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Detecting scales of pattern in boreal forest landscapes

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Abstract

A hierarchy of processes operating at different spatial and temporal scales form landscape pattern, and changes to the patterns can have impacts on habitats and forest dwelling species. Managing landscapes under the auspices of sustainable forest ecosystems and emulation of natural disturbance requires knowledge of the scale at which landscapes are patterned. To better understand the role of natural disturbance in two distinct ecoregions of the Ontario boreal forest, we used thematic landcover maps derived from satellite imagery to evaluate differences in the relevant scales and nested hierarchies of forest pattern between two regions: northwest Ontario (relatively undisturbed forest and little fire suppression) and northeast Ontario (long history of forest harvest and fire suppression). We define a relevant scale as the spatial level where non-random patterning of landscape structure occurs. Similar nested hierarchies occurred in forest and wildfire disturbance classes in northwest Ontario. In contrast, the relevant scales detected in the northeast occurred at fewer levels and in the disturbance class, which was the result of forest harvest, at only one level. The differences detected between the two regions indicate that current forest harvest practices that focus on landscape alteration at a single scale are creating new landscapes that are different from the natural landscape. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Ecosystem-based management; Hierarchy; Landscape ecology; Landscape pattern; Natural disturbance; Relevant scale; Sustainable forest management

1. Introduction

In some natural resource management agencies the notion of emulating natural disturbance (spatial landscape pattern) has been accepted as the least risky way of protecting ecosystem values and meeting forest sustainability requirements while harvesting forest landscapes (e.g., Legislative Assembly of Ontario, 1994). In adopting principles that hinge on emulating natural disturbance, such agencies must develop forest management guidelines that give direction prescribing the spatial configuration of both forest harvest patterns and habitat leave areas.

Organisms view and use landscapes at different scales for differing ecological processes, e.g., foraging and reproduction (Nellis and Briggs, 1989; Holling, 1992; Baker, 1993). Odum (1977) notes that as landscape components or subunits are combined to produce larger functional wholes, new properties can emerge that were not evident at lower levels. Holling (1992) tested several hypotheses in an attempt to explain bird and mammal body mass clumps in the

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boreal forest region and the short grass prairie, where breaks in the frequency distribution of body sizes of a range of species are considered to be clump boundaries. The only hypothesis that he could not reject was that body mass clumps are entrained by discontinuous hierarchical structures and textures of landscapes. Holling (1992) suggests that there are dominant processes that structure ecosystems. These dominant processes entrain less dominant processes, and the result is a few dominant frequencies that are discontinuously distributed. Discontinuous landscape structure and texture across scales interacting with varying temporal frequencies affect animal behavior.

A hierarchy of processes operating at different spatial and temporal scales form landscape pattern (Allen et al., 1987; Holling, 1992; O'Neill et al., 1992). Changes to forest landscape patterning can have impacts on wildlife habitats and forest dwelling species (Rempel et al., 1997). The influence of forest management on forest landscapes requires evaluating changes to pattern at relevant scales. If hierarchical processes alter and shape landscape pattern, and differences in processes (e.g., climate, soil) occur within forest regions, then we would expect the relevant scales of landscape patterning to be different between regions. We test the hypothesis that there are no differences in the relevant scales and the nested hierarchies of forest pattern between regions. We define a relevant scale as the spatial level where non-random patterning of landscape structure occurs and therefore the patterning has relevance to ecosystem structuring processes, wildlife habitat, and forest management.

2. Study area descriptions

The two study areas are in northwest and northeast Ontario, Canada (Fig. 1). The northwest area is in boreal forest consisting of jack pine (P*inus banksians* Lamb.) dominated forests with mixtures of black spruce (*Picea mariana* (Mill.) B.S.P.), balsam fir (*Abies balsamea* (L.) Mill.), white birch (B*etula papyrifera* Marsh.), white spruce (*P. glauca* (Moench) Voss), and trembling aspen (*Populus tremuloides* Michx.) on rolling rocky uplands with coarse well drained soils (Rowe, 1972). The natural wildfire cycle in the northwest is between 80 and 120 years.

Fig. 1. Location of study areas in northwest and northeast Ontario including location of seven, 75 km×75 km, sample plots (four in the west and three in the east).

The northeast portion of the study area is very different in its vegetation characteristics, natural fire cycles and sizes, soils, surficial geology and recent anthropogenic influences. It is located in boreal forest consisting mostly of black spruce dominated forests on undulating low relief clay plains (Hills, 1959). The three study plots in the northeast study area were located completely in a clay belt. The fire cycle in the northeast clay belt is about 2–3 times longer than in the northwest (Li et al., 1996). Similarly, the mean size of wildfire is in the magnitude of 2–3 times greater than in the northwest (Li et al., 1996).

The historical anthropogenic disturbances and protection in the east and west study areas are very different. Extensive forest harvest history in the northeast clay belt has occurred since the early part of the 20th century. This forest harvest history combined with recent forest fire suppression (ca. 1940s to the present) has altered landscape pattern and structure in the northeast. In contrast, forest harvest in the west has been less and fire suppression has been less intensive; consequently, the landscape is more natural.

3. Methods

We used a geographic information system (GIS) to randomly located seven non-overlapping, 75 km× 75 km sample plots; four in the northwest and three in the northeast clay belt (Fig. 1). The sample plots were located on digital provincial landcover maps. The landcover maps were derived from 1993 Landsat TM imagery (pixel with a resolution 25 m×25 m), where a supervised classification resulted in thematic map accuracy of about 75% for forest and disturbance classes.

We used lacunarity analyses to determine (i) if relevant scales (i.e., non-random patterns) were present in each sample plot, and (ii) whether more than one relevant scale (nested hierarchy) occurred within each sample plot. We analyzed three broad landcover classes: (i) conifer (80% or greater conifer), (ii) mixedwood (<80% conifer and <80% deciduous), and (iii) recent disturbance (early succession forest <25 years). The recent disturbance class included natural wildfire in the northwest study area and recent forest harvest in the northeast clay belt. At the time of the study there were very few detectable burns in the northeast clay belt.

Dispersion of patches on a landscape can range from random to clump. Lacunarity is a spatial statistic that describes a landscape's texture along this patch dispersion continuum. Lacunarity measures the clumpiness of landscape patches. The concept of lacunarity analysis has recently been explored in the landscape ecology literature to deal with the problem of scale-dependent measures of landscape pattern (Plotnick et al., 1993). The term lacunarity was first coined by Mandelbrot (1983), where he refers to geometric objects being more lacunar if gap sizes are distributed over a greater range. A landcover map would be more lacunar if patches were clumped and less lacunar if they were evenly distributed across the map (Fig. 2). Gefen et al. (1983) described lacunarity more precisely, and used the term translational invariance. Conceptually, translational invariance is a measure of the mean-to-variance ratio of landscape patches and is a continuum from a very even (random) patch dispersion where translational invariance is high, to a very irregular (clumped) dispersion where translational invariance is low. Since lacunarity is a measure of the mean-to-variance ratio of landscape patches, it is very scale-dependent as patch dispersion can change at different scales. By calculating lacunarity over progressively larger spatial extents, a spatial response function can be generated which identifies (i) if texture remains unchanged across scales, and (ii) if not, the spatial scale(s) at which patch structure is nested within a higher level patch structure. If more than one such discontinuity were present, then we would interpret this to mean that the landscape is structured or patterned hierarchically. If such a hierarchical structure exists, then abrupt changes in the lacunarity response curve will identify relevant scales of landscape pattern.

We used the spatial lacunarity statistic to detect relevant scales. Calculation of lacunarity is achieved using an algorithm developed by Allain and Cloitre (1991) that is appropriate for landcover maps. Consider a 2 pixels×2 pixels moving box applied to the hypothetical map (Fig. 3). At the upper left starting position, three pixels fall within the box, and in the terminology of lacunarity analysis, this value is termed 'box mass'. The process continues one pixel to the right-hand side until the map edge is


Landscape (A) Landscape (B)

Fig. 2. Two hypothetical 800 pixels×800 pixels landscapes where the black pixels represent the class of interest. Note that in landscape A the pixel distribution is even and in landscape B the pixel distribution is clumped.

Fig. 3. A hypothetical 200 pixels×200 pixels landscape map for which lacunarity=1.2334 at the 2 pixels×2 pixels level (Table 1).

encountered, moves down one pixel, continues to the left-hand side, etc., until box mass is calculated for the entire map. The result is a frequency distribution of box masses and a lacunarity value for that scale (Table 1).

The number of boxes of size r containing S occupied sites is designated by $n(S, r)$ and the total number of boxes of size r by $N(r)$ (Plotnick et al., 1993). The frequencies are converted to probabilities by dividing by the total number of boxes as

$$Q(S, r) = \frac{n(S, r)}{N(r)}$$

and the first and second moments of the probabilities are calculated as

$$Z^{(1)} = \sum S + Q(S, r), \qquad Z^{(2)} = \sum S^2 + Q(S, r)$$

Lacunarity is defined as

$$L(r) = \frac{Z^{(2)}}{(Z^{(1)})^2}$$

In their description of the lacunarity calculation, Plotnick et al. (1993) also note that in statistical annotation

$$Z^{(1)} = \overline{S}(r), \qquad Z^{(2)} = s_s{}^2(r) t \overline{S}^2(r)$$

where $\overline{S}(r)$ is the mean and $s_s{}^2(r)$ the variance of the number of sites per box, and consequently,

$$L(r) = \frac{s_s{}^2(r)}{\overline{S}^2(r) + 1}$$

3.1. Lacunarity analysis of baseline models

To evaluate lacunarity response of natural conditions, we first constructed models of what to expect under experimental conditions, ranging from highly random to highly clumped patch dispersion. Analysis of these simulated landscapes then form a baseline to compare results from the study landscapes. To do this, we use an algorithm to generate three hypothetical hierarchical landcover maps with nested non-random patterns (Fig. 4). The nature of the hierarchy is shown in the two levels of organization within each map. The first level of organization is in clumps of 50 pixels×50 pixels and the second level is 200 pixels×200 pixels.

Table 1

Frequency distribution and subsequent calculation of lacunarity of a 50 pixels×50 pixels landcover map, where $r = 2$ (r is the size of a box side)

S[a]	$n(S, r)$[b]	$Q(S, r)$[c]	$SQ(S,f)$	$S^2Q(S, r)$
0	139	0.05789254	0.00000000	0.00000000
1	568	0.23656810	0.23656810	0.23656810
2	977	0.40691379	0.81382757	1.62765514
3	581	0.24198251	0.72594752	2.17784257
4	136	0.05664307	0.22657226	0.90628905
$\sum n = 2401$			$Z^{(1)} = 2.0029$[d]	$Z^{(2)} = 4.9483$[d]
$L(r) = 1.2334$[e]				

[a] Number of occupied sites or box mass.

[b] Frequency of boxes with mass S.

[c] Probabilities of boxes with mass S.

[d] $Z^{(1)} = \sum S + Q(S, r)$ and $Z^{(2)} = \sum S^2 + Q(S, r)$ (i.e., first and second moments).

[e] Lacunarity, $L(r) = Z^{(2)}/(Z^{(1)})^2$ (adapted from Plotnick et al., 1993).

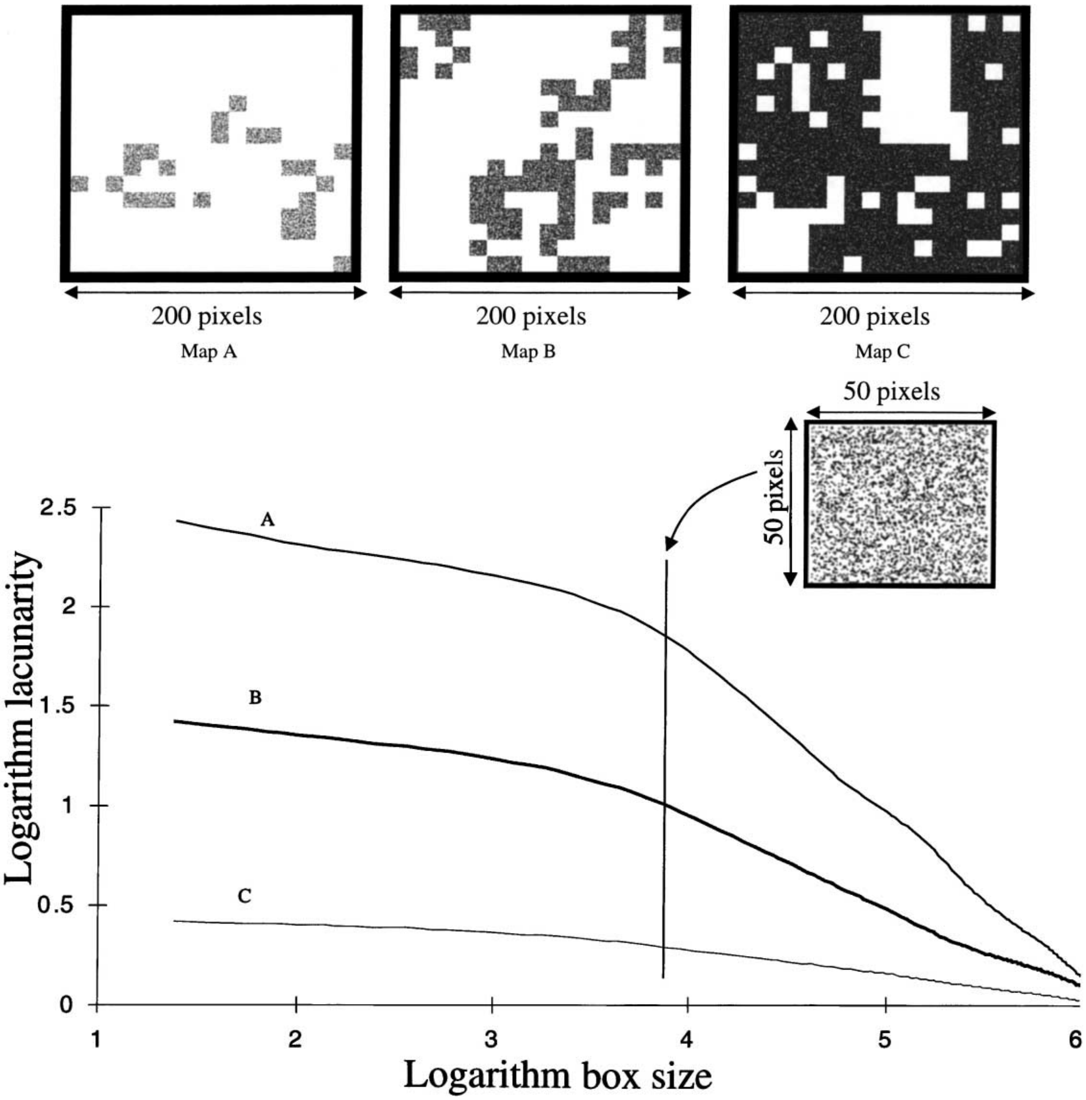

Fig. 4. Three hierarchical 800 pixels × 800 pixels hypothetical landscapes and their corresponding lacunarity response curves. The black pixels represent the class of interest. The response curve includes changes that represent midpoints of ranges where relevant scales (detected non-random pattern) occur (50 pixels × 50 pixels; logarithm box: 3.90).

The probability of pixel occupancy was set to 0.3, 0.5, and 0.8 for maps (a), (b), and (c), respectively (Fig. 4), and defines pixel density in the three maps. The slope of logarithm lacunarity versus logarithm box size changes when a relevant scale is detected (Fig. 4). For instance, a pronounced change in slope at the logarithm of box size 50 pixels × 50 pixels occurs for each map. The change in slope is most pronounced in the curve representing map (a). This is due to the greater contrast between clumps. Gap sizes are more variable in map (a) than in map (b), and more variable in map (b) than in map (c). Therefore, map (a) is relatively more lacunar than map (b), and map (b) more than map (c) (Fig. 4).

We found that the lacunarity response became less pronounced when non-random patterns occurred at broad scales, therefore, we determined that in our landscape analysis a lacunarity graph had to be created and analyzed for each scale interval and for each sample plot.

At the second level of organization (i.e., 200 pixels×200 pixels) a change in direction of the lacunarity curves is less pronounced. A curdling algorithm created these maps with two levels of organization; however, because different probabilities of pixel occupancy were used, the assigned levels of organization are not always present. Map (a) has distinct clumps of pixels at 200 pixels×200 pixels and map (c) does not. The lacunarity curves do not pinpoint the exact level of organization but do allow for interpretation of an interval of detected scale. Fig. 5 is an illustration of three hypothetical landcover maps created from the curdling algorithm. In contrast to the maps in Fig. 4, these maps are not hierarchical. Similar to Fig. 4, these maps were created with pixel densities of 0.3, 0.5, and 0.8 for maps (a), (b), and (c), respectively. The behavior of the lacunarity curves for the non-hierarchical maps differ from those of the hierarchical maps (Figs. 4 and 5). The curves for the non-hierarchical maps have no pronounced breaks in slope or distinct humps. However, similar to the hierarchical lacunarity curves, the lacunarity values are indicators of the relative distribution of gap sizes. Therefore, by plotting curves of lacunarity and examining their behavior, we can detect relevant scales and predict hierarchical characteristics. We used landscape patch statistics to verify whether the relevant scales detected were clumped small patches or single large patches.

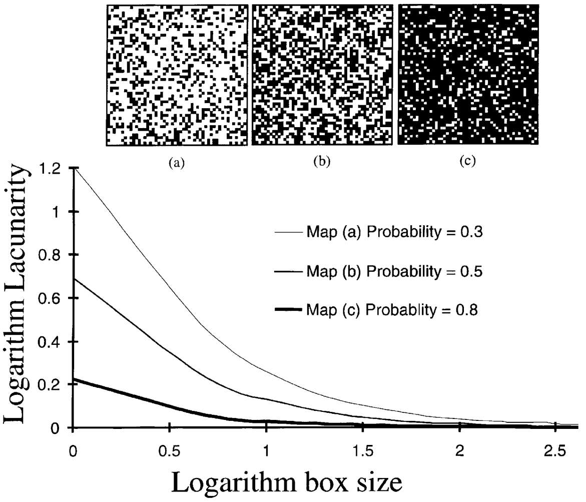

Fig. 5. Three non-hierarchical, 50 pixels×50 pixels, hypothetical landscapes (a, b, and c) and corresponding lacunarity response curves. Each landscape map was created using a curdling algorithm (Plotnick et al., 1993) with single level pixel probability occurrence set at 0.3 (map a), 0.5 (map b) and 0.8 (map c). The black pixels represent the class of interest. The response curves have no humps indicating that no relevant scales are detected in any of the three maps and that landscape patterning in each map is random. Note that the relative lacunarity values represent the pixel occurrence (high–low) on each landscape.

4. Results

Fig. 6 illustrates the conifer lacunarity curves for plot 2 (northeast clay belt) and plot 6 (northwest) for the scale range 112 130 ha (logarithm box: 7.2) to 562 500 ha (logarithm box: 8.0). In this example, no relevant scales occurred for plot 2. In contrast, a relevant scale (distinct hump) occurred between 167 278 ha (logarithm box: 7.4) and 372 284 ha (logarithm box: 7.8). Our results are based on similar interpretations of graphs that were created for each scale interval, for each landcover class and for each sample plot.

Relevant scales of landscape patterning within the forest classes (conifer and mixedwood) were detected at four spatial scales in the northwest, scale intervals A, C–D, H and J–K. This indicates nested distributions of patches (patches within patches) that will create a hierarchical patterning of the landscape (Tables 2 and 3). Similar nested patch distributions were detected in

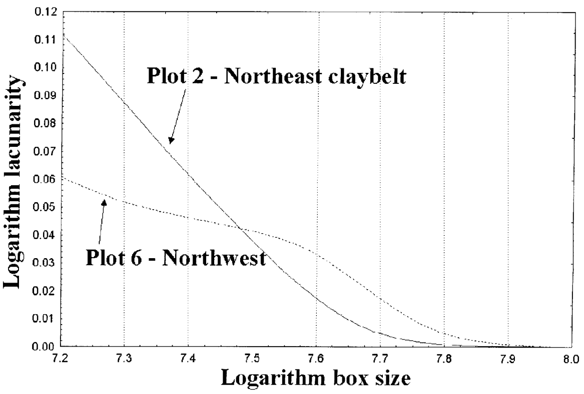

Fig. 6. Lacunarity response curves for the conifer forest landcover class, plots 2 (northeast) and 6 (northwest), scale range 112 130 ha (logarithm box: 7.2) to 562 500 ha (logarithm box: 8.0), where plot 2 indicates random pattern and plot 6 represents clumped pattern.

the disturbance class (wildfire), where relevant scales were detected at three levels, scale intervals B, H and K (Tables 2 and 3). In the northeast clay belt, we found the distribution of forested patches to be nested, but to a lesser degree. Non-random patterns were mostly detected at two levels, scale intervals H and K–L, but with one detected at scale interval A (Tables 2 and 3). In the disturbance class (forest harvest) only one level of non-random patterning was detected, at scale interval B.

Patch statistics provide supportive evidence that the patterns detected through the analyses are due to the configuration of patches in nested hierarchies as opposed to few large patches dominating the landscape. For instance, if a few large patches dominated the landscape then we would expect that at the finest

Table 2
Scale ranges and corresponding logarithm box values used to detect scales of relevant, non-random spatial patterning

Interval	Interval range (ha)	Logarithm box values
A	1–1376	1.4–5.0
B	1376–10172	5.0–6.0
C	10172–15175	6.0–6.2
D	15175–22638	6.2–6.4
E	22638–33772	6.4–6.6
F	33772–50383	6.6–6.8
G	50383–75163	6.8–7.0
H	75163–112130	7.0–7.2
I	112130–167278	7.2–7.4
J	167278–249549	7.4–7.6
K	249549–372284	7.6–7.8
L	372284–562500	7.8–8.0

Table 3
Spatial scales of detected non-random patch distribution (relevant scales)

Plot No.	Region	Scale intervals[a]											
		A	B	C	D	E	F	G	H	I	J	K	L
Conifer													
1	Northeast											O[c]	
2									O				
3									O				O
4	Northwest				X[b]								
5					X				X			X	
6					X						X		
7		X		X					X			X	
Mixedwood													
1	Northeast	O											O
2									O				
3									O				
4	Northwest								X				
5					X								
6					X					X			
7													
Disturbance — harvest													
1	Northeast		O										
2			O										
3			O										
Disturbance — fire													
4	Northwest		X						X			X	
5													
6			X									X	
7									X			X	

[a] Refer to Table 2 for scale interval range definitions.
[b] Indicates detection of a relevant scale in the northwest study area.
[c] Indicates detection of a relevant scale in the northeast clay belt.

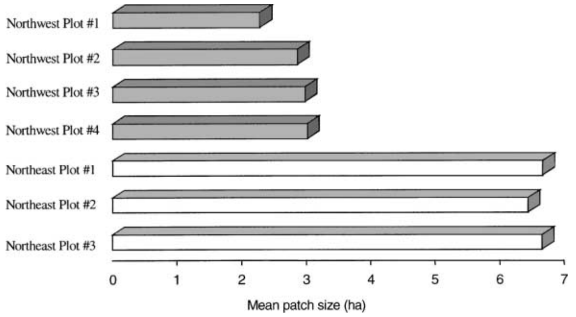

Fig. 7. Mean patch size of forest and disturbance patches in the northeast clay belt and northwest Ontario.

level (individual patches) the mean patch size would be equal to the finest level of detected scale from the lacunarity analysis. Instead the mean patch size in the northwest is between 2 and 4 ha (Fig. 7) and the detected relevant scales are all above 15 175 ha (Tables 2 and 3). Similarly, the mean size of forest and disturbance patches in the northwest landscapes are less than half the size of those in the northeast clay belt landscapes and the number of patches in the northwest is on average two times greater than the northeast (Fig. 8). This means that the detected relevant scales are a product of the nested distributions of patches. It also indicates that the landscapes are very different not only in composition, but also in structure and pattern.

In the northeast clay belt, conifer and mixedwood have non-random patterns at scales at D, H and K, whereas harvest has non-random patterns only at scale B (Tables 2 and 3). This means that the non-hierarchical pattern created by forest harvest in the northeast is not the same as the pattern created by forest wildfire disturbance in the northwest.

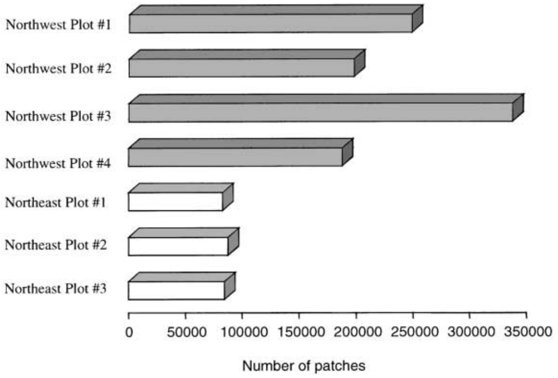

Fig. 8. Number of landscape patches in the northeast clay belt and northwest Ontario.

5. Conclusions and discussion

We found that (i) forest patterning in the landscapes with relatively little human influences have more than one detected scale and are structured hierarchically, (ii) the hierarchical structure found in the landscapes with little human influence occurs in forest and fire disturbance classes, (iii) forest patterning in the landscapes with higher human influences do not have the same hierarchical characteristics as the low human impact landscapes, and (iv) recent harvest disturbance in the landscapes with high human impact do not occur at the same scales as the forest landcover classes.

We cannot be sure that the differences in hierarchies and relevant scales in the landscapes are due to recent or historical harvest and protection (fire suppression) or were characteristics of the natural landscape. Given the high level of human influences on the northeast landscapes, it is difficult to be entirely sure what a natural landscape might have looked like in terms of pattern and structure. We do know, however, that historically this relatively humid boreal area has infrequent, but large disturbances, and that finer scale disturbance factors dominate disturbance dynamics between fire events. This type of disturbance regime is consistent with our findings. Because landscapes in the northwest are in areas with very low amounts of human intervention, and the dominant structuring processes are still wildfires, we feel more confident that the observed landscapes are similar to those created by purely natural processes.

The results from the northwest indicate that the detected scales of spatial patterning occur at the same scales in the forest and disturbance classes. Although some harvesting has occurred in the northwest, the sample plots were located in areas where the dominant disturbance is wildfire. In contrast, the northeast analysis indicates that the detected scales of spatial patterning in the forest classes are different from the disturbance class (harvest patterns). Similarly, in the forest classes we detected patterning at two broad levels and in the disturbance class at only one level.

This suggests that the spatial scale at which harvesting is creating non-random landscape patterns is not the same as the natural scales of patterning for the forest landcover classes.

6. Forest management implications

Timber management practices in the boreal forest cause a dramatic change in landscape texture relative to natural disturbances. Small, even-sized cutblocks create a fine-textured landscape that differs from the coarse-grained landscape created by sporadic wildfires. Emulating natural landscape patterns require analytical tools that allow us to describe natural landscape texture, and to detect changes in texture resulting from timber management. Holling (1992) suggests that changes in landscape structure can have significant impacts on biodiversity, so an important indicator of forest sustainability may be estimates of landscape texture. Lacunarity provides one approach to evaluating landscape texture by evaluating changes in forest pattern and nested hierarchies as forest management plans are implemented, and to monitor the direct effects of these changes on ecosystem values.

Based on our findings we feel that emulating natural disturbance requires (i) natural disturbance plans that include several levels of planning (forest management unit, subregion, region and province/state), (ii) the analysis of historic forest and disturbance landcover and attempts made to maintain historic relevant scales and hierarchies, (iii) that in the absence of historic data, analysis of current forest and disturbance cover should be evaluated and changes in current relevant scales documented and measured, (iv) that the effects of changing hierarchies should be evaluated, and (v) that the concept of hierarchical landscape patterning should be embraced and used to create landscape pattern in forest management planning processes.

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