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A Comparison of Residual Forest Following Fires and Harvesting in Boreal Forests in Quebec, Canada

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Residual forests are a key component of post-burned areas creating structure within burns and providing habitat and seed sources. Yet, despite their importance to biodiversity and ecosystem processes there is little information on how similar or different residuals in burned landscape are to harvested landscapes. Our goal was to examine and compare the density, size, shape, and spatial arrangement of residual forest vegetation after fire and clearcutting. We evaluated residual forest in two locations within the boreal mixedwood region of Quebec, Canada using aerial photo interpretation and ArcGIS 9.1 software. We found residual stands to be larger and more abundant in harvested zones relative to sites affected by fire. Differences with respect to shape and spatial arrangement of residual forest were also observed among disturbance types. Factors such as proximity to watercourses, watercourse shape, and physiography affected residual abundance and spatial distribution. Residual forest in harvested zones tended to be more elongated with greater edge due to rules governing forest operations. Despite greater quantity of residual forest in harvested areas than fires, managers should still be prudent as the surrounding forest matrix is reduced in many managed landscapes.

Keywords biodiversity, boreal mixedwood, clearcuts, disturbances, forest fires, residual forests, tree retention
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1 Introduction

Forest management, as currently practised in the boreal forest, changes forest structure and can reduce native biodiversity (Haeussler and Kneeshaw 2003, Kardynal et al. 2011). It has been suggested that forest biodiversity could be maintained in managed forest landscapes if the managed forest emulates patterns found after natural disturbances (Franklin 1993). Much work has focused on using fires as a template as this disturbance has a dominant influence on the structure and dynamics of boreal forests (Hunter 1993). A common characteristic of fire that should serve as inspiration to forest managers is that they often leave a single or large group of living trees within circumscribed burned areas (Bergeron et al. 2002, Gasaway and DuBois 1985).

In many boreal and coniferous forests, a common approach for maintaining forest biodiversity is retaining structural elements (live trees and deadwood) of forest habitat within harvest units. Immediately after disturbance, these residuals function as source pools or transitionary refuges that facilitate the survival and dispersal of native biodiversity and aid in reducing soil erosion (Franklin et al. 1997). Live mature trees can also increase the capacity of natural regeneration, preserve genetic diversity, and help to improve public perception of forest harvesting (Franklin et al. 1997, Wyatt et al. 2011). In the longterm, residual trees can help the forest regain a more heterogeneous structure typical of older forest more quickly. Thus, retaining structural variablity within harvest units is an important tool that serves to reduce forest homogenisation caused by forest harvesting (Doyon and Sougavinski 2003). Many current approaches have been designed to retain trees at the stand scale and promote structure within harvest units; however, there is a need to explore retention at landscape scales typical of large burns or multiple adjacent harvest units.

Studies of residual vegetation after fire are more common in central and western North America (DeLong and Tanner 1996, Eberhart and Woodard 1987, OMNR 1997, Stuart-Smith and Hendry 1998, Perera et al. 2009,) than further east (Kafka et al. 2001, Perron 2003). Among the studies mentioned, only Perera et al. (2009) examined residual vegetation in proximity to watercourses. However, fire skips around wet areas could be expected. Similarly, many harvesting regulations limit harvesting to within a given distance of watercourses (Bourgeois et al. 2007). Fire may be influenced by topography (Cyr et al. 2009) while forest operations are interrupted when topography is broken and not accessible to mechanised operations. As hydrography and topography can vary greatly from one region to another it could be expected that the amount of residual forest will differ between regions if these factors influence the proportion of residual forest. Residual forest proportions could potentially differ as much or more between regions than between disturbance types.

Forest operations also leave cut-block separators which may be of very different form than residual zones after fire. For example, many current regulations lead to elongated separators between harvest units or between harvest units and watercourses. Comparisons of the landscape legacies of fire and forest harvesting are, however, rare (Lee 1999, McRae 2001, Song 2002, Perron 2003). Limited knowledge of disturbance dynamics has constrained the application of management approaches based on natural fire regimes and few studies go as far as suggesting silvicultural treatments (Bergeron et al. 2002).

The purpose of our study is to examine spatial patterns of residual forest vegetation after fire, to compare it with tree retention in harvested areas and to verify whether these relationships hold between two regions of the same forest type. We hypothesized that the quantity of retention within harvest units can equal or surpass the amount of residual trees after fire, but we expect that there will be differences with respect to size, shape, composition, and spatial patterns of residual groups after these two disturbance types. Secondly, we hypothesized that a tendency exists for residuals to be concentrated near water bodies, and that this tendency would be observed in harvested areas as well as after fire.

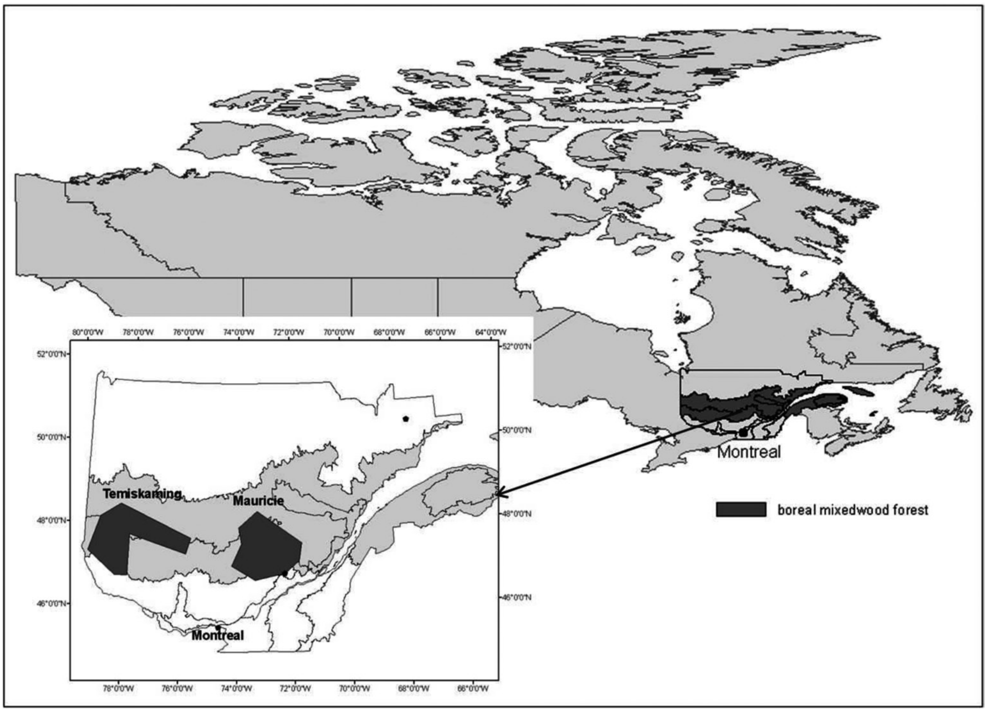

Fig. 1. Location of study areas in the West and East regions of the boreal mixedwood zone of Quebec.

2 Methods

2.1 Study Area

The study was undertaken in boreal mixedwood forests in central and western Quebec (the Mauricie and Temiskaming regions), Canada (Fig. 1.). The study area in the northern part of the Mauricie region (hereafter called East) was located between 47°00' and 48°30'N and between 71°30' and 74°00'W. The second study area in the Temiskaming region (hereafter called West) was located between 47°00' and 48°30'N and 76°00'and 79°00'W. Elevation of the East study area was between 300 and 640 m and the elevation of the West study area was between 200 and 400 m. For both regions, mean annual temperature was 1.5°C, while mean annual precipitation was 900 mm, with approximately 300 mm falling as snow (Robitaille and Saucier 1998).

In our comparison of fires and harvested sites we searched for disturbances for which aerial photographs were taken within a relatively short time interval (from several months to 10 years) after the disturbance so that residuals would still be observable. A long time interval (>10 yrs) between disturbances and the dates at which the aerial photos were taken was not accepted to avoid important changes (disaggregation and increased mortality of residuals and forest re-growth) in the disturbed areas. We surveyed these disturbances across a gradient of sizes. We identified eight sites affected by a natural fire from each region (16 total), with surface areas ranging between 136 and 7976 ha. All fires sampled occurred ten to fifty years ago (photos were taken less than 10 years after the disturbance) and were greater than 100 ha and were within the boundaries of the different study areas. Nineteen total harvested areas (10 in the East region and nine in the West) with surface areas between 142 and 1770 ha were also selected for comparison. Again harvest areas of the same type composed of multiple contiguous harvest units with a total area greater than

Table 1. Harvest retention according to MRNFQ 1996.

Role and position	Buffer strip width (meters)
Road protection (each side of major roads)	30 m
Water protection (each side of rivers)	20 m
Harvest area separation	60–100 m
40% or more slope	no harvest

100 ha were chosen. For both fires and harvest areas only areas that were affected by the target disturbance were sampled. In other words, burned areas that were affected by salvage logging were not used and similarly harvested areas that were subsequently burned or experienced windthrow were not chosen. For the selected fire and harvest sites, we visually analysed 1:15 000 or 1:15 840 aerial photos using a Sokisha MS27 stereoscope.

2.2 Definitions and Criteria Used to Differentiate Residual Groups

A residual group is an assemblage of trees partially or completely unaffected by disturbance, greater than 0.01 ha and with a minimal proportion of at least 30% remaining alive at the moment the aerial photograph was taken after the disturbance. Two types of residual groups have been distinguished by a number of authors (Fig. 2) (Stuart-Smith and Hendry 1998, OMNR 1997, Perron 2003): 1) residual islands, which are residuals found within a disturbance and separated from non-burned forest, and 2) the residual matrix, which are peninsulas or corridors situated within a fire, but physically linked to an intact forest matrix that surrounds the disturbance. Isolated residual trees, usually partially burned, were not included in this study because of the high rate of mortality in the first years after fire (Bergeron et al. 2002). Individual trees in harvested areas were generally composed of non-commercial species and these also usually died within a few years of harvesting due to hydric stress (Roy et al. 2001). To differentiate a peninsula-type residual group from intact forest, we used the maximum length: maximum width ratio as a general criterion such that, this ratio had to be greater than 1.

In Quebec, the *Regulation respecting standards of forest management for forests in the domain of the State* (MRNFQ 1996) requires the presence of forest residuals within harvested areas, wooded edges, as well as buffer strips between roads or watercourses and harvested areas (Table 1). The result is an assemblage of harvest units, buffers strips, and wooded corridors that form harvest agglomerations. The amount of retention inside these harvest agglomerations is influenced by the density of hydrographic and road networks. Intact forest represents undisturbed forest that is found adjacent to a harvesting or fire disturbance. In our study, forest strips smaller than 250 m are considered to delimit neighbouring harvest units and thus intact forests are forested areas that are larger. We divided these residuals in relation to their principal functions: separating clearcut areas, protection of watercourses, buffering roads, or other objectives in order to understand whether a specific type of residual was favoured in harvest agglomerations.

2.3 Aerial Photo Interpretation

We determined the composition of the residual forest and the intact forest within a 500 m band surrounding the edge to either coniferous or deciduous species groups. We measured the surface area covered by each species group. To determine whether a given species group was more likely to survive fire and thus comprise a residual area we compared the proportion of the area covered by each species group in residual forests to that covered by each species group in the intact forest. This provides an indication that the species groups dominating the residual forests are different than the matrix although caution must be ensured in not overinterpreting this ratio to state that the surrounding matrix was the same as the disturbed forest.

We determined the percent slope of the disturbed and residual areas using the following classes: 0–10% (low), 10–30% (medium), >30% (high). We calculated the percentage of surface area corresponding to each slope class for both the disturbed and for the residual areas. The surface areas of residual forest species groups and slope classes were evaluated.

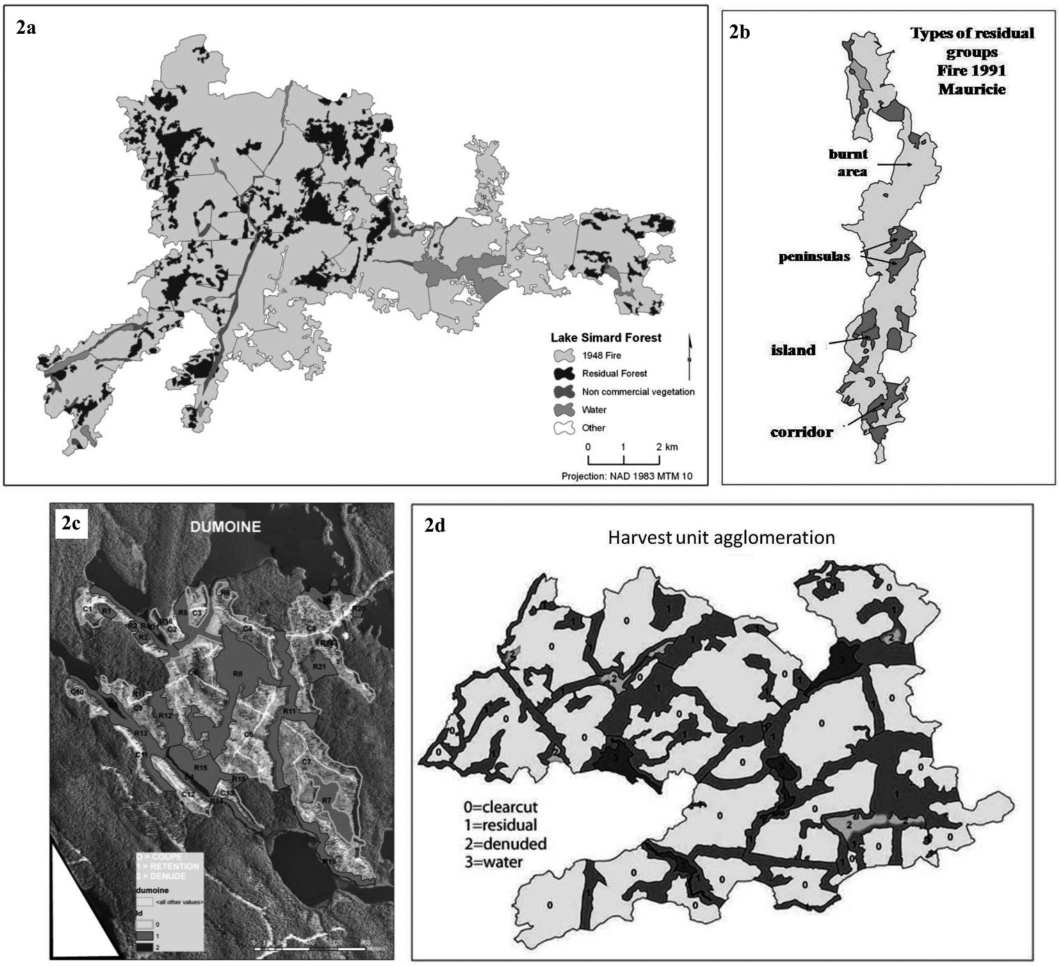

Fig. 2. Examples of residual forest groups in two fires and two harvest agglomerations. 2a is a burnt zone with residual stands from eastern Quebec and 2b is a fire map with residual tree groups from western Quebec. 2c and 2d are residual tree groups in harvest agglomerations in the East (2c) and the West (2d).

2.4 Analyses

Aerial photos were digitised at a resolution varying between 400 and 600 dpi. Geo-referencing was done using ArcGIS 9.1 software, and depending on availability of orthophotos of disturbed areas or hydrography layers of the same region, we use 3 to 8 reference points on an aerial photo visible on both the orthophoto and the hydrography layer. In the absence of a watercourse, we geo-referenced photos using a series of reference points common to neighbouring aerial photos.

Analysis was conducted on polygons that represented fire or harvest unit areas, created manually using ArcGIS 9.1. (Fig. 2). TIFF images were used in combination with stereoscopic analyses to more precisely delineate the various landform categories. We outlined the spatial extents of all fire and harvest unit sites, as well as the following categories found within or at the limit of each disturbed site: residual group, denuded land, or watercourse.

The abundance of residual forest was expressed as the ratio between the total residual forested area and total surface area of the fire or harvest unit not including non-forested areas (e.g. watercourses).

To determine the influence of watercourses on density of residual forest cover, we calculated the total abundance of residual forest as a function of proximity to watercourses; i.e., residual ratios at 100 and 200 m from a watercourse. To do this we delimited 100 m and 200 m buffer zones that surrounded watercourses situated within or at the limit of a disturbance. The analysis was done on a subsequent layer of the geometric intersection (intersect or clip in ArcGIS) between the buffer layer strip and the base layer representing the disturbance.

To evaluate the effects that different proportions of watercourses in the two regions would have, we compared the hydrography of the two regions for both the length of watercourses and for water surface area. Linear density was calculated as the ratio between the cumulative length of watercourses located within or at the edge of a disturbance and the total surface area of the disturbance. The density of lakes was calculated as the ratio between the lake surface area found within a harvest unit or fire disturbance and the total surface area of the disturbance.

To characterise the shape of residual forests, we used the mean perimeter to surface area ratio (MPAR) and the mean shape index (MSI) calculated using the Patch Analyst extension developed for ArcView 3.3 (Elkie et al. 1999). The perimeter: surface area ratio (MPAR) has a minimum value for a circle and increases with more eccentric forms and the Mean Shape Index (MSI) has a value close to 1 if the shape is closest to a circle or square.

2.5 Statistical Analyses

JMP version 5 software was used for all statistical analyses. An ANOVA was used to test whether the proportion of residual forest differed between regions or disturbance types. ANOVAs were used to test all differences between possible influencing factors on quantity of residual forest by disturbance type and region. Thus separate ANOVAs were conducted to test whether residual forests were more abundant on particular slope classes or within a given distance to watercourses (e.g. within 100 or 200 m buffers). ANOVAs were also used to test differences in hydrography, slope classes, the proportion of residuals, between the regions (see above). ANOVAs were used to evaluate the proportion of residual forest found within different buffer zones (see above) for each disturbance type and region. ANOVAs were also used to test differences in residual shape (e.g. MPAR or MSI) between disturbance types and regions. Tukey's HSD test was used when significant interactions or main effects were observed.

Slope analyses included only Classes 1 and 2, as too few Class 3 results were obtained to make meaningful comparisons. Because of the random nature of harvest unit site selection and of fire ignition, a random effects ANOVA analysis was run. In situations where model assumptions were not met, we transformed data using a rank averaging technique.

3 Results

3.1 Total Residual Forest

The proportion of forest left by fire varied between 7.3 and 19.1% of the total surface area of fire, with regional averages being similar ($p = 0.26$), 12.7% in West and 11.3% in East. The mean proportion of retention in harvest units is 32.3 and 28.4% in West and the East, respectively; both being double the proportion observed after fire ($p = 0.04$). In addition to being more abundant, retention in the harvest units had a greater mean size relative to after fire ($p = 0.02$). However, there was no correlation between the total area of the agglomerated harvest units and the forest retained (Table 2). Positive relationships were, however, observed between total area burned and post-fire residual forest mean and maximum surface area (Table 2).

The surface area of the largest residual stand had a similar variation between regions and disturbance types. The largest residual stands were 84.1 ha in East and 80.7 ha in West in fire-affected sites and 80.1 ha in the East and 47.8 ha in West after cutting.

Table 2. Correlations (presented as a proportion from 0 to 1.0) between surface area of disturbances and residual area.

Correlation	Total residual area	Mean residual area	Maximum residual area
Total study area	MN (–0.44)	NA (0.15)	MP (0.64)
East fire	SN (–0.83)	SP (0.71)	MP (0.50)
East harvest units	NA (0.16)	NA (0.14)	NA (0.28)
West fire	NA (0.03)	MP (0.65)	SP (0.93)
West harvest units	NA (–0.15)	NA (0.20)	MP (0.61)

MP – moderate positive (0.3 to 0.7); SP – strong positive (0.7 to 1.0); MN – moderate negative (–0.3 to –0.7); SN – strong negative (–0.7 to –1.0); NA – no association (–0.3 to 0.3)

Table 3. Mean percentages of residual proportions and mean shape indices for residuals after fire and harvesting.

Index	Region	Fires	Harvest units
Total residual ratio (%)	East	11.3*	28.6*
	West	12.7*	32.3*
Residual ratio within 100 m (%)	East	2.8*	12.0*
	West	2.1*	10.6*
Residual ratio within 200 m (%)	East	5.0*	15.5*
	West	4.0*	16.0*
Residual area within 100 m (%)	East	25.3	42.8
	West	16.1	32.7
Percent residual within 200 m	East	43.5	55.3
	West	30.7	50.0
Maximum residual surface area (SmaxRes) (ha)	East	21.6	40.1
	West	29.1	35.5
SmaxRes / Total disturbed area	East	0.018	0.043
	West	0.018	0.085
Mean Perimeter: Area Ratio (MPAR)	East	0.065*	0.042*
	West	0.053	0.066
Mean Shape Index (MSI)	East	1.65*	2.57*
	West	1.5*	2.64*
Core area (ha)	East	104.6	209.0
	West	197.54	120.24
Percent core area	East	0.062	0.21
	West	0.096	0.22

Statistical differences at $p \leq 0.05$ are indicated with an asterisk*, sample sizes are explained in the methods

3.2 Shape and Size of Residuals

The number of island-type residual groups is much lower after cutting than after fire. In our study, although fires in the East had a larger mean perimeter: surface area ratio (MPAR) than the harvest units whereas in the West no significant difference was observed. For both regions, residual forests in harvest units had an MSI significantly higher than those after fire, and therefore had a more elongated shape. There was no difference among regions for MSI in harvest units. In contrast, residual groups after fire in East had a more elongated form than those found in West.

The quantity of interior surface area (Core Area, CA) calculated by subtraction of a 10 m strip from the residual forest edge was not different among regions and disturbance types ($p = 0.05$)

3.3 Topography, Disturbance and Vegetation

Greater percent slope was observed in the East versus the West region such that the total area observed to have a 10–29.9% slope was greater in the East (p = 0.04). As areas with a severe slope (>30%) occupy a relatively small proportion of the total area (between 5 and 9% of the total area), they were not considered in further analyses. Despite the difference in the area with different slopes between regions, the mean slope of the land occupied by residual forest did not significantly differ from the mean slope of the disturbed sites. Further, we did not observe a tendency for residual forest to be situated in one topographic position more than another.

The species compositions of residual groups and of the intact forest situated along disturbance edges did not vary significantly (p = 0.08) as a function of study region or disturbance type, suggesting that vegetation conditions were similar in all sites examined.

3.4 Riparian Buffer Zone

Within the harvest units, retention is always present beside rivers, whereas after fires, this is not always the case. Post-fire residual forest varies from near-absence to having 60% of residual groups within a 100 m buffer of a waterbody. We observed a tendency for residual groups to be concentrated near sinuous rivers and to be almost absent when in proximity to more linearly-shaped rivers, in flat areas, or if the dominant direction of fire, determined by the disturbance shape, is parallel to river direction.

We found that within both 100 and 200 m buffers from a waterbody there was more retention after cutting than after fire ($p_{100m} = 0.02$, $p_{200m} = 0.04$) and that the percentage of the retention was similar among the two regions (about 30% of the total disturbance area).

After fire, the quantity of residual groups found within 100 m of a waterbody is approximately half (57% in East and 52% in West) the quantity found at 200 m, which suggests a relatively uniform spatial dispersion (among groups). After harvesting, the residual forest was most concentrated in the first 100 m band. Increasing the buffer out to 200 m only slightly increased the amount of residual forest included. The percentage of the total residual surface area found within 100 m of a waterbody shows that residuals are more concentrated near water after harvest than after fire (p = 0.01) and more so in the East than in the West (p = 0.02). In contrast, at 200 m from a waterbody, no relationship was observed, suggesting that effects of waterbodies on the aggregation of residual groups is stronger in the first 100 m than out to 200 m from a waterbody.

4 Discussion

4.1 Residual Area in Burns vs Harvest-Unit Agglomerations

The fire cycle is longer than the harvest cycle for the same given surface area throughout much of the boreal forest especially in eastern Canada suggesting that certain habitat characteristics may be decreasing below natural thresholds (Cyr et al. 2009). Some authors have also suggested that even for a fire cycle equivalent to a harvest cycle, harvesting results in greater homogenization of the landscape (Johnson and Van Wagner 1985). Decreases below threshold values of habitats and the homogenization of the landscape are arguments that we should compare managed landscapes to naturally disturbed landscapes to identify potential differences and potentially readjust prescriptions. Differences can be expected at many scales with previous research showing differences between age class structures across large landscapes or regions (Cyr et al. 2009) as well as modifications to the matrix of managed and natural forests (Hunter 1990).

Our study demonstrates that despite regional variation there are important differences in residual characteristics between fires and clearcuts in boreal mixedwood forests. Our results show that the area of residual forest in harvest units (28.6 to 32.3%) is more than double the area in residual forest after fire in our two study areas, thus confirming our first hypothesis. In order to maintain biodiversity Cissel et al. (1999) propose a mean proportion of 30% (range between 15 and 50%) of residual forest cover after clearcutting which corresponds to the mean residual ratio of harvests found in our study. The abundance and richness of understory species are substantially reduced at a ratio of 15% retention compared to a ratio of 40% (Aubry et al. 2004). Similarly Lõhmus and Kull (2011) have shown that maintenance of single isolated green trees (i.e. instead of groups) does not improve species diversity of rare plants more than clearcuts.

Further north in the black spruce boreal zone, Perron (2003) observed similar quantities of residual forest cover among fires and harvest units. This difference with our study may be explained by the greater quantity of residual forest after fire in black spruce-feather moss forests: between 16 and 22%, compared to a mean of 12% in the hardwood-conifer boreal mixedwoods observed here. The larger proportion of residual area may be a consequence of the much larger size of fires studied by Perron (30 000 ha versus 8 000 ha in our study), as larger fires often contain a greater proportion of residuals (Eberhart and Woodard 1987, DeLong and Tanner 1996). However, other factors may need to be invoked for within the size gradient we studied we found a negative correlation (83%) between fire size and the residual ratio in the East. Sites in the East had a more hilly topography than in West, suggesting that physiography (flat vs hilly regions) may influence the relationship between the size of the disturbance and the proportion of forest left by fire.

In contrast with the total proportion of residual area, we found that fire size is positively correlated with the mean size of residual groups; in agreement with Perron's (2003) results for black spruce-feather moss forests found further north. Stuart-Smith and Hendry (1998) did not observe this type of correlation, however with two exceptions they analysed fires smaller than 500 ha in size. Future studies should investigate the influence of fire size on residual proportion and mean size of residuals over a large gradient of fire sizes to determine if greater residual area should be maintained if harvest areas exceed a threshold size. Currently, in the harvest units studied, no correlation between harvest unit size and mean residual size was observed, probably because the regulations that govern the non-cutting zones within harvest units are based on physiographic and hydrographic features that are independent of total size.

4.2 Abundance of Riparian Residuals

At the landscape scale, watercourses are often considered to be barriers to fire spread (Dansereau and Bergeron 1993); and in our study, lakes (those large enough to act as barriers) are an example. According to our results, a relatively linear river or a flat terrain is less likely to have residual trees than a more sinuous river or areas surrounded by hilly terrain. Masters (1990) suggests that if the orientation of the valley faces the dominant direction of fire this will influence the spatial pattern of residual groups. Our observations are in agreement as they show that there are almost no residual groups on relatively flat areas if fires follow the direction of the river.

We found that residual forests that were <100 m from a watercourse were significantly more abundant in harvest units than after fire, given the obligation of forest companies to leave buffer strips near water, while fires can burn to water's edge. Between regions there was a difference only in the fire-disturbed sites, as the quantity of residuals 100 m from a watercourse was significantly greater in the East than in West, likely because of the greater relief found in the sites in the East. Lee and Smyth (2003) found that the quantity of riparian residuals was positively correlated with the size of the river as well as the type of forest, size of trees, and the distance to the river. Our study shows that the mean residual ratio at 100 m in the sites disturbed by fire is about half of the mean residual ratio at 200 m, which suggests a relatively uniform distribution of residual forests near water. In contrast, in the harvest units, the quantity of residuals at 100 m represented 66% (East) and 77% (West) of the quantity at 200 m, as the majority of buffer strips are between 20 and 100 m in width (Table 3).

4.3 Shape, Composition, and Surface Area of Residual Forests

With respect to the spatial pattern of residual groups, our results showed that after fire there are many randomly dispersed more circular shaped residual islands (MSI = 1.5–1.6 thus a more circular form), while retention after cutting was more linearly shaped (mean shape index (MSI) of 2.5–2.6) with islands of retention being virtually absent in harvest units. These observations are consistent with regulations to maintain residual forest bands along watercourses during harvesting operations (Bourgeois et al. 2007). The relatively circular form of residuals after fire has also been observed in other studies as Anderson (1983) reported an MSI of 1.5 while Andison (2004) found values between 1.3 and 2.9 depending on the size of fire.

The interior surface area that is important for some wildlife species depends on the size and shape of the stand (Baskent and Jordan 1995), as well as the width of the edge under consideration (Kleinn et al. 2011). In our study, residuals in harvest units although more elongated had a mean size larger than residual groups after fire. For a 10 m wide edge, there was no significant difference between the proportion of interior residual forest in harvested areas and after fires, while the total quantity (in absolute terms) of residuals in our study is more than double in harvest units than in burns. The elongated, irregular edges of harvest units residuals significantly reduced the quantity of interior forest compared to residuals after fires of similar size; consequently fires and harvests had on average similar amounts of interior forest. Habitat differences are thus not immediately obvious between the two disturbance types because of this difference between quantity and form. These differences should be a priority area of research in understanding the effect of residuals for wildlife.

5 Conclusion

The quantity and size of residuals after clearcutting is significantly greater than after fire. Despite this, we do not suggest decreasing the proportion of residual forest as the forest matrix in natural landscapes dynamised by fires is typically composed of mature or old-growth forest whereas as forest management advances the forest matrix changes to one that is primarily younger (Landres et al. 1999). In other word, patterns in harvest units could perfectly emulate those following fire, but also repetition of these patterns through forest management could consume the entire landscape leaving no immature or other matrix conditions, and thus transform the landscape. A balancing of ecological objectives creating similar habitat structures with visual quality objectives suggests that small buffer strips near water or along roads, especially in more remote areas could be decreased while increasing the proportion of residuals in the form of more regularly-shaped islands. Because there is no single quantity and spatial arrangement of residual forest that favors all boreal species simultaneously, the most prudent strategy will be to ensure some degree of variability across the landscape when determining residual levels in management plans (Serrouya and D'Eon 2005).

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