mots clés :** variabilité temporelle, forêt boréale, régime de feu, aménagement forestier, distribution d'âge des peuplements, distribution de taille des feux, distribution de taille des chantiers de coupes

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## Introduction

Industrial forest harvesting activities are now replacing wildfires as the main stand-replacing disturbance in the Canadian boreal forest (Mladenoff *et al.* 1993, Delong and Tanner 1996, Perera and Baldwin 2000, Schroeder and Perera 2002, Perron 2003). The differences in the disturbance rate of human industrial activities and wildfire, and divergences in their patterns, have raised concerns about the way we have historically managed the forest and how we should manage it to maintain natural forest processes and patterns (Godron and Forman 1983, Franklin and Forman 1987, Hessburg *et al.* 1999, Spies and Turner 1999, Seymour *et al.* 2002).

Wildfires are generally considered to be a stochastic process, mainly driven by weather condition, fuel availability, soil type, forest type and age, topography, and presence of natural fire breaks (Johnson 1992, Larsen 1997, Johnson *et al.* 1998, Kafka *et al.* 2001, Lefort *et al.* 2003, Bergeron *et al.* 2004b). The area affected by fire events is considered to be highly variable in time and fire histories have shown a wide range of disturbed area sizes (2 ha to more than 100 000 ha) (DeLong and Tanner 1996, Thompson 2000, Canadian Forest Service 2002, Bergeron *et al.* 2004b). It is also suggested that, independently of the fire cycle, fire size distribution influences landscape mosaic characteristics (Bergeron *et al.* 2004b). In contrast, harvesting activities are the results of detailed planning processes that focus on the next five to 25 years. These processes tend to generally maximize the rate of sustainable timber extraction ($m^3$/year), while considering a limited number of other forest values (e.g., visuals, wildlife habitat). Harvest rules, usually dictated by federal, state or provincial governments, define among other things the size and dispersion constraints of cutovers as well as the amount of forest (volume or area) that can be harvested per year. Legislation that presents few constraints on cutover agglomeration has led to a cutting front that leaves behind large homogenous regenerating areas with little habitat for edge/core sensitive or mature-and old-forest-dependant species (Imbeau *et al.* 1999, Imbeau and Desrochers 2002, Drapeau *et al.* 2003, Perron 2003). In regions where legislation favours small cutovers and high adjacency constraints, spatial heterogeneity and landscape fragmentation have increased and forest interior integrity has decreased (Franklin and Forman 1987, Wallin *et al.* 1994, DeLong and Tanner 1996, Gustafson and Crow 1996, Cissel *et al.* 1999, Betts *et al.* 2003).

One proposed avenue to limit the negative impacts of forest activities on the ecosystem is the use of natural disturbance-based management as an alternative to traditional forest management (Bergeron *et al.* 1999, Burton *et al.* 1999, Hunter 1999, Perera *et al.* 2004a). Supported by a strong knowledge of historic disturbance regimes, natural disturbance-based management encourages the use of harvest treatments and/or harvest scheduling that restore or maintain aspects of historic variability at stand and landscape levels without completely excluding timber exploitation (Bergeron *et al.* 1999, 2002; Burton *et al.* 1999; Hunter 1999). Based on fire cycle estimates, these approaches present a general description of the natural forest dynamic; they prescribe target proportions of different forest types or age-cohort states to be maintained, and they often suggest potential treatments or rotation times that can be used to maintain these forest types or age-cohort states. These approaches, however, mostly focus on a static view of equilibrium conditions, and so do not help to establish an exhaustive range of temporal variability within which strategic decisions and social compromises can be made. In addition, due to their non-spatial character, they do not establish general guidelines concerning the pattern of even-aged regenerating areas in space and time. Within the paradigm of natural disturbance-based management, guidance is needed on the level at which harvest should be aggregated in time (spatial constraint) and the agglomeration size distribution over a rotation time period.

Great importance is usually attributed to the maintenance over time of a given mean proportion of forest older than 100 years in a managed area (Bergeron *et al.* 1999). As forest management increases the proportion of even-aged stands, we focus in this paper on what happens with its counterpart, stands younger than 100 years. Hence, we specifically wish to explore the effect of mean fire size on the temporal variability in the proportion of forest younger than 100 years. In a second step, we look at the influence of fire cycle length and mean fire size on the size distribution and the spatial dispersion of regenerating agglomerations. Finally, we propose flexible harvest prescriptions on harvest agglomeration size with associated dispersion constraints that allow enough leeway at the landscape level to satisfy some compromises between social, ecological and economic values.

## Methods

### Fire model

In order to achieve the previously stipulated goals, we needed to use a simulation model. Some studies have used complex spatially explicit simulation models to address the question of natural landscape variability (Baker *et al.* 1991, Mladenoff and He 1999, Klenner *et al.* 2000, Keane *et al.* 2002, Perera *et al.* 2003, Perera *et al.* 2004b). However, implementation of these models requires substantial effort to calibrate fire behaviour and landscape characteristics to a particular region. The conclusions or guidelines obtained from these models are therefore often limited to the studied territory and are inherent to the initial state. These models are quite powerful and allow management scenarios to be assessed dynamically at a regional scale, but they are too complex and specific to be useful for establishing general guidelines on temporal variability and spatial constraints that aim to be applied to boreal regions subject to different disturbance regimes. Several other tools are available to explore historical variability in size distribution of burned areas at a large scale, but most have limitations and are analysed over a restrained time period. For instance, fire history maps, based on the age of live trees, fire scars, soil charcoal and aerial photography interpretation, are commonly used to evaluate fire regime characteristics (Johnson 1992, Lertzman *et al.* 2002, Bergeron *et al.* 2004b). This approach usually gives a good approximation of the fire cycle or forest mean age but presents limitations for evaluating fire size distribution and dispersion (i.e., landscape patterns). National and provincial records of recent fire events give us more accurate information on fire size distribution and dispersion (Direction de la conservation des forêts 2000, Canadian Forest Service 2002, Alberta Forest Protection 2004). However, the short record length and the influence of humans on fire patterns limit the use of these records for a direct evaluation of natural variability. Nevertheless, fire regime indicators can be established from fire history maps and fire records with reasonable reliability, and can be used to seed simulation routines that can provide replication, unlimited recording time periods and a greater control over parameters. In this context, simulation models can provide a dynamic projection of possible conditions based on fire history information, providing a method to make inference. Therefore, we chose a simulation approach based on a simple fire/growth model that allowed us to apply fire history results available across the Canadian boreal region to analyse spatiotemporal variability of size and dispersion of regenerating agglomerations. To define *agglomeration*, we retained a cutoff of 25 years, i.e., contiguous burnt areas (that can result from different fire events) younger than or equal to 25 years old were clustered before calculating size and nearest-neighbour distance on simulated maps.

In order to explore the variability in size, occurrence and dispersion of burned areas under different fire regimes we implemented a fire model using SELES (Spatially Explicit Landscape Event Simulator) modelling environment (Fall and Fall 2001). SELES is a tool that provides a high-level declarative modelling language to specify key processes at the landscape scale in order to create spatially explicit grid-based models. One advantage of using SELES to build our model instead of using an existing model, such as DISPATCH (Baker *et al.* 1991), LANDIS (Mladenoff and He 1999) or TELSA (Kurz *et al.* 2000), lies in the ability to integrate the degree of complexity that we judge appropriate to the question (i.e., we only needed to include the minimum level of detail and complexity required to address our objectives).

Since our objective is to establish management guidelines that are general enough to cover a wide range of situations with the minimum number of parameters that are available in most boreal areas, our model consists of two sub-models and depends on two key fire regime parameters—length of fire cycle and mean fire size. These parameters are recognized in the literature to describe fire regimes reasonably at the landscape scale and we assumed that they integrated the regional influences of topography, soil deposit, species and climate. We also assumed that climate remains stable during the simulation period (a reasonable assumption since our goal is to derive system understanding not make predictions).

The first sub-model progressively ages forest stands on an annual time step until an upper limit of 350 years. The age limit was fixed to help data compilation even if forest mean age could be slightly underestimated in the case of long fire cycles (although forest inventory information is rarely accurate for stands older than 250 years). For simplicity and generality, every cell in the landscape was presumed to be forested.

The second sub-model drives disturbance events, which set the stand ages back to zero) and depends on the following fire parameters. First, based on the territory size (*Extent,* see below*)*, and on the *fire cycle* and the *mean fire size* simulated during the run, the number of fire events by year is randomly chosen from a Poisson distribution (Baker *et al.* 1991, Boychuk *et al.* 1997, Wimberly *et al.* 2000) where $\mu$ is assumed to be the annual average fire occurrence and is equal to:

$$[1]\ \ FireOccurence = \frac{Extent(ha)}{MeanFireSize(ha) * FireCycle(yr)}$$

Second, the size of each fire event is randomly selected from a negative exponential distribution based on the mean fire size. Although other distributions could potentially fit the empirical fire size distribution (e.g., lognormal), the negative exponential was preferred because it is largely accepted in the boreal forest and has been recently used elsewhere (Baker *et al.* 1991, Boychuk *et al.* 1997, Wimberly *et al.* 2000), and it only requires a single parameter to estimate. Based on the premise of Van Wagner (1978) that stands burn independently of their age, fire start locations are randomly chosen over the entire grid (whole territory). Once initiated, a modelled fire randomly spreads to one or two of the eight neighbouring cells that have not burnt during the event time step. Once initiated, a fire will spread until the chosen fire event size is reached. The shape of the fire was not directly controlled, but the alternate spreading to one or two cells of the eight neighbours avoids creation of circular shape. Compared visually with empirical data, fire shapes appear realistic.

#### Fire regime parameters

This study used fire event registers from different Canadian boreal regions from northern Alberta to south-eastern Labrador (Fig. 1). Because there is no long-term forest fire history that covers the entire area, we selected the most representative regional studies available to fix a range of fire regime parameters that characterise the Canadian boreal forest (Table 1). Based on these studies, twenty-one different fire regimes have been defined and selected for the simulation. They are composed of seven fire cycles varying from 50 to 400 years and three mean fire sizes: 60 000, 15 000 and 3000 ha. Mean fire sizes in Table 1 have been estimated in accordance to cumulative size distributions of the national and provincial recent fire records (Direction de la conservation des forêts 2000, Canadian Forest Service 2002, Alberta Forest Protection 2004), assuming the size distributions followed a exponential negative (Boychuk *et al.* 1997, Wimberly *et al.* 2000).

#### Simulations and analyses

The simulations were conducted using a 10-ha cell resolution on a grid of 548 × 100 by 548 cells. This size was chosen as it was the smallest square grid that could be used to represent a territory of at least a 30 000 km$^2$. This size limits scale and boundary effects by keeping a ratio greater than 50:1 between map extent and the mean fire size used in the simulation (Shugart and West 1981). This has been found to be large enough to capture the maximum size that can be reached by a fire event, with any reasonable likelihood and to limit the influence of large fire events on overall stand age structure. Each cell represents a homogenous 10-ha area of the landscape; stands emerge as adjacent cells with the same characteristics. One hundred replicates of each fire regime scenario were simulated for a period of 1000 years to ensure mean stand age stabilisation (at least twice the fire cycle length; Baker 1995). In order to limit effects from stand age legacy, each simulation was started with a blank sheet having stand age set to zero. Since we assume no dependence between stand age and burning vulnerability, starting the landscape at

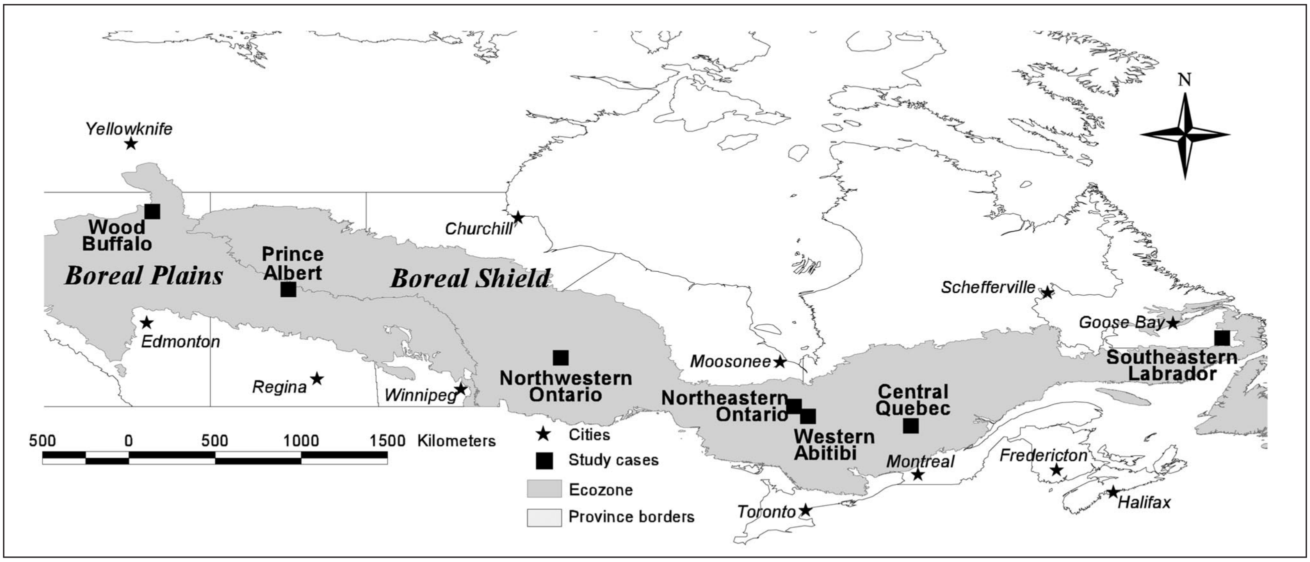


**Fig. 1.** Locations of study sites and representative boreal regions.

**Table 1. Fire regime characteristics of representative regions of the Canadian boreal forest, presented in a west-to-east direction (data on fire cycles have been extracted from Bergeron et al. 2004b and Bergeron et al. 2001).**

| Study case | Reference | Study area ($km^2$) | Fire mean size (ha)[a] | Fire cycle (time period) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Past | | Current[c] | |
| North Alberta | Larson (1997) | 44 807 | 61 030 | 71 | (1860–1989) | 151 | (1959–1989) |
| Central Saskatchewan | Weir *et al.* (2000) | 3 461 | 58 608 | 97 | (< 1890) | 213 | (1959–1989) |
| Northwestern Ontario | Suffling *et al.* (1982) | 24 000 | 58 370 | 52 | (~ 1870–1974) | 217 | (1959–1989) |
| Northeastern Ontario | Lefort *et al.* (2003) | 8 245 | 1 224 | 172 | (1740–1998) | 521 | (1920–1999) |
| Northwestern Abitibi (Quebec) | Bergeron *et al.* (2004b, 2001) | 7 500 | 17 657 | 135 | (1850–1920) | 398 | (> 1920) |
| Southwestern Abitibi (Quebec) | | 7 500 | 969 | 111 | (1850–1920) | 326 | (> 1920) |
| Central Quebec[b] | Lesieur *et al.* (2002) | 3 844 | – | 123 | (1850–1920) | 273 | (1920–1999) |
| Southern–eastern Labrador | Foster (1983) | 48 500 | 20 289 | 500 | (1870–1975) | 2639 | (1959–1989) |

[a]Mean fire sizes have been estimated from the Canadian large fire database or from the provincial database when available (Northern Alberta and Abitibi). Note: fires < 200 ha are not included and mean sizes have been evaluated on the basis of the study area size and approximate location.
[b]The limited number of fire events recorded in this area during the last 80 years makes evaluation of the mean fire size difficult.
[c]Fire cycles established for the time period 1959 to1989, have been evaluated from the Canadian large fire database (LFDB) (See Bergeron *et al.* 2004a).

age zero will not affect the effective fire size distribution, burned area dispersion, or long-term stand age structure.

In order to establish guidelines for even-aged or harvest agglomeration size distributions, maps of the cumulative areas burned over a period of 25 years were saved every 25 years. This was done during the last 200 years of the simulation for a subset of 20 runs out of the 100 (180 replicates). A period of 25 years since the last stand replacing disturbance was assumed to be sufficient for boreal stands to reach more than 4 m in height, at which time there is a recovery of forest characteristics such as canopy closure and partial wildlife habitat recovery (Imbeau *et al.* 1999, Jacqmain 2003). Finally, at the end of each run the forest age structure was recorded in 10-year classes and compared to the null model, i.e., the aspatial proportion of forest that would be expected in each age class if all stands had were equally likely to burn regardless of age (Van Wagner 1978). This comparison allows us to evaluate the model output, i.e., to make sure that the simulation time and extent are adequate to allow equilibrium in mean age and to limit the border effect before looking at the temporal variability and dispersion.

*A posteriori* analysis of the extracted maps was used to evaluate the size distribution of regenerating areas. For each map, regenerating agglomerations were categorized into three size classes: small (5000 ha or less), medium (between 5000 and 20 000 ha) and large (greater than 20 000 ha). Mean nearest-neighbour distances between adjacent regenerating areas of same size class or without consideration of size classes were both computed for each map. For these calculations, maps that did not contain any young patches were not used. Thus, for each fire regime we calculated, by class size and overall, the mean, minimum, and 10$^{th}$ and 90$^{th}$ percentile

Table 2. Spacing constraints (km) of harvest agglomerations (n= maximal and minimal number of maps analysed; the minimal value has been noted if it was different).

| Mean fire size (ha) | Harvest agglomeration size (ha) | Fire cycle (years) 50 | 100 | 150 | 200 | 250 | 300 | 400 |
|---|---|---|---|---|---|---|---|---|
| | | Mean distance (minimum allowed[a])size (ha) | | | | | | |
| 3 000 | Small (< 5 000 ha) | 6.2 (5.0) | 5.3 (4.4) | 5.9 (4.9) | 6.7 (5.5) | 7.4 (6.1) | 8.4 (6.9) | 9.8 (7.8) |
| | Medium (between 5 000 and 10 000 ha) | 20.9 (11.9) | 12.4 (8.4) | 14.2 (9.3) | 17.2 (11.2) | 18.7 (12.6) | 21.5 (13.1) | 27.6 (15.1) |
| | Large (> 10 000 ha) | This agglomeration size should not be allowed (see table 3) | | | | | | |
| | Any size | 1.3 (1.2) | 2.3 (2.0) | 3.3 (2.8) | 4.1 (3.5) | 4.9 (4.1) | 5.7 (4.7) | 7.0 (5.7) |
| | n | 180 | 180 | 180 | 180 | 180 | 180 | 180 |
| 15 000 | Small (< 5 000 ha) | 29.8 (17.1) | 31.5 (19.7) | 39.3 (21.8) | 44.9 (20.9) | 49.2 (25.0) | 54.4 (25.1) | 58.9 (26.1) |
| | Medium (between 5 000 and 10 000 ha) | 45.5 (18.0) | 43.6 (19.2) | 50.4 (24.5) | 55.5 (22.9) | 55.3 (20.3) | 56.8 (24.4) | 58.3 (24.8) |
| | Large (> 10 000 ha) | 4.1 (2.4) | 8.6 (5.3) | 12.4 (7.2) | 16.9 (9.2) | 20.5 (11.1) | 25.5 (12.8) | 29.8 (15.0) |
| | Any size | 3.3 (2.3) | 6.1 (4.4) | 8.6 (6.1) | 11.2 (7.4) | 13.2 (8.5) | 15.1 (9.7) | 19.4 (11.7) |
| | n | 180–165 | 180–167 | 180–171 | 180–158 | 180–141 | 180–132 | 180–121 |
| 60 000 | Small (< 5 000 ha) | Rare events like these should represent a maximal dispersion, as a precautionary measure to ensure that the "Any size" statistic is respected | | | | | | |
| | Medium (between 5 000 and 10 000 ha) | 62.4 (13.5) | 68.6 (19.2) | 63.6 (30.8) | 65.1 (32.1) | | as above | |
| | Large (> 10 000 ha) | 9.3 (4.3) | 17.8 (7.9) | 25.0 (10.9) | 31.6 (13.1) | 38.7 (14.8) | 41.7 (13.6) | 48.7 (17.7) |
| | Any size | 8.5 (4.4) | 15.6 (7.7) | 23.6 (11.0) | 28.7 (12.7) | 34.3 (14.0) | 38.1 (15.2) | 46.9 (17.6) |
| | n | 180–33 | 180–19 | 180–15 | 178–10 | 176–169 | 166–158 | 140–129 |

[a]The lower limit is based on the $10^{th}$ percentile.

edge-to-edge distances to adjacent areas (McGarigal and Marks 1995). Note that for some fire cycle and mean fire size combinations, some regenerating area size classes were uncommon and replication was consequently low (see Table 2). In these cases no guidelines have been provided as the events were considered too rare, limiting our ability to evaluate their temporal variability.

## Results and Discussion

### Temporal variability in the relative proportion of even-aged stands and regenerating areas

The mean proportions of forest stands younger than 25 and 100 years obtained from our simulation and from the null model for the different combinations of fire cycle lengths and mean fire sizes are presented in Fig. 2. Within a forest management unit (FMU) the proportion of stands regenerating (< 25 years) and the proportion of stands < 100 years were together considered as the allowable area to be managed with an even-aged strategy. As expected, and considering the stochastic nature of the model, the figure shows that the proportions obtained in our simulation are similar to the values predicted with the null model, i.e., if all stands are equally likely to burn, regardless of age. As predicted (Bergeron *et al.* 1999), the proportion of even-aged post-fire (i.e., < 100 years) forest decreases with elongation of the fire cycle. The even-aged proportion varied from about 86% to 24% as fire cycle lengthened from 50 to 400 years. Similarly, the proportion in regenerating areas (forest younger than 25 years old) varied from 39% to 6% as the fire cycle lengthened. While changes in mean fire size have no influence on age class structure, it does have a large influence on temporal variability as expressed by the $10^{th}$ and $90^{th}$ percentile (Fig. 2). We observe that for the same fire cycle, a fire regime characterized by a mean fire size of 60 000 ha shows a temporal fluctuation about four times greater than one with a 3000-ha mean, and about two times greater than one with a 15 000-ha mean. Thus, forest management unit size within should ideally reflect fire regime characteristics, such as mean fire size, to limit undesirable large fluctuations.

### Size class distribution of regenerating areas

The analyses of the burned agglomerations of 25 years old and younger allowed the evaluation of the occurrence of regenerating areas by size class (Fig. 3). To keep the figure simple and succinct only the fire cycles of 100 and 300 years have been illustrated (results for the other fire regimes are found in Table 3). The results show that size class distribution of regenerating areas is primarily a function of the mean fire size with a slight influence of the fire cycle. Without consideration of the fire cycle length, the maximum sizes of regenerating areas during the simulations were 647 696 ha, 795 523 ha and 1 394 687 ha for the 3000- 15 000- and 60

Table 3. Proportion (%) of the even-aged part of the FMU that should be harvested in different size classes

| Mean fire size (ha) | Harvest agglomeration size (ha) | Fire cycle (years) 50 | 100 | 150 | 200 | 250 | 300 | 400 |
|---|---|---|---|---|---|---|---|---|
| | | Mean proportion (maximum allowed[a]) | | | | | | |
| 3 000 | 0–2 000 | 2.8 (3.6) | 6.4 (8.2) | 8.4 (10.7) | 9.6 (13.2) | 10.6 (14.9) | 10.9 (15.3) | 11.6 (16.1) |
| | 2 000–5 000 | 4.6 (6.4) | 13.6 (17.7) | 19.3 (24.4) | 21.6 (28.1) | 25.1 (32.0) | 25.5 (33.8) | 28.8 (38.2) |
| | 5 000–10000 | 92.7 (94.5) | 80.0 (84.6) | 72.3 (78.4) | 68.8 (76.1) | 64.1 (72.6) | 63.6 (72.4) | 59.6 (70.5) |
| | Max size reached (ha) | 647 696 | 139 264 | 84 809 | 72 933 | 54 505 | 47 372 | 39 888 |
| 15 000 | 0–2 000 | 0.4 (0.7) | 0.6 (1.0) | 0.6 (1.3) | 0.8 (1.6) | 0.7 (1.4) | 0.9 (2.0) | 0.8 (1.8) |
| | 2 000–5 000 | 1.2 (2.0) | 2.4 (4.2) | 2.7 (4.9) | 3.1 (6.1) | 3.4 (6.5) | 3.6 (7.2) | 3.7 (7.3) |
| | 5 000–10 000 | 2.7 (4.8) | 5.5 (9.3) | 7.3 (12.3) | 7.9 (12.9) | 8.7 (15.1) | 9.6 (19.8) | 9.6 (18.4) |
| | 10 000–20 000 | 5.8 (10.0) | 13.2 (21.9) | 16.9 (29.2) | 19.2 (33.7) | 19.0 (33.9) | 22.3 (38.2) | 22.6 (45.1) |
| | 20 000–50 000 | 89.8 (94.8) | 78.4 (87.4) | 72.5 (85.8) | 69.0 (84.7) | 68.2 (84.6) | 63.6 (84.4) | 63.3 (84.8) |
| | Max size reached (ha) | 795 523 | 274 7855 | 202 062 | 181 013 | 199 191 | 151 209 | 242 191 |
| 60 000 | 0–2 000 | 0 (0.2) | 0.1 (0.3) | 0.1 (0.2) | 0.1 (0.4) | 0.1 (0.4) | 0.1 (0.2) | 0.1 (0) |
| | 2 000–5 000 | 0.2 (0.5) | 0.3 (0.9) | 0.2 (0.7) | 0.6 (1.9) | 0.7 (1.6) | 0.4 (1.3) | 0.7 (1.4) |
| | 5 000–10 000 | 0.5 (1.4) | 0.8 (2.2) | 1.0 (3.4) | 1.6 (4.5) | 1.7 (4.2) | 1.6 (5.1) | 1.8 (4.3) |
| | 10 000–20 000 | 1.4 (3.6) | 2.3 (5.9) | 3.1 (8.8) | 5.7 (12.9) | 4.6 (9.9) | 4.8 (11.7) | 4.8 (13.9) |
| | 20 000–50 000 | 6.2 (13.7) | 11.5 (24.6) | 14.7 (36.3) | 20.1 (51.9) | 19.1 (56.6) | 18.6 (56.6) | 14.4 (45.1) |
| | 50 000–100 000 | 91.7 (97.9) | 85.0 (97.1) | 80.9 (97.8) | 70.8 (96.7) | 71.6 (98.7) | 66.7 (98.6) | 55.9 (99.7) |
| | Max size reached (ha) | 1 394 687 | 1 234 914 | 687 824 | 561 216 | 478 759 | 644 694 | 451 886 |
| | Predicted even-aged management proportions (%) if burn risk is equal in each stand regardless of age | 86.5 | 63.0 | 48.4 | 39.1 | 32.8 | 28.2 | 22.0 |

[a]The upper limit of the distribution is based on the 90th percentile.

000-a mean fire sizes respectively (Table 3). The majority of the regenerating areas are observed in the size classes from 1000 to 10 000 for the 3000-ha mean fire size fire regime, in the size classes from 10 000 to 100 000 for the 15 000-ha regime, and in the 100 000 and > 100 000 size classes for the 60 000-ha regime. The lowest occurrences are almost always observed in the smallest size classes for all of the simulated regimes. Those results are unexpected and contrary to observed fire size distributions, where many small fires and a few large fires are observed (Boychuk *et al.* 1997, Wimberly *et al.* 2000, Bergeron *et al.* 2004b). These results suggest that at the time scale of 25 years, most of the small fire events are eclipsed by a large fire event. Fig. 3 also illustrates the proportion represented by each size class of the total area in regeneration. It appears that size class distribution of the area regenerating is also a function of the mean fire size and of the fire cycle. Burned agglomerations between 1000 and 100 000, 10 000 and 100 000, and larger than 100 000 ha were found to be responsible for more than 50% of the area regenerating under fire regimes characterized by a 3000-, 15 000- and 60 000-ha mean fire size, respectively. Again, based on fire landscape studies, it was expected that the greater size classes would represent the larger proportion of the area burned (Boychuk *et al.* 1997, Wimberly *et al.* 2000, Bergeron *et al.* 2004b). Therefore, it seems that the size of regenerating areas created by agglomerations of fires is larger than would be expected if only individual fires are considered. The agglomeration sizes fluctuate around the mean fire size, which largely influences the size class distribution. The variability associated with the occurrence and distribution of the area regenerating areas among size class is also expressed in Fig. 3. The fluctuations observed between the fire regimes that were simulated are a function of the mean fire size.

### Spacing of the regenerating areas

Given that mean fire size and fire cycle influence the size distribution of the regenerating areas, it becomes of interest to evaluate their influence on the nearest-neighbour distance between regenerating areas in a FMU. Fig. 4 shows the mean nearest-neighbour distance between adjacent small (less than 5000 ha), medium (between 5000 and 10 000 ha), large (greater than 10 000 ha) and all regenerating area sizes combined. Fig. 4 also shows the 10th and 90th percentile as a measurement of temporal variability. The 10th percentile was considered to be the ultimate minimal distance that should constrain the spatial distribution of agglomerated regenerating areas. In regards to fire regime parameters, three main trends were observed. First, mean nearest-neighbour distance between regenerating areas increased with fire cycle, and minimum distance (10th percentile) between areas was on average greater when size classes were rare in a given fire regime. For instance, in the case of a long fire cycle characterized by a

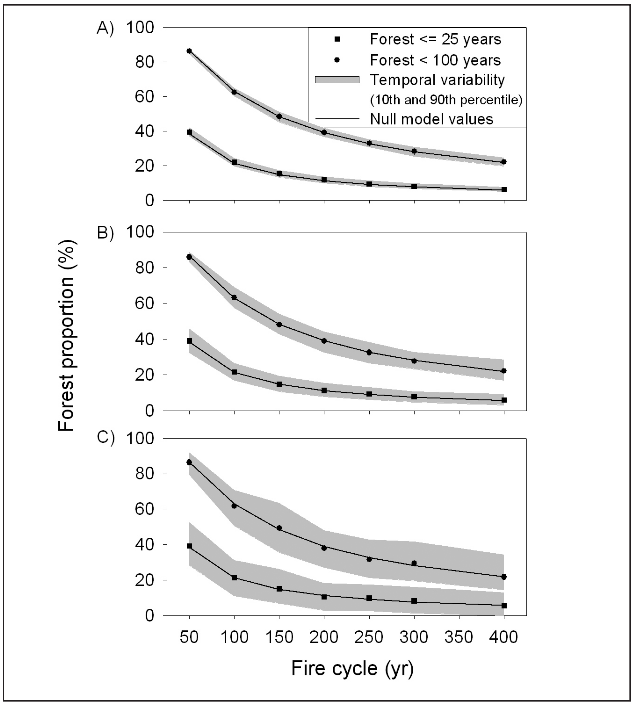


**Fig. 2.** Comparison of mean forest proportions (%) in even-aged (< 100 years) and regenerating areas (≤ 25 years) expected from the null model (i.e., if burn risk is equal for all stands regardless of age) and from the spatial explicit model with different fire regimes: A) fire regimes controlled by a 3000-ha mean fire size, B) 15 000-ha mean fire size and C) 60 000-ha mean fire size. The 10$^{th}$ and 90$^{th}$ percentile indicators of the natural variability are illustrated by the grey zone (n = 100 for the even-aged stand and n = 180 for the regenerating areas).

small 3000-ha mean fire size, large regenerating areas are rare and, consequently have the greatest nearest neighbour distances. In contrast, under a regime with a 60 000-ha mean fire size, small and medium regenerating areas are the rare events and they present the maximal dispersion. Under this latter regime, dispersion of small and medium regenerating areas are in some cases considered to be infinite due to rarity. This does not imply that small individual fires are not generated during the simulation, but rather that they are rare and/or coalesce into larger patches when areas burnt are combined over 25 years as suggested by the distribution of the regenerating areas (Fig. 3). The second trend illustrates that when considering dispersion by size class, the mean nearest-neighbour distance between small or medium areas increases more or less with mean fire size, as does the associated temporal variability. In contrast, large areas showed a slight decrease of the mean nearest-neighbour distance with mean fire size increment. The mean nearest-neighbour distance and the variability seemed to be related to rarity of certain size classes under certain fire regimes (e.g., large areas under 3000-ha mean fire size regimes, small and medium areas under 60 000-ha mean fire size regimes). The third trend illustrates that regardless of the size of the adjacent areas, distances between regenerating areas, as well as the range of variability, increase with fire cycle length and mean fire size. Trends in the minimum nearest-neighbour distances are not as clear as in the means. However, variability in those values seems to be related to rarity of certain size classes and minimal distances seem to mainly increase with mean fire size and fire cycle length. Thus, constraints on minimal distances between disturbed areas are likely harder to achieve in regions where the fire regime is characterized by large fires and a long fire cycle.

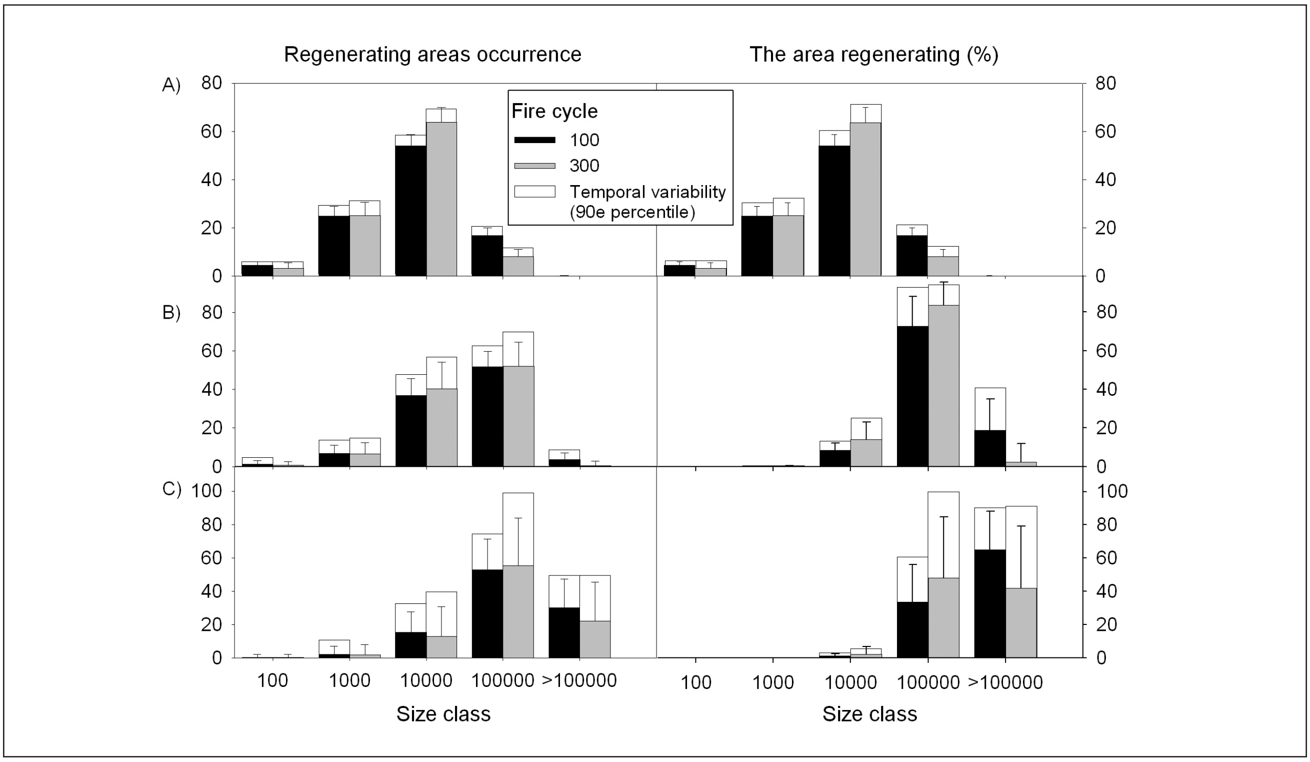


**Fig. 3.** Mean number of regenerating areas by size class (right) and mean proportion represented by each size class of the total area in regeneration (left) for 100 and 300 fire cycle regimes (A: fire regimes controlled by a 3000-ha mean fire size, B: 15 000-ha mean fire size and C: 60 000-ha mean fire size). Regenerating areas have been compiled for a 30 000 km$^2$ extent (n = 180).

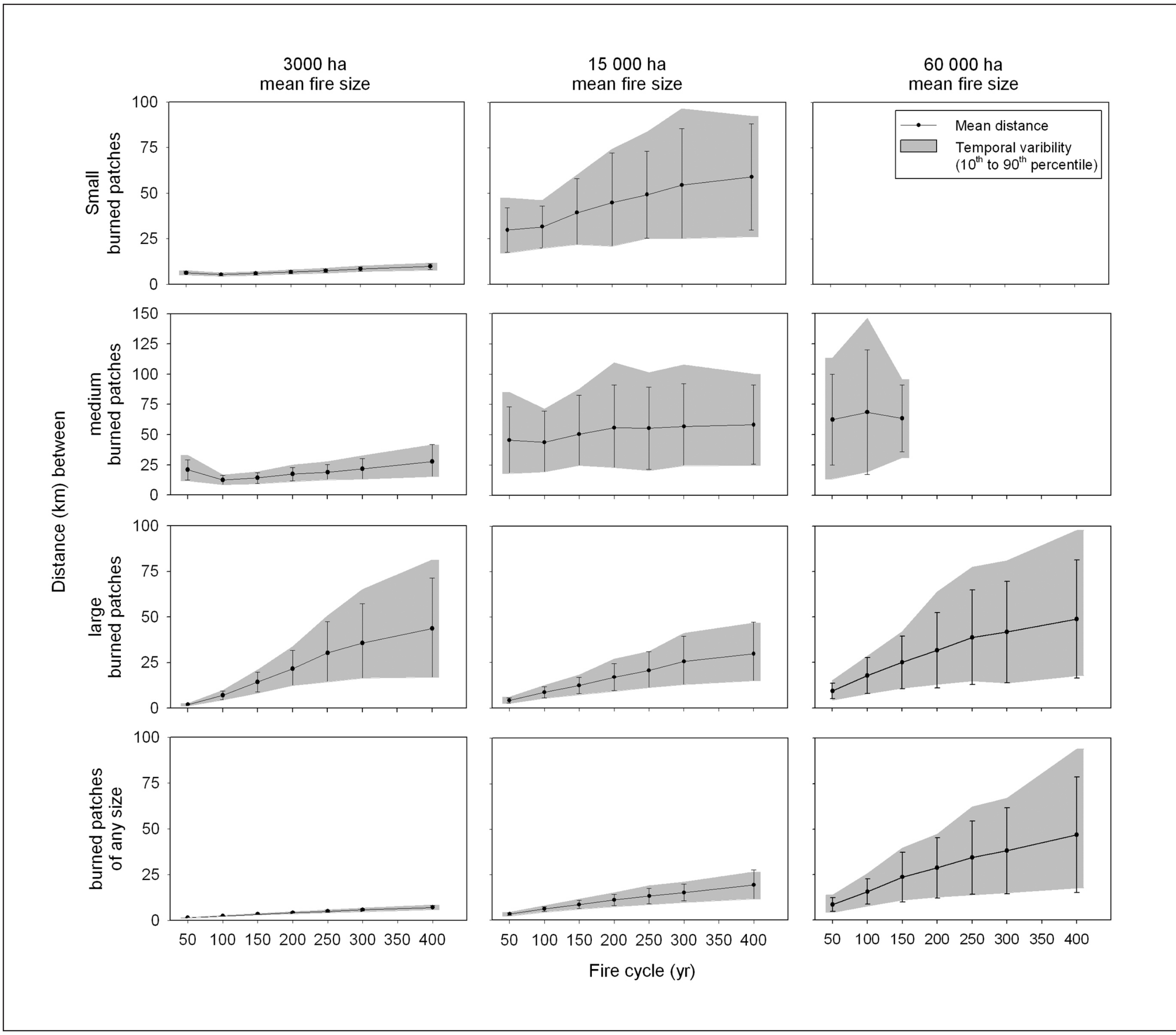


**Fig. 4.** Distance (km) to adjacent regenerating area (burnt areas of 25 years old or less) for different fire regimes. Mean minimum distances are illustrated by area size class combinations, small: area less than 5000 ha in size, medium: between 5000 ha and 20 000 ha, large: greater than 20 000 ha, any size: distance between areas no matter the areas size. Mean smaller distances are illustrated by black solid lines, standard deviation by "T" bars and the differences between $10^{th}$ and $90^{th}$ percentile by the grey zone (n varied from 44 to 180).

**Forest management implications**

The significant influence of fire cycle length and mean fire size on landscape structural attributes has been reported elsewhere in the literature (Baker 1995; Bergeron *et al.* 1999, 2004b; Spies and Turner 1999; Thompson 2000; Keane *et al.* 2002; Seymour *et al.* 2002; Perera *et al.* 2004b). The importance of establishing management objectives in accordance with the historical disturbance regime and regional context has been also expressed (Delong and Tanner 1996, Cissel *et al.* 1999, Landres *et al.* 1999). A brief look across Canadian boreal regions (Table 1) illustrates the importance of including variability in our practices. Combining observations from Table 1 with the results of Fig. 2 shows that, due to a shorter fire cycle, western Canadian forests are expected to include a larger proportion of even-aged younger stands than eastern regions, and could more easily accommodate a system dominated by even-aged management (Fig. 2). We also note that southeastern Labrador presents an extreme case (with a fire cycle estimated at 500 years) in which more than 75% of the stands are expected to exceed 100 years in age. In that case, a strict even-aged management approach is not likely to sustain ecological values, and alternative silvicultural treatments as well as conservation strategies should be considered to maintain old forest attributes (Kneeshaw and Gauthier 2003).

Beyond the general influence of fire cycle on landscape patterns, it was observed by Bergeron *et al.* (2004b) that two regions showing similar fire cycles may differ in terms of mean fire size. In a context of natural disturbance-based management, this divergence leads to various management implications. First, as expressed in Fig. 2, for the same-sized landscape, the temporal variation in the proportion of forest in even-aged classes will be more restrained in an area characterized by small fires, and higher under fire regimes with larger fires. This dependency between spatial scale and fire disturbance regime has also been observed by Boychuk *et al.* (1997). Consequently, in the boreal forest of southwestern Quebec, where fire events are usually smaller, we suspect that in a reasonably small forest management unit, a forest age structure without large fluctuations in the proportion of the forest younger than 100 years should be maintained. In contrast, in the boreal forest of northwestern Quebec where larger fires occur, larger forest management units would ideally be used to maintain forest age structure. Based on our results, and as a default when better information on optimal size is unavailable, a limit on fluctuations of the mean proportion of even-aged forest to ± 6% in regions where the fire regime is driven by a mean fire size of about 3000 ha, to ± 15% for regions affected by a mean fire size of about 15 000 ha, and to ± 30% for regions with a mean fire size of about 60 000 ha, as a precautionary principal. Second, as suggested in Fig. 3 and 4, the size distribution of the regenerating areas and their dispersion should differ between two regions that have different mean fire sizes such as southwestern and northwestern Abitibi (Table 1). For instance, in southwestern Abitibi we should plan the majority of the regenerating forests in areas less than 10 000 ha in size whereas in northwestern Abitibi, harvest treatment agglomerations should create regenerating areas that vary between 10 000 to 100 000 ha in size (Fig. 3). Similarly, mean dispersion constraints between small regenerating areas (less than 5000 ha) should be around 5 km in the south, which is about six times closer than the distance that should be targeted in the north (an average of 31 km).

To help managers improve their even-aged management strategies and guide them through the establishment of strategic management objectives based on temporal variability, we suggest using Tables 2 and 3 as limits within which management targets should be established. These tables summarize Fig. 2, 3 and 4, which were derived based on fire history information across boreal Canada, and have been designed to be used with relevant historical fire parameters. For areas characterized by mean fire sizes or fire cycles not represented, the nearest values could be used or interpolated from other regimes in the tables. Furthermore, to take into account catastrophic events and possible interactions between cutting activities and uncontrolled fire events (Klenner *et al.* 2000, Fall *et al.* 2004), we have truncated the harvest agglomeration size distribution to 100 000 ha for the fire regime controlled by 60 000-ha mean fire size and to about the 90$^{th}$ percentile of the fire size distribution for regimes with 3000-ha and 15 000-ha mean fire sizes. Resulting maximum class sizes are 5000–10 000 ha and 20 000–50 000 ha for the 3000-ha and 15 000-ha mean fire size regimes, respectively (Table 3). Additionally, to facilitate the use of these guidelines for FMUs of different sizes, results in Table 3 are presented as a percentage of the even-aged proportion of the FMU. Thus, for a given fire regime (fire cycle and mean fire size), Table 3 gives (at the bottom) the FMU proportion that should be targeted for even-aged management and the mean fraction of this even-aged proportion that should be cut in each harvest agglomeration size class for a 100-year planning forecast. Given that over 25 years agglomeration of individual fires, particularly of small fires into large fires, was common as reflected by a high occurrence of large regenerating areas (Fig. 3), agglomeration of harvest cut blocks in time should be justified and promoted as long as the proportion of even-aged forest is respected. Note that the size of regenerating areas and their spacing should fluctuate in time and space, as under a natural disturbance regime, instead of following a static guideline that would promote uniform patterns. Thus, the 10$^{th}$ and 90$^{th}$ percentiles are given as the bottom line over which no compromises in spacing and size should be granted to achieve social or economic goals.

To imitate large agglomerations of fire in time with limitations due to annual harvest levels and timber supply sustainability constraints, large harvest agglomerations will have to be built up over several consecutive years. We propose that the duration of harvest activities in one agglomeration should be shorter than the regeneration stage, which we consider here to be forest cover greater than 4 m tall and assumed to take around 25 years. This will ensure the creation of regenerating areas more or less contrasting with the surrounding mature forest. In addition, we consider the 25-year spacing constraint proposed in Table 2 to be long enough to limit excessive proximity of harvest agglomerations. The spacing proposed in Table 2 includes the mean and minimum nearest-neighbour distance that should be targeted and maintained during at least 25 years between agglomerations. Although temporal variability should be large in some regions, and should accommodate other dispersion constraints such as social concerns or road construction, we suggest that over a rotation period, an attempt be made to achieve the mean values. Consequently, use of only the smallest constraint will not achieve the goal of natural disturbance-based management.

Visual impacts of large harvest agglomerations are one of the most socially unacceptable effects of the suggested guidelines (Pâquet and Bélanger 1998b). Thus, mitigation measures should be applied to reduce these negative impacts. Inspired by fire events that leave unburnt or partially burnt patches behind (Kafka *et al.* 2001, Bergeron *et al.* 2002, Perron 2003), we encourage green retention in regenerating areas. In addition to providing a visual green screen, retention of live trees and snags should enhance stand structure diversity, provide refuge for some species, speed up snag recruitment, and increase connectivity between residual forest stands (Imbeau and Desrochers 2002, Sougavinski and Doyon 2002, Drapeau *et al.* 2003, Perron 2003, Ribe 2004). To favour green retention, progressive harvest strategies as a checkerboard could be used. This kind of strategy will divide large harvest agglomerations into sub-units and use several passes (years) to cut over the whole agglomeration. For a certain time it should leave sub-blocks uncut or partially cut that are next to the currently cut sub-blocks. Combined with use of irregular shape when building up harvest agglomerations and with a fast planting after clearcut, retention strategies will reduce the contrast between the disturbed zone and mature forest (Pâquet and Bélanger 1998a). Without presuming that harvest retention or other strategies will completely make harvest agglomerations more visually acceptable over the entire landscape, negative visual impact is balanced since large areas should be left undisturbed by harvesting at any time.

No matter the means used to satisfy social concerns, it is important to remember that disturbed area sizes in a landscape vary naturally in time and space, and that both large and small patches present values that need to be preserved (Forman 1995). Thus, choosing to only use the smallest size classes of the distribution and limiting their agglomeration in time to facilitate social compromises will not enhance the emergence of a natural pattern, but instead increase landscape fragmentation and reduce integrity of the interior forest. Similarly, favouring only the larger size classes to limit road construction or equipment moving will also not enhance the natural pattern and will unnecessarily increase local pressure on the ecosystem (Franklin and Forman 1987, Forman 1995, Delong and Tanner 1996).

## Conclusion

Application of natural disturbance-based management prescriptions to a specific region, for which one has a good idea of the historic fire cycle and mean fire size, involves a major shift from conventional even-aged management systems: it implies the maintenance of more mature and over-mature stands in a forest management unit (FMU) over time. This means that a significant part of the FMU must be left unmanaged or managed in a manner to maintain attributes of mature and over-mature forest stands. In this paper, we do not address problems related to maintaining all aspects of natural forest conditions in a managed system; we look only for an appropriate portion of a given FMU that could be under even-aged management practices while remaining within the historical range of variation in the context of its historical fire regime and its boreal location. Even though there are no experimental guarantees of success, we are confident that a management compromise could be achieved with this kind of approach and in its capacity to meet biodiversity and ecosystem sustainability goals. Obviously, we are aware of application limitations, such as social acceptability of large areas in regeneration, economic profitability and limited size of management units, which restrain the range of harvest agglomeration sizes. Incremental dispersion of harvest agglomerations across the landscape and its impacts on road construction and maintenance also need to be evaluated, as well as impacts of large fire events that could occur even with fire suppression.

Ideally, this kind of approach should take place in an area where forest harvesting activities have not yet begun or have just recently begun. However, such areas are rare and most of the commercial forest is already allocated with forest harvesting underway. Thus, to apply the recommendations presented here, active planning of the next cutting round would have to be done in a way that in the mid-term (e.g., approximately one rotation) available forest would be able to include a relatively large range of harvest agglomerations. Development of adequate spatio-temporal simulating tools will be imperative in order to evaluate the consequences of management on the desired future landscape and to help managers in their decision processes. In the long term these tools will also allow monitoring of the capacity of proposed approaches to maintain natural variability and to allow adjustments in order to reach management goals.

## Acknowledgements

This work was supported by Tembec Inc. and Quebec's funds in nature and technology research (FQRNT) by providing a PhD. student industry immersion grant, by the Sustainable Forest Management Network (SFMN) and the Chaire industrielle CRSNG-UQAT-UQAM en aménagement forestier durable (CAFD). We acknowledge Mike Wotton for fruitful discussion in the early phase of model development (INTELAND). We thank Nicole Fenton and Thuy Nguyen for reviewing the manuscript. Finally, we thank all colleagues and students that have worked on the fire historical reconstructions that have been used in this paper.

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