Analysis of Hierarchical Characteristics of Landscapes in Ontario: Detecting Emergent Levels of Organization

by

Philip C. Elkie ©

A Graduate Thesis Submitted

In Partial Fulfilment of the Requirements

for the Degree of Master of Science in Forestry

Faculty of Forestry

Lakehead University

March 31, 1998

0-612-33367-1

ABSTRACT

Elkie, P.C. 1998. Analysis of hierarchical characteristics of landscapes in Ontario: Detecting emergent levels of organization.

Key Words: landscape ecology, hierarchy, lacunarity, emergent level of organization, natural disturbance, landscape pattern, remote sensing.

Hierarchy theory suggests that complex systems such as ecosystems will develop hierarchical structure that can be reflected in multiple emergent levels of organization in landscape patterning. Emergent levels of organization are defined as the scales where non-random patterning of forest landcovers occur. Forest policy initiatives that address sustainable forest ecosystems, as opposed to sustainable fibre yield, provide direction for the emulation of natural landscape patterns when allocating timber harvest blocks. Emergent levels of organization and scale-dependent structure of landscapes are new issues, which until recent advances in technology, have been difficult to tackle. I use thematic landcover maps, derived from satellite imagery, to evaluate the hypotheses that among regions divided by boundaries that are based on broad-scale climatic processes, emergent levels of organization within landscape structure do not exist, and if they do, that they do not differ among regions. I use lacunarity and landscape statistic analyses on sample plots of 400 km^2 and 5,625 km^2 to detect and compare emergent levels of organization. Hierarchical characteristics, in the form of multiple emergent levels of organization, were not consistently detected in the 400 km^2 sample plots. In contrast, multiple emergent levels of organization were detected in the 5,625 km^2 sample plots located in northwestern Ontario but not in northeastern Ontario. The hierarchical characteristics detected in northwestern Ontario were in both mature overstory forest and recent fire disturbance. Current landscape patterns are a result of recent historic disturbance regimes. The results indicate that by emulating current patterns at fine-scales through forest harvest, the resulting landscape patterns could be mature forests with hierarchical characteristics similar to natural systems. Broad-scale patterns in the form of emergent levels of organization exist within and among individual forest management units. The results indicate that if sustainable ecosystems are an objective of natural resource management, management strategies that include multi-scale analyses and planning techniques are necessary.

CONTENTS

TABLES

FIGURES

LIBRARY RIGHTS STATEMENT

In presenting this thesis in partial fulfilment of the requirements for the M.Sc.F. degree at Lakehead University at Thunder Bay, I agree that the University shall make it freely available for inspection.

This university thesis is made available by my authority solely for the purpose of private study and research and may not be copied or reproduced in whole or part (except as permitted by appropriate Copyright Laws) without my written authority.

Signature ______________________________

Date _________________________

CAUTION TO THE READER

This M.Sc.F. thesis has been through a formal process of review and comment by at least three faculty members and an external reader.

It is made available for loan by the faculty for the purpose of advancing the practice of professional and scientific forestry.

The reader should realize that the opinions expressed in this document are the opinions and the conclusions of the student and do not necessarily reflect the opinions of either the supervisor, the faculty, or the University.

ACKNOWLEDGEMENTS

This thesis is dedicated to my father, Ron Elkie, who passed away suddenly in my second year of graduate studies.

It is with much gratitude that I thank Dr. Rob Rempel. Rob has been nothing less than a mentor and friend to me over the last five years.

I also thank Anne, Krista, and Zachary who have put up with my dreams to study forests and ecology. Thanks also go out to Dr. Ulf Runesson, Dr. Peter Duinker, Michael Gluck, and Dr. Gustafson for providing direction on the thesis project.

INTRODUCTION

LANDSCAPE ECOLOGY

Habitat fragmentation is one of the most influential impacts humans have had on forested landscapes (Spies *et al.* 1994). The size, shape, and composition of landcover themes (i.e., overstory forest vegetation classes) in landscapes can influence ecological processes such as animal dispersal, speciation, and extinction (Krummel *et al.* 1987, Holling 1992, Spies *et al.* 1994, Rempel *et al.* 1997,). Understanding how the geometric shape and size of landcover themes are related to natural and human processes can help in determining the appropriate spatial and temporal scales to use in studying and managing ecological systems (Krummel *et al.* 1987).

Landscape ecology is the study of relationships between spatial structure and ecosystem function at various scales (Turner 1989). It considers development and dynamics of spatial heterogeneity, interactions and exchanges across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes, and management of spatial heterogeneity (Turner 1989). Ecosystem function is the flow of energy, materials, species, and genes in relation to ecosystem components (Forman and Godron 1986). Structure refers to the distribution of energy, material, species, and genes in relation to the sizes, shapes, numbers, kinds, and configurations of ecosystems (Forman and Godron 1986) at any given level of organization (Allen *et al.* 1987).

Distinct patterning of habitats and landcover types often exist in heterogeneous landscapes. Heterogeneity is the spatial variance in two components of landscape structure, contrast and aggregation (Kotlair and Wiens 1990). Contrast is the degree of difference between patches, and aggregation is the spatial distribution or clumpiness of patches (Kotlair and Wiens 1990). A patch is an area that differs from its surroundings and contains a relative degree of homogeneity within (Kotlair and Wiens 1990, LaGro 1991).

Terminology related to scale and emergent levels of organization (ELO) in landscape ecology must be defined carefully. I use the definition of scale proposed by Turner and Gardner (1991): scale is the spatial dimension of an object, characterized by grain and extent, where grain is the finest level of spatial resolution in an observation set, and extent is the areal expanse over which observations with a particular grain are made (King 1991, Turner and Gardner 1991). I define an ELO as the scale within a landscape where a non-random pattern of landcover structure is evident. I define a non-random pattern as a spatial arrangement in a landscape where the overstory forest vegetation characteristics exhibit specific clumping or aggregation.

HIERARCHY THEORY IN ECOLOGY

At any point in time the state of an ecosystem can be characterized, but an event or series of events (i.e., processes) can change that state (Rudd *et al.* 1984). Complex processes can be divided into simpler processes (e.g., landscape dynamics - stand succession - plant growth - photosynthesis - Krebs cycle), hence a hierarchy of processes (Rudd *et al.* 1984). Similarly, ecosystem structure in the form of landscape patterning can exhibit hierarchical characteristics. For example, a single patch in a landscape at a certain resolution might form a series of smaller patches at a finer resolution, or in contrast, might be one of several patches contributing to a single patch at a broader resolution (Kolasa 1989, Kotlair and Wiens 1990, Baker 1993).

Hierarchy theory states that complex natural systems, such as landscapes, will develop hierarchical structure (O'Neill *et al.* 1992). The hierarchical structure can be reflected in multiple levels of spatial patterning, composition (O'Neill *et al.* 1992), and texture (Plotnick *et al.* 1993). Klijn and Udo de Haes (1994) present a simplified hierarchical model of an ecosystem (Figure 1). The hierarchical character of the model

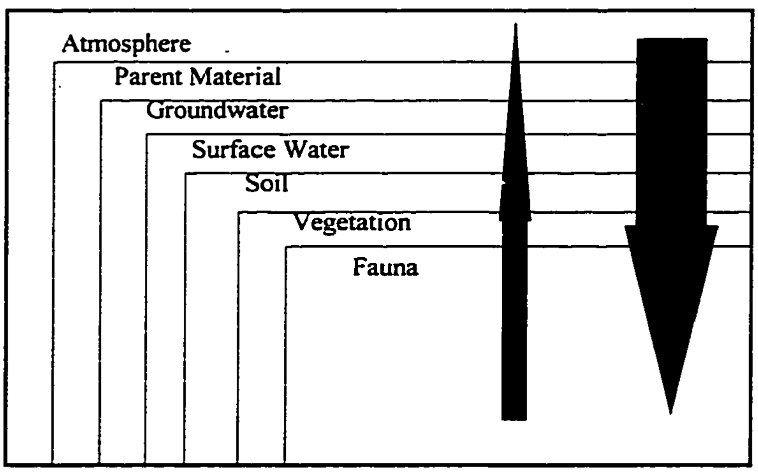


Figure 1. A simple hierarchical model of an ecosystem. The width of the arrows represents the relative degree to which the lower and higher components depend on each other (Klijn and Udo de Haes 1994).

is illustrated in that the lower components are relatively dependent on those above, and to a lesser degree, the higher components are relatively dependent on those below. The model is supported by a hierarchy of structure (i.e., spatial extents diminish in size:

parent material > soil > vegetation > fauna) and a hierarchy of processes (i.e., energy and matter are generally directed downward).

King (1991) presents a more detailed hierarchical model representing ecosystem dynamics in a forest landscape (Figure 2). Both spatial and temporal scales contribute to

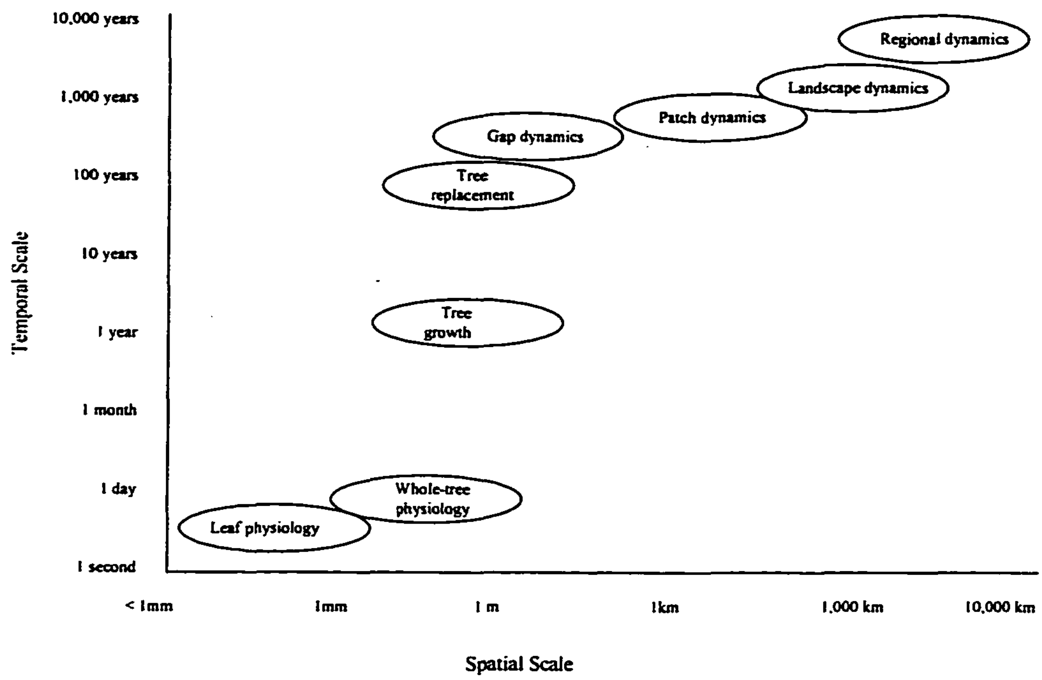


Figure 2. A nested hierarchical representation of carbon/biomass dynamics in a forested landscape. The ellipses represent emergent levels of organization within a structured hierarchy (King 1991).

the hierarchical characteristics of the model. The nested hierarchy includes successively higher ELO with each level linked by changes in grain and extent of the observation set describing that system (King 1991).

Organisms view and use landscapes at different scales for different ecological processes (e.g., foraging and reproduction) (Plowright and Galen 1985, Nellis and Briggs 1989, Holling 1992, Baker 1993). Odum (1977) states that as components or sub-units are combined to produce larger functional wholes, new properties emerge which did not exist or were not evident at lower levels. These differences in scale--dependent properties can influence decisions made by animals (Holling 1992). Kolasa (1989) suggests that specialization between species differs, and as a result, resource requirements will also differ. Species that are specialists respond to finer-grained patches than species that are generalists (Kolasa 1989).

Baker (1993) suggests that in landscapes subject to broad-scale natural disturbance such as fire, scale-dependent patterns of landscape change are apparent. These types of natural disturbance landscapes exist in the Boreal forest region of Ontario (Johnson 1992).

Holling (1992) tested several hypotheses in an attempt to explain bird and mammal body-mass clumps in the Boreal forest region and the short-grass prairie, where breaks in the frequency distribution of body sizes of a range 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. Holling (1992) suggests that discontinuous landscape structure and texture across scales interacting with varying temporal frequencies affect decisions made by animals. In concluding he provides direction for future research to evaluate, monitor, and predict ecosystem and community changes across scales, including analysis of remotely sensed imagery to identify spatial discontinuities and regions of scale invariance (Holling 1992).

SITE REGIONS IN ONTARIO

Development and refinement of site regions in Ontario have continued since the 1950's (Hills 1952, Hills 1960, Hills 1976, Burger 1993). Burger (1993) defined site regions as:

> "Regions within which specific plant successions occur upon specific landform positions. Or, conversely, similar positions in a landform (as characterized by relief and geological material) within different site regions will support different plant successions."

Thirteen site regions have been established primarily along macroclimatic gradients within the province (Figure 3) (Burger 1993). Humid regions exist over a west to east gradient (Figure 3). The site regions have been developed to assist forest and land resource managers to understand the dynamic relationships among trees, soil, and climate (Burger 1993). A substantial component of the province's timber harvest occurs in site regions 3E, 3S, 3W, 4W, 4S, and 4E (Figure 3). Major differences in physiographic features (e.g., topography and soil regimes) exist among site regions. For instance, the most common landform in site region 3E is undulating clay plains (Hills 1959). 3E is unique when compared to the other regions in northern Ontario where timber is harvested. For example, in regions 3W, 3S, 4S, 4W, and 4E the most common

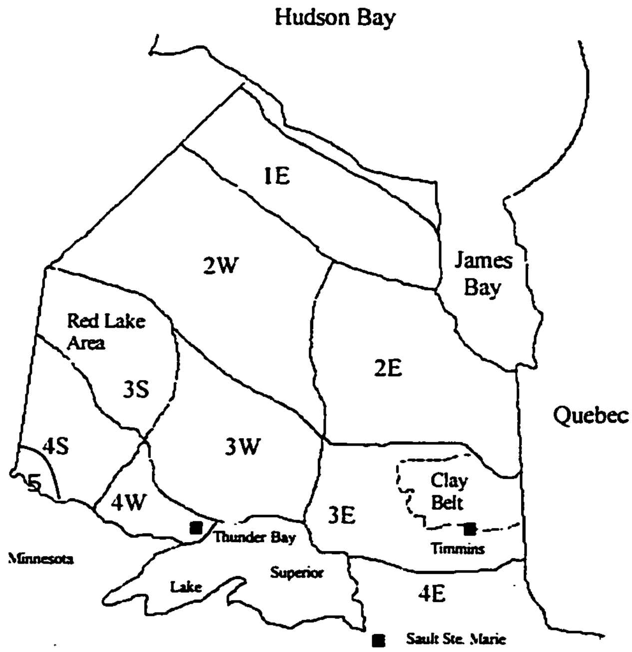


Figure 3. Location of Site Regions, Clay Belt, and Red Lake Area in northern Ontario. Regions based on effective humidity include: E-humid eastern Ontario, W-humid western Ontario, and S-subhumid western Ontario (Burger 1993, Jones *et al.* 1983).

landforms are rolling rocky uplands with ridges of lime rich sand and clay plains (Hills 1959). In fact, 3E contains the western section of a clay belt (Figure 3) (Jones *et al.* 1983, Rowe 1972).

Although all of the site regions where timber harvest is common are found in the Boreal forest region with common flora throughout, Rowe (1972) subdivided the forest region into finer classes indicating differences in spatial extent and distributions of common flora. For example, 3E contains the Ontario extent of the Boreal Forest - Northern Clay Forest Region (Figure 3). Rowe (1972) characterizes 3E as containing seemingly endless stretches of black spruce (*Picea mariana* (Mill.) B.S.P.) stands that cover the gently rising uplands and the lowland flats. In contrast, Rowe (1972) describes the main body of forest cover in the Boreal Forest - Upper English River Forest Region, an area east of Lake Nipigon and Northwest of the City of Thunder Bay, as consisting of black spruce and jack pine (*Pinus banksiana* Lamb.) with mixtures of white spruce (*P. glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.), trembling aspen (*Populus tremuloides* Michx.), and white birch (*Betula papyrifera* Marsh.).

FOREST POLICY IN ONTARIO

Differences in forest landcovers among regions have not been completely recognized in the context of forest management policy. Forest policies in Ontario include guidelines designed to assist forest managers in producing and protecting wildlife values, fish values, and tourism values. The guidelines are general, and although they address differences in broad forest regions (e.g., Great Lakes St. Lawrence and Boreal), they do not necessarily address differences in specific site regions. The northwest and southeast regions of the province are located in Canadian shield topography that is characterized by rough and rolling rock outcrops, extensive sand and gravel deposits, and shallow swamps and bogs (Rowe 1972). The physical characteristics of these areas facilitate relatively small timber harvest cutblocks (i.e., +/- 120 ha as prescribed in the Timber Management Guidelines for the Provision of Moose Habitat) (OMNR 1988). In contrast, the Clay Belt in the northeast is composed of wide-spread, water-worked tills and lacustrine materials with very little variation in topography (Figure 3) (Rowe 1972). Given these physical characteristics, the Clay Belt can facilitate much larger cuts.

In the early 1990's the sustainable development paradigm shifted to a sustainable ecosystem paradigm. This is reflected in many policy initiatives including Ontario's Crown Forest Sustainability Act (CFSA) (Legislative Assembly of Ontario 1994). The CFSA is a result of several provincial activities, including decisions based on the environmental assessment hearing on timber management on Crown lands in Ontario (Ontario Environmental Assessment Board 1994), an Environmental Bill of Rights (Legislative Assembly of Ontario 1995), and the Ontario Forest Policy Panel's report "Diversity: Forests, Peoples, Communities" (Ontario Forest Policy Panel 1993), which led to a Policy Framework for Sustainable Forests (OMNR 1994), to name a few.

The CFSA states:

> "The long term health and vigour of Crown forests should be provided for by using forest practices that, within the limits of silvicultural requirements, emulate natural disturbances and landscape patterns while minimizing adverse effects on plant life, animal life, water, soil, air, and social and economic values, including recreational values and heritage values" (Legislative Assembly of Ontario 1994).

As part of the terms and conditions of the Class Environmental Assessment for Timber Management on Crown Lands in Ontario, the Environmental Assessment Board states in its reasons for decision and decisions:

> "MNR shall undertake long-term scientific studies to assess the effectiveness of the provincial guidelines for moose and fish habitat and tourism values. These studies shall include an assessment of the effects of current timber management practices on moose and other wildlife habitat, fish habitat, and tourism values" (Ontario Environmental Assessment Board 1994).

To manage forested ecosystems in ways that emulate natural disturbances and consequently create natural landscape patterns, we need baseline data and knowledge of natural landscape patterns. Forest harvesting and fire suppression have been ongoing for over a century in many parts of the province and this makes it difficult to obtain relevant natural disturbance and landscape pattern data.

HYPOTHESIS

In the context of ecological hierarchy theory, atmospheric processes that include precipitation and temperature occur at broad temporal and spatial scales. Therefore, the macroclimatic boundaries used and further developed by Hills (1952, 1960, and 1976) and Burger (1993) should explicitly represent areas where similar hierarchical characteristics in landscape patterns occur. Similarly, wildfire is a natural process that occurs at broad spatial and temporal scales (Johnson 1992). Areas that experience similar spatial and temporal frequencies of wildfire should have similar hierarchical characteristics in landscape patterning.

Based on Holling's (1992) premise that dominant processes entrain less dominant processes and these processes structure ecosystems, I test the null hypotheses that among regions divided by boundaries that are based on differences in broad scale climatic processes, ELO within natural landscape structure do not exist, and if they do, that they do not differ among regions.

I define natural landscape structure and composition in terms of mature (ca. >30 yr.) overstory forest detected by the Landsat Thematic Mapper (TM) satellite system and mapped by the Ontario Ministry of Natural Resources's (OMNR) ecological landcover mapping program. Although I use the term natural landscape structure, many of the forests have been harvested and the overstory compositions are a direct result of second and often third generation post-harvest growth. Similarly, within the last 30 –50 years an extensive fire suppression program has been ongoing in much of the province and the resulting landscape patterns could be affected.

DETECTING EMERGENT LEVELS OF ORGANIZATION

LACUNARITY

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 launar if they were evenly distributed across the map (Figure 4).

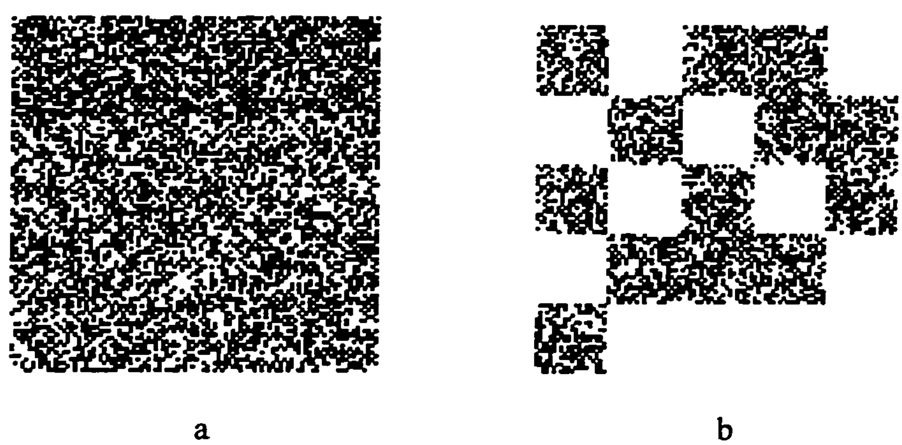


Figure 4. An example of two hypothetical landcover maps with different relative lacunar properties. At the finest resolution, map (a) is translationally invariant and less lacunar than map (b).

Gefen *et.al.* (1983) described lacunarity more precisely, and used the term translational invariance. Conceptually, translational invariance is a continuum from a very even (random or regular) patch dispersion where translational invariance is high, to a very irregular (contagious or clumped) dispersion where translational invariance is low. Lacunarity can be used as a spatial metric that describes a landscape's texture in terms of its position along this continuum. Lacunarity, however, 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: (1) if texture remains unchanged across scales, and (2) if not, the spatial scale(s) at which the texture changes.

This scale-dependent metric of landscape pattern can then be used to search for textural discontinuties in the landscape, and test my hypothesis that such discontinuities are absent. If the discontinuties exist, then there exists an emergent level of organization (ELO) where a lower-level patch structure is nested within a higher-level patch structure. If more than one such discontinuity is present, then I would interpret this to mean that the landscape is structured or patterned hierarchically. If such a hierarchical structure exists, then abrupt changes or inflections in the lacunarity response curve will identify the spatial scales at which the ELO occur.

Method of Calculation

The method of calculating lacunarity is statistically analogous to calculating the variance to mean ratio for boxes of progressively larger size. This approach to the study of spatial dispersion has a long history in the biological sciences. For example, Elliot (1977) discusses use of the variance to mean ratio of benthic sample plots to detect deviation from a Poisson (random) distribution. He also discusses use of progressively larger sample plots to detect the scale at which clumped distributions occur. A conceptually similar approach will be described here to detect deviations from a random patch distribution, and to detect the spatial scale at which clumping occurs. Consider the maps depicted in Figure 4, where black pixels equal 1 (i.e., have a mass of 1) and white pixels equal 0. In Figure 4a the distribution of black pixels is more or less random, while in Figure 4b, the distribution is clumped. By passing boxes, or "sample plots" of progressively larger size across the landscape, the mean density (mass) of black pixels, and resulting variance to mean ratio (i.e., lacunarity), can be calculated for the range of box sizes. The lacunarity function decreases monotonically with box size because as box size increases, variance from the average decreases. If no clumping is present in the landscape the curve will be a smooth, decreasing line simply reflecting the increasing box size. If clumping occurs, an inflection in the line will occur at the point where an abrupt change in the variance to mean ratio occurs.

Calculation of lacunarity is achieved using an algorithm developed by Allain and Cloitre (1991) that is appropriate for landcover maps. Figure 5 is a 50 pixel x 50 pixel map with a probability of 0.5 that any given pixel is black. Consider a 2^2 pixel gliding box applied to Figure 5. At the upper left starting position, 3 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 until the map edge is encountered, moves down one pixel, continues to the left, etc., until box mass is calculated for the entire map. The result is a frequency distribution of box masses (Table 1).

Figure 5. A single-level 50 pixel X 50 pixel map created by the curdling algorithm with probability of pixel occurrence set at 0.5.

Table 1. Frequency distribution and subsequent calculation of lacunarity of a 50 pixel x 50 pixel landcover map (Figure 5), where $r = 2$. S is number of occupied sites or box mass; $n(S,r)$ is the frequency of boxes with mass S; $Q(S,r)$ are corresponding probabilites; $Z^{(1)} = \sum S + Q(S,r)$ and $Z^{(2)} = \sum S^2 + Q(S,r)$ (i.e., first and second moments). Lacunarity $L(r) = Z^{(2)}/(Z^{(1)})^2$. Adapted from Table 1, Plotnick *et.al.* 1993.

Image Size: 50 x 50

S	n(S,r)	Q(S,r)	SQ(S,f)	S²Q(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	$Z^{(3)}$=4.9483

L(r) = 1.2334

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 probabilites by dividing by the total number of boxes:

$$Q(S,r) = n(S,r)/N(r)$$

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

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

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

Lacunarity is defined as:

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

In his description of the lacunarity calculation, Plotnick *et.al.* (1993) also notes that in statistical annotation:

$$Z^{(1)} = \bar{S}(r),$$

$$Z^{(2)} = s^2_s(r) \text{ t } \bar{S}^2(r)$$

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

$$L(r) = s^2_s(r)/\ \bar{S}^2(r) + 1.$$

Lacunarity Analysis of Baseline Models

To evaluate lacunarity response of natural conditions, I first constructed a model 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, I used the curdling algorithm to generate 3 hypothetical hierarchical landcover maps with nested non-random patterns (Figure 6) (Allain and Cloitre 1991). The curdling algorithm is a method of producing

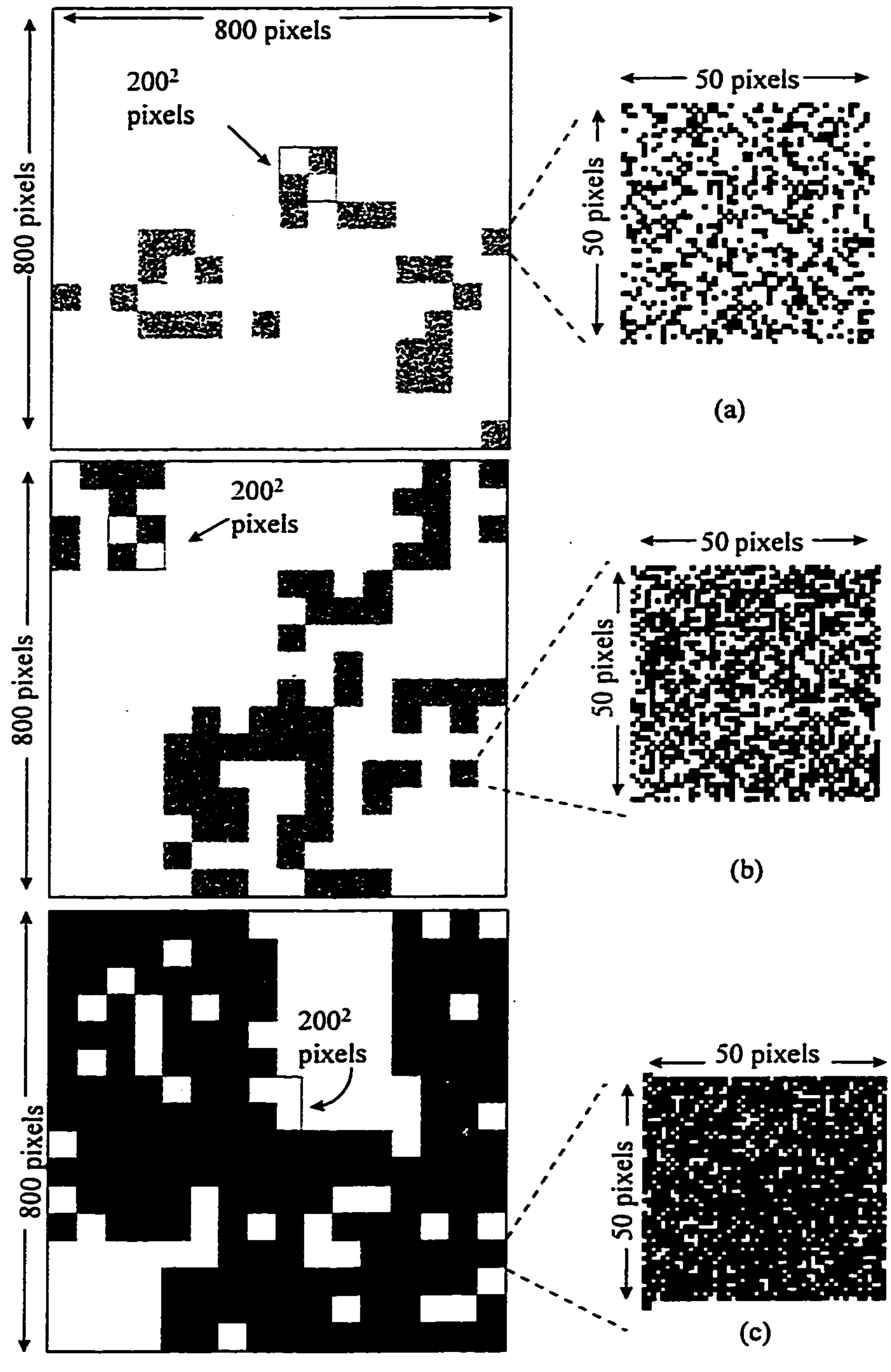


Figure 6. Three hierarchical maps, each with two levels of organization, generated using the curdling algorithm. The first level of organization is 50^2 pixels and the second level is 200^2 pixels. For both levels of maps (a), (b), and (c), respectively, the probability of pixel occurrence is 0.3, 0.5, and 0.8.

maps of pixels with differing texture characteristics. The texture characteristics are based on pixel probability occurence being set at single or multiple scales (e.g.,ELO). The nature of the hierarchy is shown in the two levels of organization within each map. The curdling algorithm uses a top-down approach when building hierarchical maps. The first level of organization is in clumps of 50^2 pixels and the second level is 200^2 pixels (Figure 6). The probability of pixel occupancy was set to 0.3, 0.5, and 0.8 for maps (a), (b), and (c), respectively, and defines pixel density in the three maps. The slope of log lacunarity versus log box size changes abruptly when an ELO is detected (Figure 7). For instance, a pronounced change in

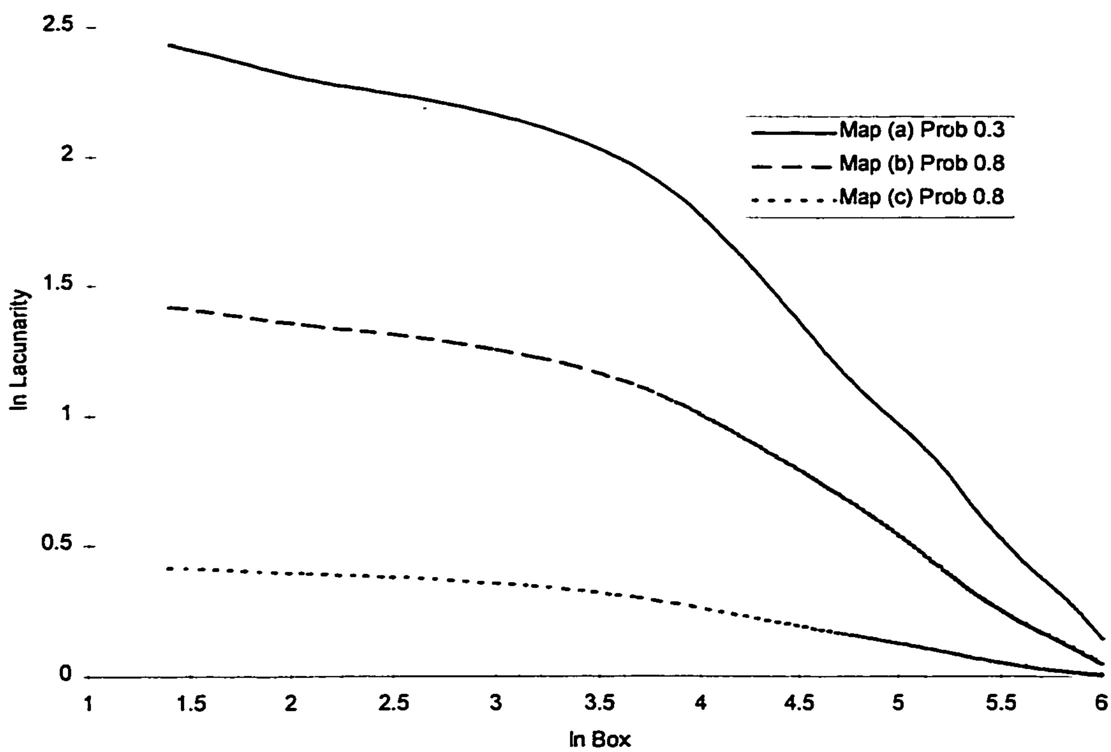


Figure 7. Lacunarity curves for three landcover maps, generated using the curdling algorithm, each at two levels of organization (e.g., 50^2 pixels and 200^2 pixels). The probability of pixel occurrence was set at 0.3, 0.5 and 0.8 for maps (a), (b) and (c), respectively (Figure 6).

slope at ln Box 3.9 (i.e., 50^2 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 of 50^2 pixels in map (a). Gap sizes are more variable in map (a) than map (b), and more variable in map (b) than map (c). Therefore, map (a) is relatively more lacunar than map (b), and map (b) more than map (c).

At the second level of organization (i.e., ln 5.29, or 200^2 pixels) a change in direction of the lacunarity curves is less pronounced. The 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 200^2 pixels and map (c) does not. The lacunarity curves highlight these differences.

Figure 8 is an illustration of three hypothetical landcover maps created from the curdling algorithm. In contrast to the maps in Figure 6, these maps are not hierarchical. Similar to Figure 6, these maps were created with pixel densities of 0.3, 0.5, and 0.8 for maps (a), (b), and (c), respectively. The behaviour of lacunarity curves for the non-hierarchical maps differ from those of the hierarchical maps (Figure 9). 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 behaviour, I can detect ELO and predict hierarchical characteristics. By examining the y - intercept, I can make relative comparisons of the distribution of gap sizes and the magnitude of lacunarity at detected scales.

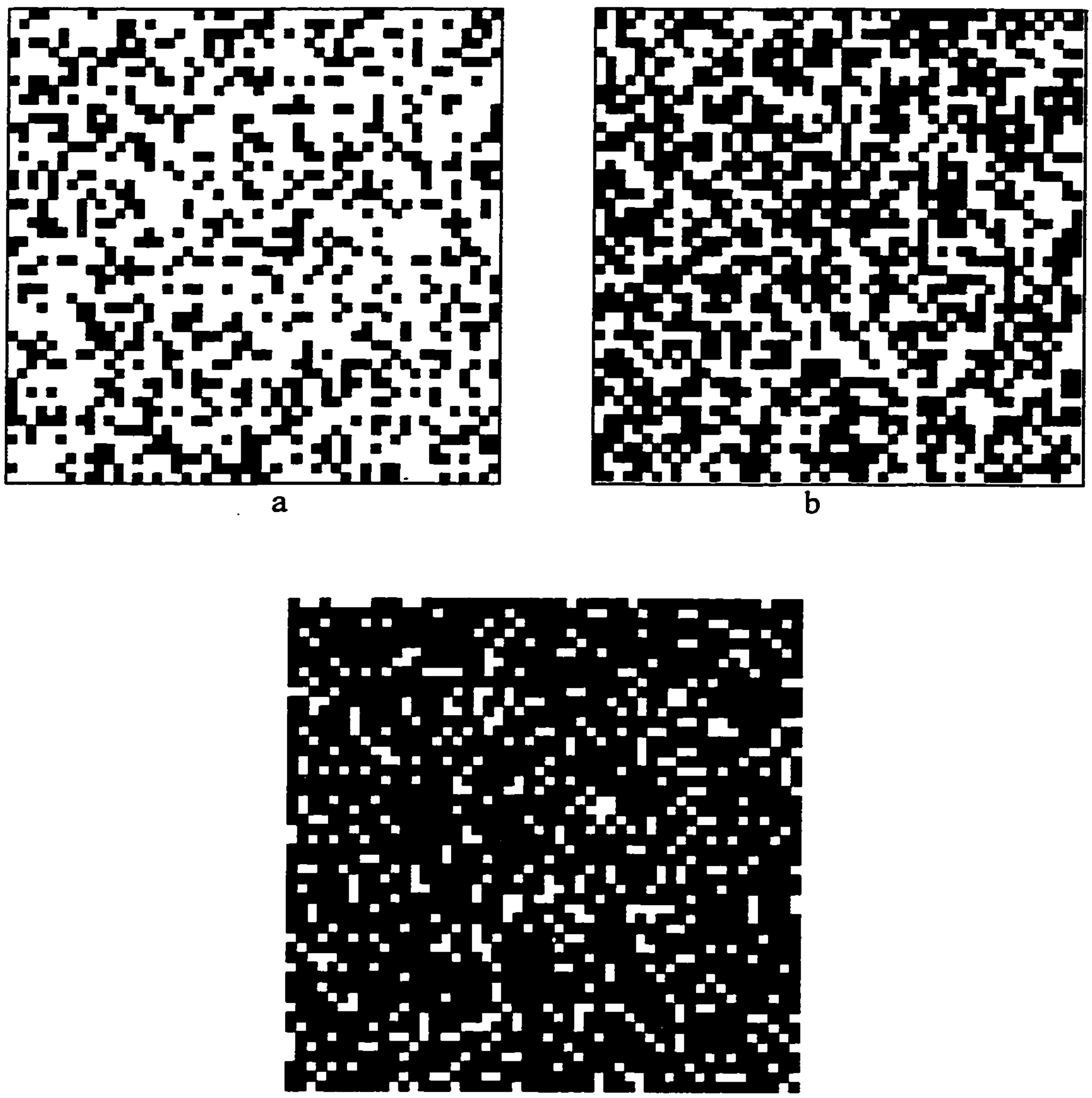


Figure 8. Three 50^2 pixel non-hierarchical hypothetical landcover maps created using the curdling algorithm with single pixel occurrence probabilities set at 0.3, 0.5, and 0.8 for maps (a), (b), and (c), respectively.

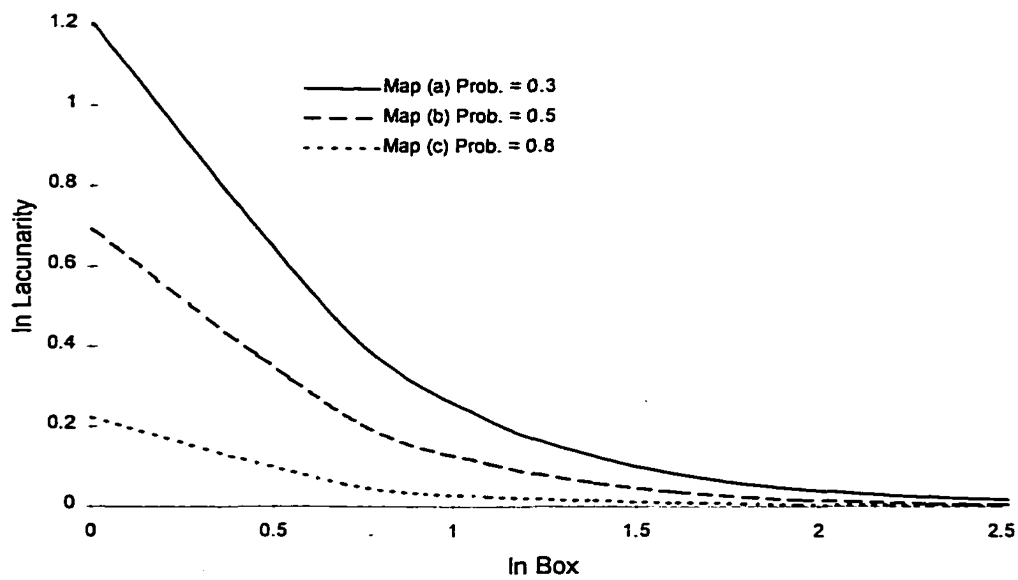


Figure 9. Lacunarity curves derived from three 50^2 pixel hypothetical non-hierarchical landcover maps (Figure 8) with single pixel occurrences of 0.3, 0.5, and 0.8.

ACCURACY ASSESSMENT OF PROVINCIAL LANDCOVER MAPS

THEMATIC LANDCOVER MAPS

The Ontario Ministry of Natural Resources (OMNR) has produced a provincial landcover map through a classification of LANDSAT TM imagery, and my lacunarity analysis is based on an aggregation of landcover classes from these maps (Table 2). The classification of the imagery was supervised and post-processing included resampling the maps to 25 metre resolution. The provincial map was created by 3 producers (2 contractors and OMNR staff) over the period 1993-96 in 9 separate stages (Figure 10). Only maps 1, 2, 3, 5, 6, and 8 were used in this study, and of these, map 6 was created by contractor B, and the other 5 by contractor A. Only a qualitative assessment of accuracy existed for these maps, so I conducted a quantative analysis of thematic accuracy on all 6 maps, and then contrasted thematic detail and accuracy of maps created by contractor A versus contractor B. The purpose of the analysis is to assess whether the data is of sufficient quality to test my hypothesis, and to determine any limitations.

METHODS

I assessed the accuracy of the thematic landcover maps using 150 1:15,840 panchromatic black and white aerial photographs taken between 1978 and 1994. I randomly choose the photographs within a stratification among thematic maps 1, 2, 3, 5, 6, and 8 (Figure 10). I used the stratification to assess classification accuracy equally across the spatial extent of the study area. Up to 161 points for each landcover class

Table 2. Landcover themes of the Provincial ecological landcover maps.

Landcover Class Number	Theme and Definition
1-3	Water bodies - shallow, sedimented and deep water
13-22	Wetlands - all including treed shrub rich, treed bog and open graminoid
24	Dense deciduous forest - > 80 % deciduous
26	Dense coniferous forest - mainly (>80%) jack pine
27	Dense coniferous forest - mainly (>80%) black spruce
29	Mixed forest - mainly deciduous (>50% deciduous)
30	Mixed forest - mainly coniferous (>50% coniferous)
31	Sparse / open conifer
32	Sparse / open deciduous
34	Recent clear Cuts (<10 years old)
35	Recent burns (<10 years old)
36	Old burns and cutovers (>10 years old)
37	Bedrock
38	Mine tailings
39	Urban areas
42	Agriculture

were randomly located on the photographs and thematic maps. Less-variable classes (e.g., water) were assigned fewer points than more-variable classes (e.g., conifer). Rather than evaluating individual pixels, I evaluated clusters of between 10 and 25 pixels. I compared my interpretation of points on the photographs to those on the thematic maps, and vice versa (Congalton 1991). I combined landcover classes because it became apparent when comparing maps that differences in levels of detail existed. The greatest amount of contrast in levels of detail were observed between map 6 and maps 2 and 8. The differences generally included a broader classification of the conifer classes (i.e., 26 and 27), mixedwood classes (i.e., 29 and 30), and sparse classes (i.e., 31 and 32) by the contractor (Table 3).

Figure 10. Location of ecological thematic landcover maps. Solid lines represent map and lake boundaries. Maps 1,2,3,5,6, and 8 were used in this study. Maps 1,2,3,5, and 8 were produced by contractor A, and map 6 by contractor B.

Table 3. Combined landcover classes from the Provincial ecological landcover maps, for which accuracy was assessed.

Combined landcover class theme	Combined landcover classes *
Conifer	26 and 27
Mixedwood	29 and 30
Sparse	31 and 32
Disturbance	34, 35 and 36

* Refer to Table 2 for definitions of landcover classes.

I produced an accuracy matrix for maps 1, 2, 3, 5, and 8 combined, and another for map 6. Exclusion accuracy (omission), inclusion accuracy (commission), and total map accuracy with 95% confidence levels were calculated (Equations 2, 3, and 4, respectively).

Exclusion (omission) accuracy for a single theme:

$$= \frac{\text{\# of photograph observations in agreement with classified image}}{\text{total number of photograph observations}} \text{ X } 100 \quad (2)$$

Inclusion (commission) accuracy for a single theme:

$$= \frac{\text{\# of classified image observations in agreement with photographs}}{\text{total number of classified image observations}} \text{ X } 100 \quad (3)$$

(Congalton 1991, Gluck *et al.* 1996)

$$\text{Total Map Accuracy} = \frac{\text{Sum of all observations in agreement}}{\text{Sum of all observations}} \quad (4)$$

(Congalton 1991, Story and Congalton 1986)

RESULTS

Both the map produced by contractor A and B are the same in total map accuracy, 73% (Tables 4 and 5). However, differences in exclusion and inclusion of mature forest between maps is apparent (Tables 4 and 5). For instance, as compared to map 6, the maps produced by contractor A have higher inclusion accuracy in wetlands, deciduous, conifer and mixedwood classes. In contrast, the maps produced by

Table 4. Exclusion, inclusion, total map accuracy, and 95% confidence levels for the landcover maps producéd by contractor A (i.e., maps 1, 2, 3, 5 and 8- Figure 10). Confidence levels based on binomial distribution and sample size.

Class	Exclusion (%)	95% confidence Interval (%)	Inclusion (%)	95% confidence interval (%)
Wetlands	67	55 - 78	90	81 - 98
Deciduous	61	49 - 72	75	64 - 87
Conifer	78	71 - 86	85	78 - 91
Mixedwood	77	70 - 85	63	55 - 71
Sparse	60	47 - 72	57	45 - 69
Young	76	65 - 87	62	51 - 74
Water	97	91 - 100	100	n/a

Total Map Accuracy 73 % (69% - 77%)

Table 5. Exclusion, inclusion, total map accuracy, and 95% confidence levels for the landcover map produced by contractor B (i.e., map 6 - Figure 10).

Class	Exclusion (%)	95% confidence Interval (%)	Inclusion (%)	95% confidence interval (%)
Wetlands	68	48 - 89	76	56 - 97
Deciduous	71	38 - 100	45	16 - 75
Conifer	98	93 - 100	71	60 - 83
Mixedwood	50	28 - 72	53	30 - 75
Sparse	39	21 - 57	79	57 - 100
Young	83	66 - 100	94	82 - 106
Water	100	n/a	100	n/a

Total Map Accuracy 73% (66% - 80%)

contractor A have lower inclusion accuracy in the sparse and young classes (Tables 4 and 5). Confusion between sparse and mature forest, and young and wetland, is higher in the maps produced by contractor A (Tables 6 and 7).

Table 6. Confusion matrix for the landcover map produced by contractor B (i.e., map 6 - Figure 10). Values within the matrix are number of groups of pixels assessed.

Landcover Class	Wetlands	Deciduous	Conifer	Mixedwood	Sparse	Young	Water	Totals
Wetlands	13	0	0	0	2	2	0	17
Deciduous	3	5	0	2	0	1	0	11
Conifer	0	0	40	7	9	0	0	56
Mixedwood	1	2	0	10	6	0	0	19
Sparse	1	0	1	1	11	0	0	14
Young	1	0	0	0	0	15	0	16
Water	0	0	0	0	0	0	13	13
Totals	19	7	41	20	28	18	13	146

Table 7. Confusion matrix for the landcover maps produced by contractor A (i.e., maps 1, 2, 3, 5 and 8 - Figure 10).). Values within the matrix are number of groups of pixels assessed.

Landcover Class	Wetlands	Deciduous	Conifer	Mixedwood	Sparse	Young	Water	Totals
Wetlands	44	0	1	0	3	0	1	49
Deciduous	2	43	0	9	2	1	0	57
Conifer	1	1	94	8	7	0	0	111
Mixedwood	6	25	9	91	9	4	0	144
Sparse	3	1	10	6	37	8	0	65
Young	10	1	6	4	4	42	0	67
Water	0	0	0	0	0	0	0	0
Totals	66	71	120	118	62	55	1	493

DISCUSSION

The maps produced by contractor A and B have the same overall accuracy, but exclusion and inclusion accuracy are different. As an end user of pre-classified thematic maps I am mostly concerned with how well the map themes represent the actual landscape features, and inclusion accuracy best describes this relationship. When I sample an area and measure landscape indices, it is important to realize that the thematic maps are models of the real landscape. Effective spatial resolution is 30 m with Landsat TM data (Lillesand and Kiefer 1987). Landscape features finer than 30 m can be lost, and often non-linear features up to 60 m are lost.

Discrete classification of Landsat TM data into forest classifications based on statistical spectral groupings can be limiting. For instance, topography, mixed species, complex vertical structures, bidirectional reflectance, and the limited number of spectral bands can all contribute to the spectral groupings. However, the hierarchical hypothesis being tested focuses primarily on broad-scale mature-forest landcover classes. Inclusion accuracies for mature mixedwood and conifer forest are above 73% in maps 1,2,3,5, and 8, and above 63% in map 6. Mixedwood and conifer are the primary landcover themes of interest.

I believe that the provincial landcover maps are appropriate, and sufficiently accurate, for testing the hierarchical hypothesis. Confusion in discriminating between mature forest landcover classes exists and is a small source of inaccuracy. Confusion between the sparse and mature-forest landcover classes could introduce some errors, but the area in the sparse class is small and large areas are few. This could have the effect of detecting erroneous ELO at fine scales.

HIERARCHICAL LANDSCAPE STUDY DESIGN

I used two approaches to test the hypotheses that ELO do not exist within natural landscape structure, and if they do, that they do not differ among regions. In the first approach, which hereafter is referred to as the fine-scale approach, I located 97 sample plots (400 km^2) on the landcover maps (Figure 11). The locations of the sample plots were selected by moving a 400 km^2 box across the landcover maps and stopping when selection criteria were reached. The objective was to measure spatial variance in natural landscape structure defined by mature overstory forest, so I selected plots with as little human activity, water, and disturbance as possible. ELO in natural landscape patterns may be affected by levels of water, disturbance, and human activity, and 97 was the maximum number of sample plots that fit on the landcover maps and still met the selection criteria. I chose 400 km^2 as the size of sample plots because: (i) if plots were larger, the number of plots that met the selection criteria was much lower than 97, and the degrees of freedom associated would be low, and (ii) based on harvest-block sizes of +/- 120 ha, as prescribed by the provincial moose habitat guidelines (OMNR 1988), 400 km^2 sample plots are about 300+ times greater than 120 ha, and hence would be feasible for detection of multiple levels of organization within a forest management context. Figures 12-14 are examples from each humid region.

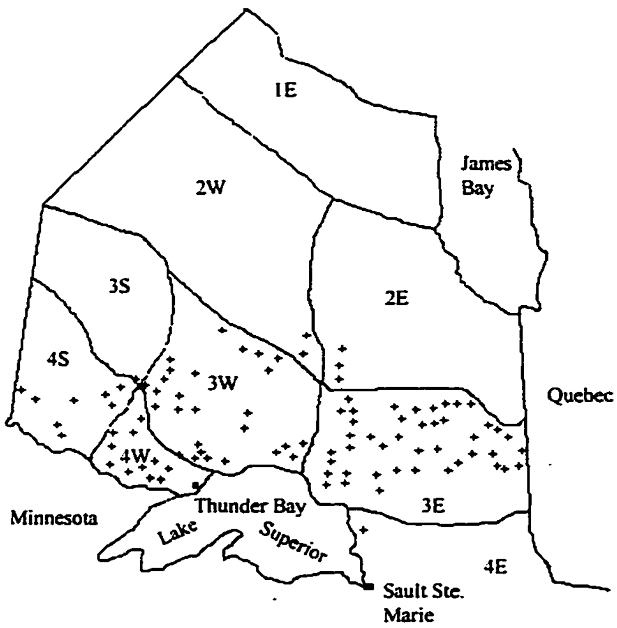


Figure 11. Distribution of 400 km^2 sample plots. Where +'s represent the approximate centre points of sample plots. E - East humid region, W - West humid region, and S - sub humid region.

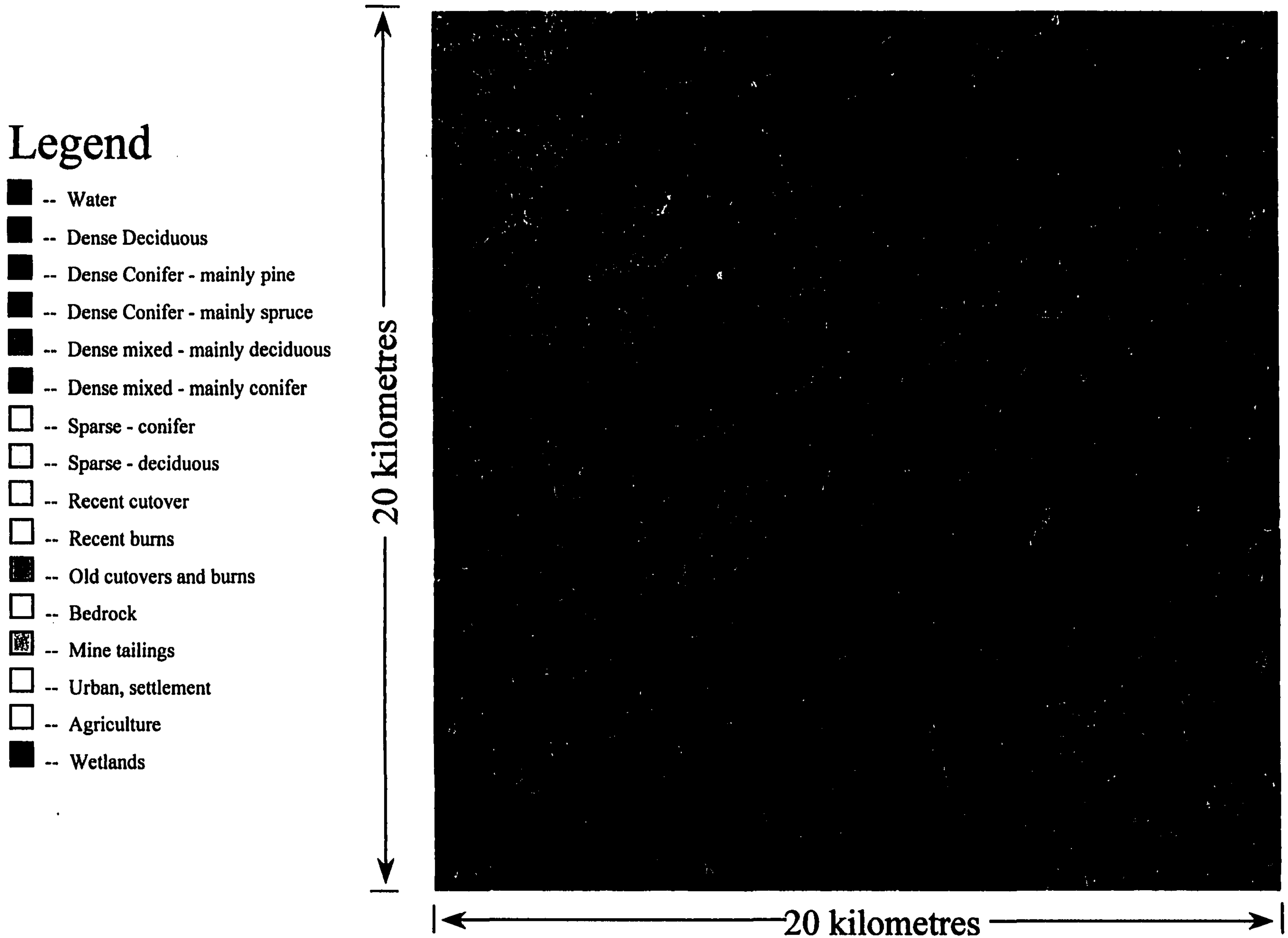


Figure 12. A typical 20 km x 20 km sample plot from the E humid region.

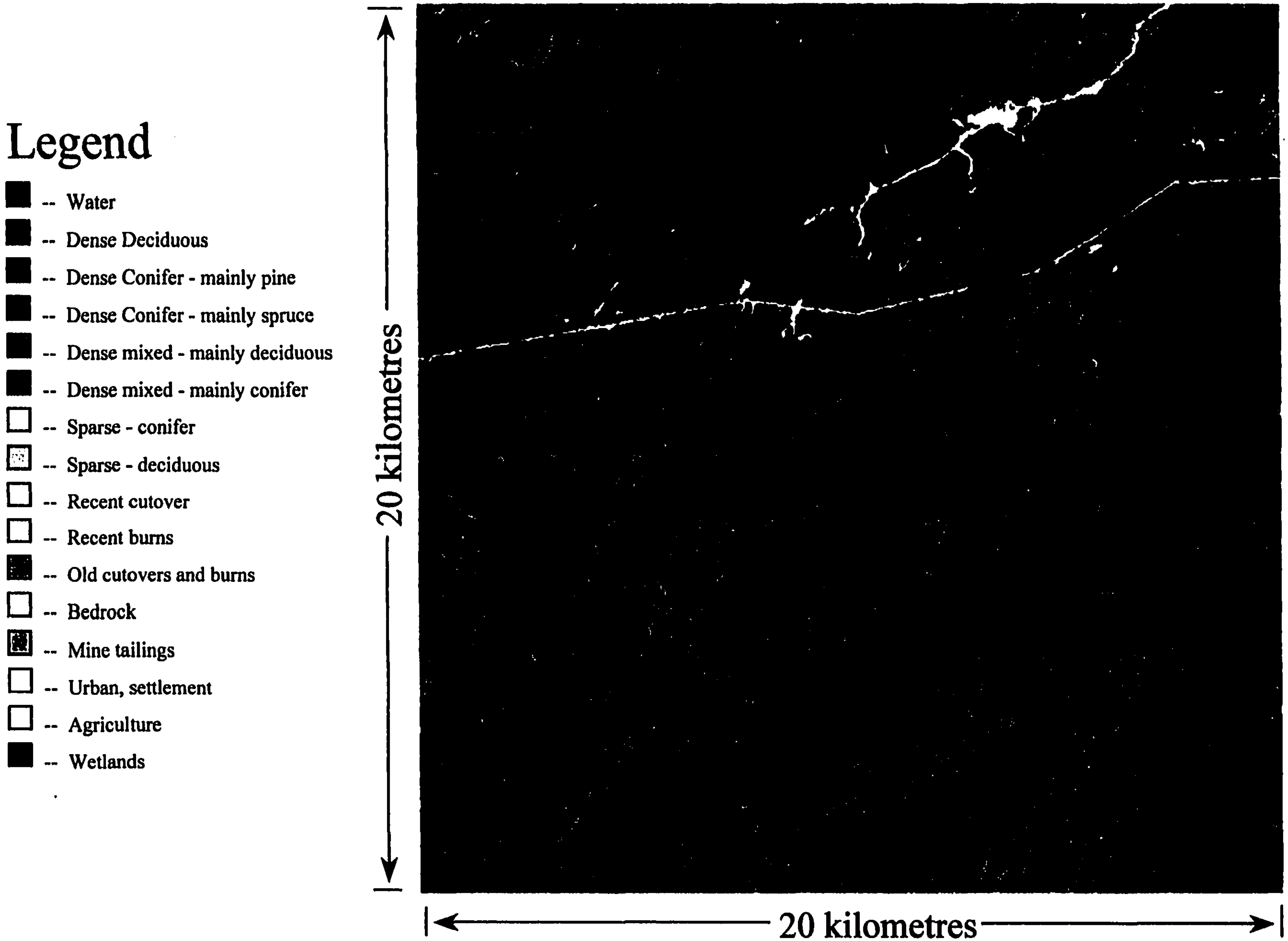


Figure 13. A typical 20 km x 20 km sample plot from theW humid region.

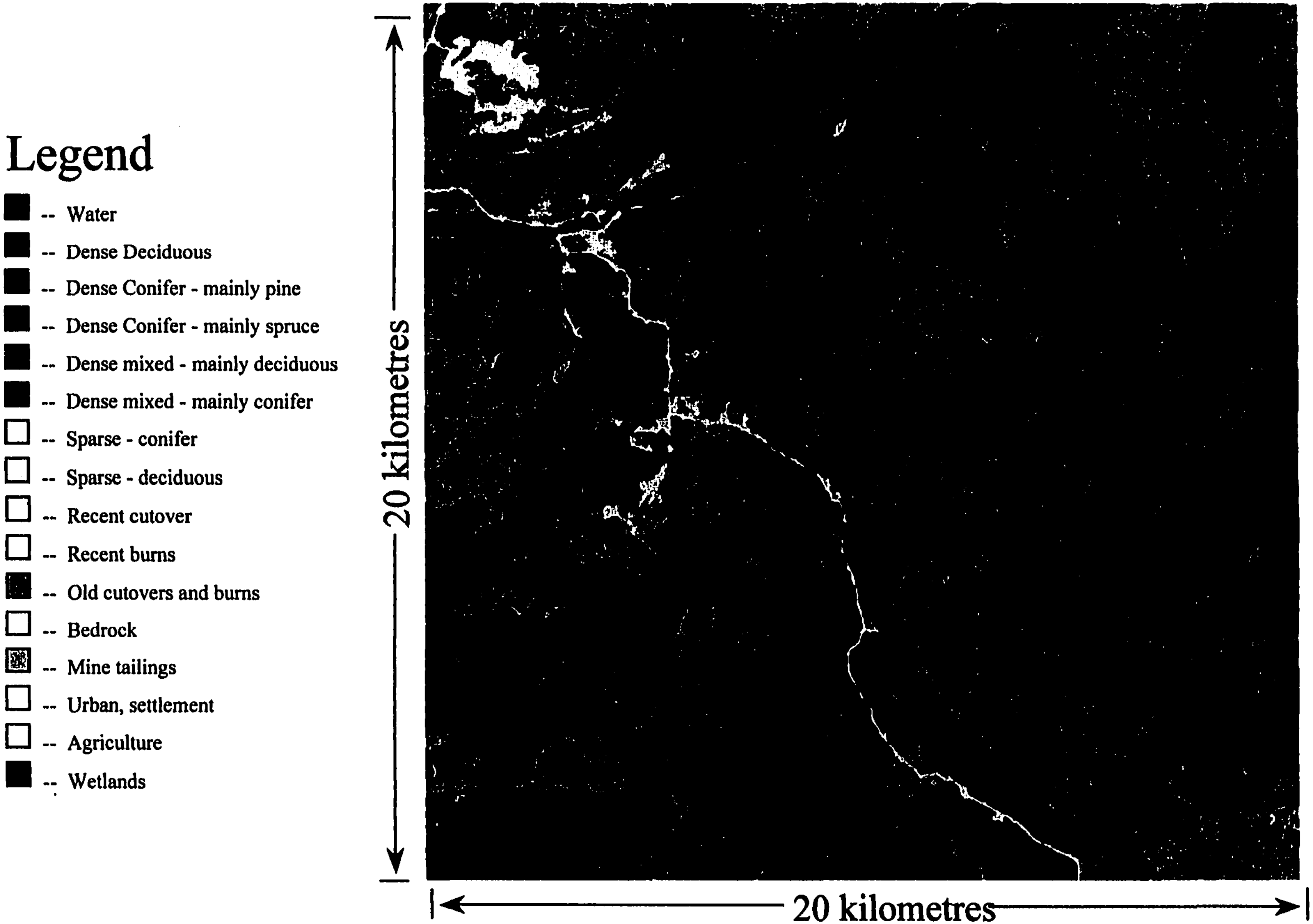


Figure 14.A typical 20 km x 20 km sample plot from the S- subhumid region.

In the second approach, which hereafter is referred to as the broad-scale approach, I located seven 5,625 km^2 sample plots, four in the Red Lake area, and three in the Clay Belt area (Figure 15). The criteria for plot location were less stringent than

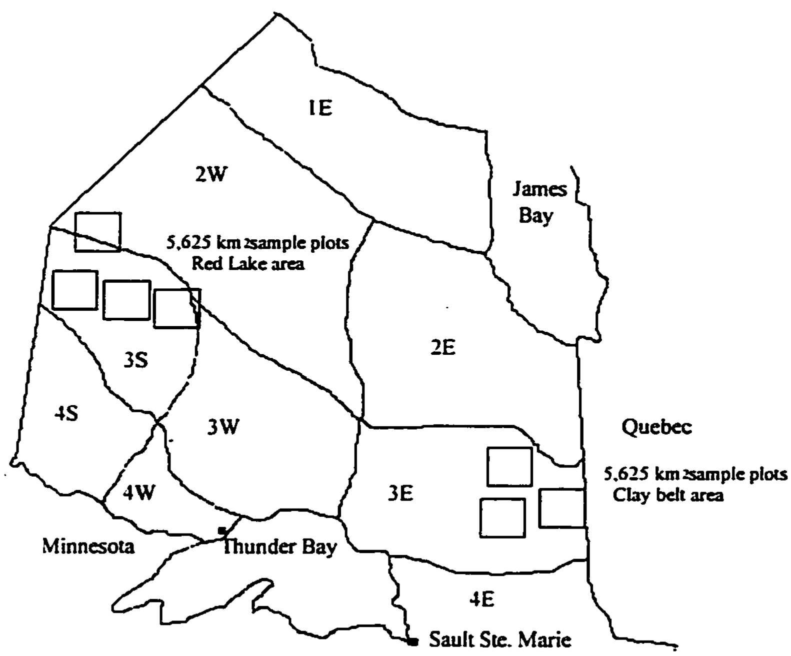


Figure 15. Location of 5,625 km^2 sample plots in the Red Lake and the Clay Belt areas.

for the fine-scale approach, and human activity and the number of large lakes in the Red Lake area are low. Therefore, I located the plots randomly and without replacement or overlap. The objective in the Red Lake area was to measure natural landscape patterns defined by mature overstory forest and wildfire disturbance. The objective in the Clay Belt area was to measure natural landscape patterns as defined by mature overstory forest. I did not include wildfire because only one small wildfire was detected in the creation of the thematic landcover map. Forest cut-blocks in the form of large contiguous clearcuts are numerous in the Clay Belt area. Therefore, I located sample plots randomly without replacement or overlap, and not including large contiguous clearcuts.

LACUNARITY ANALYSIS

In the fine-scale approach, I calculated lacunarity values for box sizes ranging from 100 m x 100 m up to the extent of the plots (i.e., 400 km^2), in intervals of 100 m (e.g., 100 m x 100 m, 200 m x 200 m, 300 m x 300 m, etc.), for the mature forest classes. In the broad-scale approach, I calculated lacunarity values for the same box sizes as the fine-scale approach, and above 20,000 m x 20,000 m (i.e., 400 km^2), I calculated lacunarity values for box sizes in intervals of 500 m (e.g., 20,000 m x 20,000 m, 20,500 m x 20,500 m, 21,000 m x 21,000 m, etc.). I also calculated lacunarity for fire classes in the Red Lake area and the timber harvest disturbance class in the Clay Belt area.

I applied a natural log transformation to the lacunarity values and corresponding box sizes, divided the transformed lacunarity values into intervals (Table 8), and created log-log graphs of lacunarity versus box size for each landcover class, in each sample plot, and at each scale interval (Figure 16). I then grouped each graph into one of two classifications to create an independent dichotomous variable, where 1 = ELO detected (i.e., an abrupt change in slope), and 0 = ELO not detected.

I used logistic regression to evaluate statistically whether a sample belongs to a specified Region (Menard 1995). A separate model was formulated for both mixedwood and conifer and used to discriminate Region E from S and W.

Table 8. Scale intervals used for the lacunarity classification. The interval range is the on-ground areal expanse of the interval. The corresponding ln Box sizes are equal to the ln of the number of pixels of a single side of a gliding box for which lacunarity was calculated (e.g., for scale interval A, 1 ha = 100 m x100 m = 4 (25 m) pixels x 4(25 m) pixels, and ln(4) = 1.38).

Interval	Interval Range (ha)		Corresponding ln Box values
	Fine Scale Approach 400 km^2 sample plots	Broad Scale Approach 5,625 km^2 sample plots	
A	1 - 1,376	1 - 1,376	1.38 - 5
B	1,376 - 10,172	1,376 - 10,172	5 - 6.
C	10,172 - 15,175	10,172 - 15,175	6 - 6.2
D	15,175 - 22,638	15,175 - 22,638	6.2 - 6.4
E	22,638 - 40,000	22,638 - 33,772	6.4 - 6.6
F		33,772 - 50,383	6.6 - 6.8
G		50,383 - 75,163	6.8 - 7
H		75,163 - 112,130	7 - 7.2
I		112,130 - 167,278	7.2 - 7.4
J		167,278 - 249,549	7.4 - 7.6
K		249,549 - 372,284	7.6 - 7.8
L		372,284 - 562,500	7.8 - 8

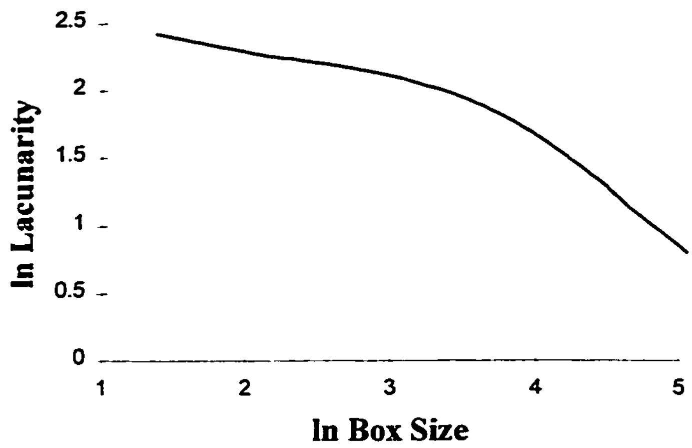


Figure 16. An example of a log-log graph of lacunarity vs. box size in interval A (1 ha - 1,376 ha) (i.e., ln box size 1.38 - 5.0) for a typical plot from the conifer landcover class in Region E. The change in direction of the line indicates an emergent level of organization.

This was done to test the statistical null hypothesis that ELO occur at the same levels across regions. The independent dichotomous variables used in the models were presence or absence of an ELO at each of the 5 scale intervals, i.e.:

$$CA = A, B, C, D, E,$$

where: CA = 1 if correctly assigned, 0 if not; and A, B, C, D, E = 1 if ELO occurs at the indicated scale interval, 0 if not. For instance, in the example data (Table 9) there is clear discrimination between Region E and Regions S and W, CA = 1 for all plots falling in Region E, and 0 if not. For this example, then, the five scale intervals successfully discriminate Region E from W and S.

Table 9. An example of data where there is a clear discrimination between Region East and Regions Subhumid and West (i.e., CA = 1 if East, 0 if not). The discrimination is based on the presence (1) or absence (0) of emergent levels of organization in the five scale intervals.

Region 1 if East, 0 if West or Subhumid		Scale intervals Presence (1) or Absence (0) of ELO				
CA	=	A	B	C	D	E
1	=	1	0	1	1	0
1	=	1	1	1	1	0
1	=	1	0	1	1	0
0	=	0	1	0	0	0
0	=	0	0	0	0	1
0	=	0	1	0	0	0
0	=	0	0	0	0	1
0	=	0	0	0	0	0

I used Chi-square statistics to test if the logistic regression coefficients could discriminate Region E from S and W (SPSS 1994, Menard 1995). I used contingency tables to compare observations and predictions of sample plots belonging to their respective regions. This was done to compare the strength of the logistic regression models in discriminating among regions. The contingency tables use all model coefficients. In contrast, Wald statistics were calculated for conifer and mixedwood models to test if individual model coefficients = 0, and hence contribute to the discrimination between Regions.

I also used the partial correlation (R) values to estimate the magnitude that the scale intervals contribute to the logistic regression model. The partial correlation between the independent dichotomous variables and the classification variable can range from -1 to +1. A negative value indicates a low probability that the sample is in the region of interest and the opposite if the value is positive (Menard 1995). I also created bar graphs with 95% confidence levels indicating the percentage of plots with detected ELO in each region for each mature forest class.

Logistic regression was not used in the broad-scale approach due to insufficient degrees of freedom. However, I did use the interval approach and interpreted ln Box size from the x-axis at each ELO.

LANDSCAPE INDICES

I used Fragstats spatial analysis software to calculate landcover class and landscape indices. Class statistics included: percentage of land in sample plot occupied by landcover class of interest (%LAND), mean patch size (MPS), patch size standard deviation (PSSD), total edge (TE), and mean shape index (MSI). MSI describes shape complexity, and is calculated as:

$$MSI = \frac{\sum_{j=1}^{n} \left(\frac{2 \ln (.25 p_{ij})}{\sqrt{a_{ij}}} \right)}{n_i}$$

where, j is the number of patches of a class i, p is the proportion of the sample plot occupied by patch type i, and a is the area (m^2) of patch ij. MSI equals 1 when all patch types are square and increases without limit when patch shapes become more irregular. The landscape indices analyzed included: PSSD, TE, MPS, and number of patches (NP). In the fine scale-approach, analysis of variance and Student Newman Keul multiple comparison tests were used to compare means among regions for the class and landscape indices.

RESULTS

FINE-SCALE APPROACH

Lacunarity Analysis

The percentage of plots, within an ecoregion, where an inflection in the lacunarity response curve was detected (hereafter termed a response) is reported for the conifer (Figure 17) and mixedwood (Figure 18) landcover classes. Each graph reports the analyses for spatial scales A-E; thus Figures 17 and 18 graphically depict, in a semi-quantitative manner, the change in landscape texture across spatial scales.

Results indicate that there may be multiple levels of organization within each of the 97 sample plots, but that the results are variable with no strong tendency for ELO to occur at a particular discrete scale interval. The result is more a "textural gradient" than a "textural discontinuity". For instance, in mixedwood from Region W, no more than 40% of plots show evidence for an ELO at any one scale, but there is a trend for increasing frequency lacunarity response at scales B and scale D. Region W has a strong trend for an ELO at scale A in conifer, but this ELO is absent in the mixedwood landcover class (Figures 17 and 18). Similarly, Region E has no strong trend of an ELO at any scale in conifer, but a weak trend for an ELO at scales B and E in mixedwood. Although Region S has the fewest number of samples (n=9), there is a strong trend of ELO at scale A in conifer, and weaker trends at scales A and E in mixedwood.

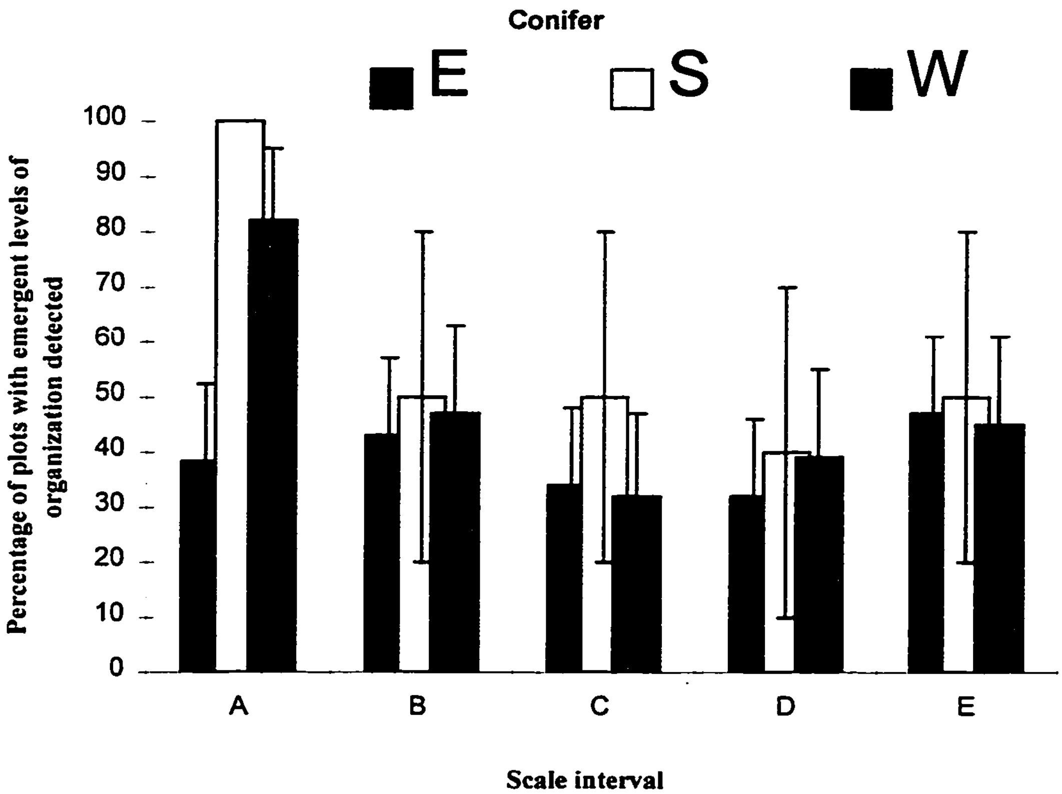


Figure 17. Percentage of 400 km^2 sample plots with emergent levels of organization detected and 95% confidence levels, in each region and for each scale interval in the conifer landcover class. Regions include: E-humid east (n = 47), S-subhumid (n = 9), and W-humid west (n = 41). Scale intervals include: A(1 ha - 1,376 ha), B(1,376 ha - 10,172 ha), C(10,172 ha - 15,175 ha), D(15,175 ha - 22,638 ha), and E(22,638 ha - 40,000 ha).

To statistically test for differences among ecoregions, I used logistic regression to determine if I could discriminate ecoregions using the presence/absence of an ELO within sample plots (Table 10), essentially a quantitative analysis of Figures 17 and 18. The model Chi-square statistic for both conifer and mixedwood are significant (P = 0.0002 and P = 0.0177, respectively); however, only one coefficient from each model is

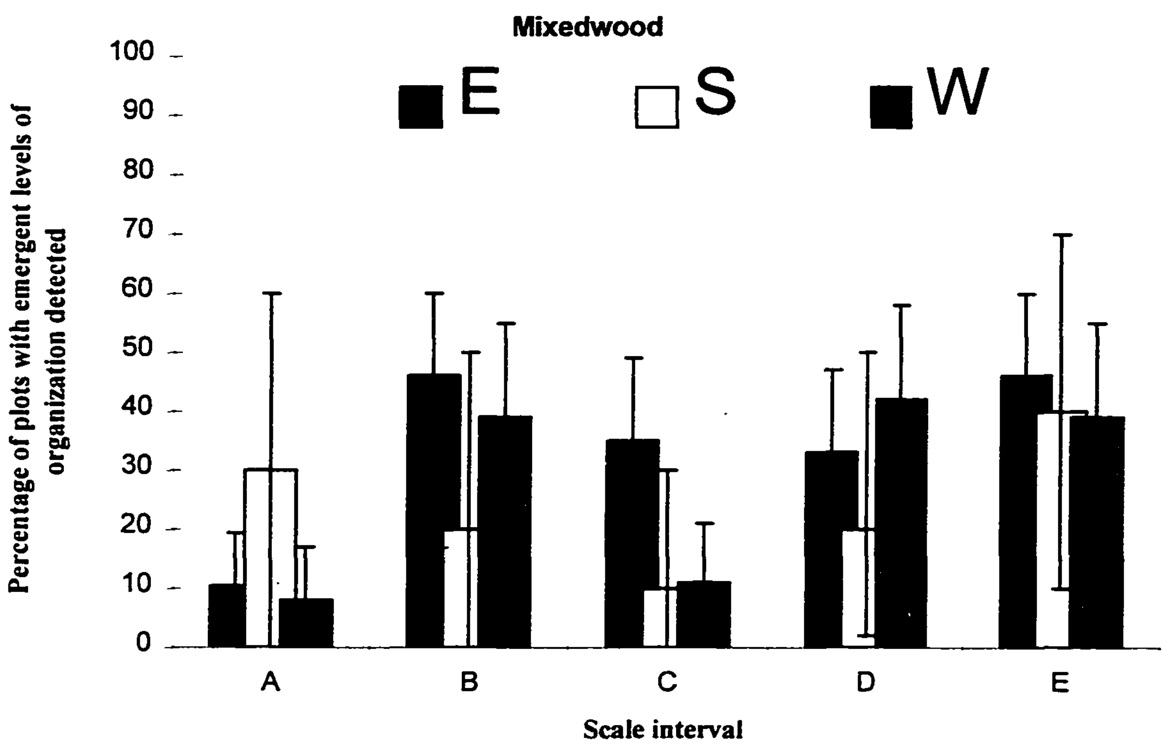


Figure 18. Percentage of 400 km^2 sample plots with emergent levels of organization detected and 95% confidence levels, in each region and for each scale interval in the mixedwood landcover class. Regions include: E-humid east (n = 47), S-subhumid (n = 9), and W-humid west (n = 41). Scale intervals include: A(1 ha - 1,376 ha), B(1,376 ha - 10,172 ha), C(10,172 ha - 15,175 ha), D(15,175 ha - 22,638 ha), and E(22,638 ha - 40,000 ha).

Table 10. Logistic regression results for the 400 km^2 sample plots comparing Region E versus W & S for conifer and mixedwood classes, including: model coefficients (B), partial correlation values (R), Wald statistics (W), Wald statistic significance, and Model Chi-square significance.

	Scale Interval					Model Chi
Logit Model Summary	A	B	C	D	E	Square (P)
Conifer						
Model Coefficients (B)	1.15	0.14	- 0.07	0.16	-0.16	0.00*
Partial Correlation(R)	0.36*	0.00	0.00	0.00	0.00	
Wald Statistic (W)	19.24*	0.31	0.08	0.38	0.42	
Wald Significance (P)	0.00	0.58	0.78	0.54	0.52	
Mixedwood						
Model Coefficients (B)	0.10	-0.48	- 0.93	0.05	-0.24	0.02*
Partial Correlation(R)	0.00	-0.11	- 0.24	0.00	0.00	
Wald Statistic (W)	0.08	3.73	9.77*	0.03	1.18	
Wald Significance (P)	0.78	>0.05	0.00*	0.85	0.29	

* indicates significance at the P<0.05 level.

significant (Table 10). For instance, interval A is significant (B = 1.1484, R = 0.3618, W = 19.2363, and P < 0.001) from the conifer model, and interval C (B = -0.9322, R = -0.2416, W = 9.7708, and P = 0.0018) from the mixedwood model. This indicates that there are differences between Region E and Regions S and W below 1,326 ha (i.e., interval A) in conifer, where Region E has less ELO (Figure 17). Similarly, there are differences between Regions E and W in mixedwood between 10,172 ha and 15,175 ha (i.e., interval C), where Region E has more ELO (Figure 18). Ecologically, this means that there are some differences in the scales where textural discontinuities occur between these forest types, but multiple ELO do not exist within any one forest type. Consequently, there is no detected hierarchical patterning within the five scale intervals.

The ability to classify sample plots to their respective regions is highest in conifer at Region E, and lowest in mixedwood at Region E (Table 11). This means that

Table 11. Prediction accuracy results from logistic regression models including the percentage of plots correctly predicted to belong to their respective regions.

Landcover Class	Predicted Accuracy: Plots belonging to Region E (%)	Plots belonging to Regions W&S (%)
Conifer	80.56	69.49
Mixedwood	66.67	68.89

the combination of scale intervals that make up the conifer logistic model is strongest, and because only scale interval A is significant in the model, interval A is the discriminating variable. Although the mixedwood prediction accuracy is lower at interval C, C is still significant in discriminating Region E from W and S, but differences in texture discontinuities are not as strong as in conifer at interval A (Table 10). The mean lacunarity values, from the median resolutions where ELO were detected, are highest in Region W mixedwood (Table 12). Lacunarity measures variability in gap sizes, so the higher lacunarity in mixedwood means the variation in gap sizes is higher. Similarly, Region W has the lowest mean lacunarity value in the conifer class, indicating less variation in gap sizes.

Table 12. Mean lacunarity values from scale intervals where emergent levels of organization were detected in the 400 km^2 sample plots. The lacunarity values are taken from the median resolutions of the scale intervals, where relative differences in emergent levels of organization occurred.

Landcover Class	Humid Region	Scale Interval A	Scale Interval C
Conifer	E	1.55	1.07
	W	1.29	1.03
	S	1.65	1.08
Mixedwood	E	1.36	1.05
	W	3.00	1.16
	S	1.36	1.04

Landscape Metric Analysis

Significant differences between regions were detected for class metrics in conifer ($P < 0.05$) (Table 13). All differences are between Regions E or W and Region S (Table 13). In contrast, comparisons of landscape metrics reveal significant differences between Regions E and W in TE, MPS, and NP ($P < 0.05$), where Region E has higher TE and NP, and lower MPS (Table 14). This means that the greater number of ELO in interval A from Regions W and S are not due to smaller conifer patches. Region E has higher TE and MSI of conifer and higher TE and NP at the landscape level, but no differences in MPS at the class level. Therefore, the greater number of ELO in Regions W and S are due to patches that are less complex.

Table 13. Landscape metric (means) comparisons where landcover classes are considered separately among humid regions. %LAND is relative percent of land, MPS is mean patch size, MSI is mean shape index, PSSD is patch size standard deviation, TE is total edge, and SNK is Student-Newman-Keul.

Landscape Metric	Regions East	West	Subhumid	*F*	*P*	SNK test results
Conifer						
%LAND	23.99	30.09	16.14	2.34	0.10	W>S
MPS (ha)	33.91	43.81	17.84	1.42	0.25	
MSI	1.41	1.38	1.21	9.55	0.00	E>S, W>S
PSSD(ha)	404.21	470.57	156.38	1.19	0.31	
TE(km)	1595.61	1406.98	814.13	6.94	0.00	E>S, W>S
Mixedwod						
%LAND	35.65	34.59	22.76	2.66	0.07	W>S
MPS (ha)	56.57	49.34	23.03	0.92	0.40	
MSI	1.41	1.44	1.21	1.14	0.32	
PSSD(ha)	667.18	497.11	133.15	2.38	0.10	
TE(km)	1614.70	1299.82	1604.15	1.90	0.15	

Table 14. Landscape metric (means) comparisons among humid regions. PSSD is patch size standard deviation, TE is total edge, CON is contagion, MPS is mean patch size, NP is number of patches, and SNK is Student-Newman-Keul.

Landscape Metric	Regions East	West	Subhumid	*F*	P	SNK
PSSD(ha)	96.36	121.54	111.58	1.39	0.25	
TE(km)	5791.59	4345.79	3547.72	5.87	0.00	E>S, E>W
CON	53.76	54.76	52.73	0.84	0.44	
MPS (ha)	6.85	10.51	13.87	35.79	0.00	W>E, S>W, S>E
NP	6730	4460	2955	9.04		E>S, E>W

BROAD-SCALE APPROACH

Lacunarity Analysis

Lacunarity analysis in the Red Lake and Clay Belt areas used fewer plots (4 and 3) than used in the fine scale analysis, but the plots covered a much greater extent (5,635 km^2). This allowed a more extensive spatial analysis of landscape structure, but prevented the use of logistic regression and other statistics. In the Red Lake area, inflections in the lacunarity response curve were consistently detected (i.e., 50% of sample plots) at spatial scales K, H, and D for the conifer and mixedwood landcover classes (Table 15). Patch structure was also detected at spatial scale B in the fire class. This indicates that ELO occur at about the 310,000 ha, 94,000 ha, and 19,000 ha spatial scales. In the fire landcover class, an additional ELO occurs at about the 6,000 ha scale.

In the Clay Belt area, inflections in the lacunarity response curve occurred at spatial scales K-L, and H in conifer and mixedwood classes, while a response in the man-caused disturbance class occurred only at spatial scale B (Table 16). This indicates that ELO in conifer and mixedwood occur at about the 406,000 ha and 94,000 ha spatial scales, and that in the man-caused disturbance class, only a single ELO occurs at about the 6,000 ha scale.

The semi-quantitative, broad-scale analysis indicates: (1) both the Red Lake and Clay Belt areas have multiple ELO spanning the 6,000 - 406,000 ha spatial scales, (2) the lacunarity response is consistent, but rarely exceeds 50% of sample plots, (3) the Clay Belt area lacks the ELO that occurs in the 19,000 ha scale for Red Lake conifer and mixedwood classes, (4) both fire and man-caused disturbance have an ELO that uniquely occurs at the 6,000 ha spatial scale, and (5) the man-caused disturbance in the Clay Belt is the least complex of the landscapes, and lacks the ELO that occurs at the 94,000 and 406,000 ha spatial scales.

Table 15. Emergent levels of organization from lacunarity analysis in the 5,625 km^2 sample plots in the Red Lake area.

Emergent Levels of Organization*

Plot No.	A	B	C	D	E	F	G	H	I	J	K	L
	Scale Interval											
		Conifer										
4				X								
5				X				X			X	
6				X						X		
7	X		X					X			X	
		Mixedwood										
4								X				
5				X								
6				X					X			
7												
		Fire										
4		X						X			X	
5												
6		X									X	
7								X			X	

* X - indicates that a level of organization was detected within the scale interval.

Scale Interval Legend

A= 1-1,376 ha	G= 50,383-75,162 ha
B= 1,376-10,172 ha	H= 75,162-112,129 ha
C= 10,172-15,175 ha	I= 112,129-167,277 ha
D= 15,175-22,638 ha	J= 167,277-249,549 ha
E= 22,638-33,772 ha	K= 249,549-372,283 ha
F= 33,773-50,383 ha	L= 372,283-562,500 ha

Table 16. Emergent levels of organization from lacunarity analysis in the 5,625 km^2 sample plots in the Clay Belt area.

Emergent Levels of Organization*

Scale Interval

Plot No.	A	B	C	D	E	G	G	H	I	J	K	L
Conifer												
1											X	
2								X				X
3								X				
Mixedwood												
1	X											X
2								X				
3								X				
Disturbance												
1		X										
2		X										
3		X										

* X - indicates that a level of organization was detected within the scale interval

Scale Interval Legend

A=	1-1,376 ha	G=	50,383-75,162 ha
B=	1,376-10,172 ha	H=	75,162-112,129 ha
C=	10,172-15,175 ha	I=	112,129-167,277 ha
D=	15,175-22,638 ha	J=	167,277-249,549 ha
E=	22,638-33,772 ha	K=	249,549-372,283 ha
F=	33,773-50,383 ha	L=	372,283-562,500 ha

Landscape Metrics Analysis

Sample plots in the Red Lake area have 20% - 45% conifer and less than 12% mixedwood in each sample plot (Figure 19). Mixedwood in each Clay Belt plot is higher than in the Red Lake plots. Mixedwood in plots 2 and 3 from

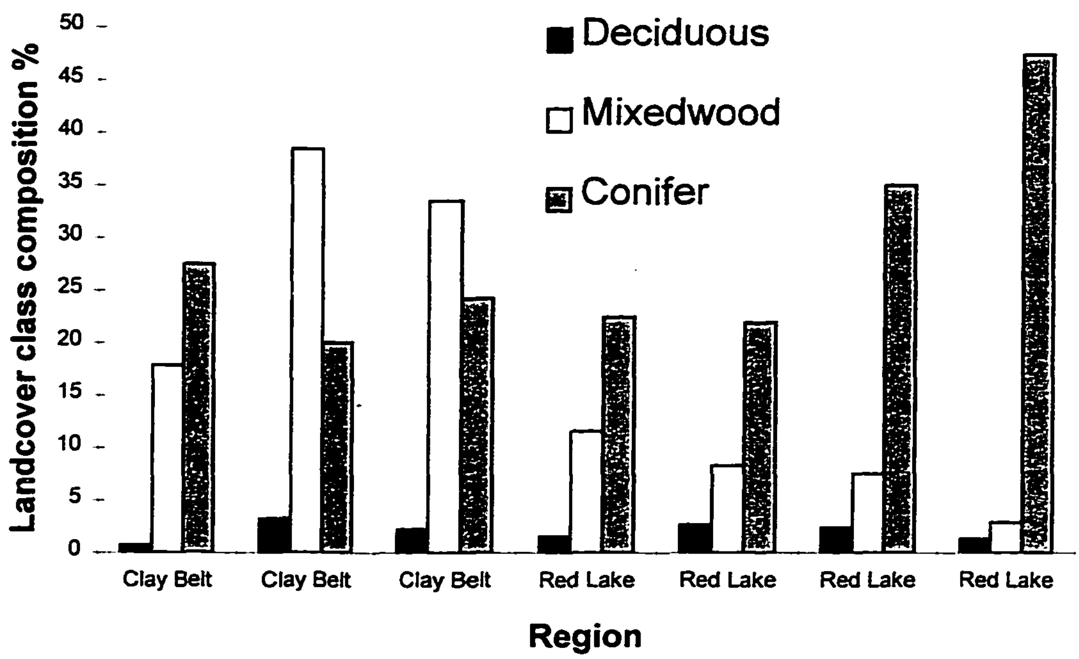


Figure 19. Percentage of deciduous, mixedwood, and conifer in the three 5,625 km^2 sample plots in the Clay Belt area, and four sample plots in the Red Lake area.

the Clay Belt is higher than conifer in the same plots (Figure 19).

NP for conifer is higher in all Red Lake plots than Clay Belt plots; however, NP of mixedwood is only greater in three of the four plots (Figure 20). PSSD, MSI, and MPS of all mature forest classes is greater in the Clay Belt than Red Lake (Figures 21-23). In contrast, TE of conifer patches is greater in Red Lake than the Clay Belt

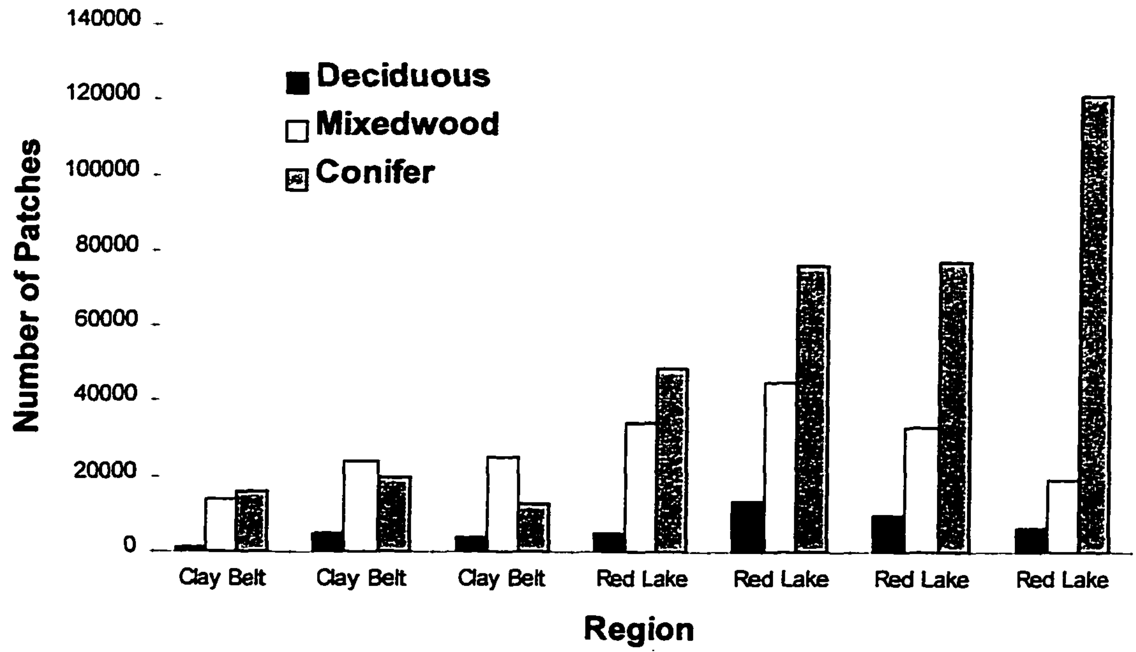


Figure 20. Number of patches of deciduous, mixedwood and conifer in three 5,625 km^2 sample plots in the Clay Belt area, and four sample plots in the Red Lake area.

(Figure 24). Similarly, TE of mixedwood patches is generally greater in the Clay Belt than Red Lake (Figure 24). This means that the hierarchical characteristics, in the form of multiple ELO, are not the result of large contiguous forest patches, but are clumps or groups of patches.

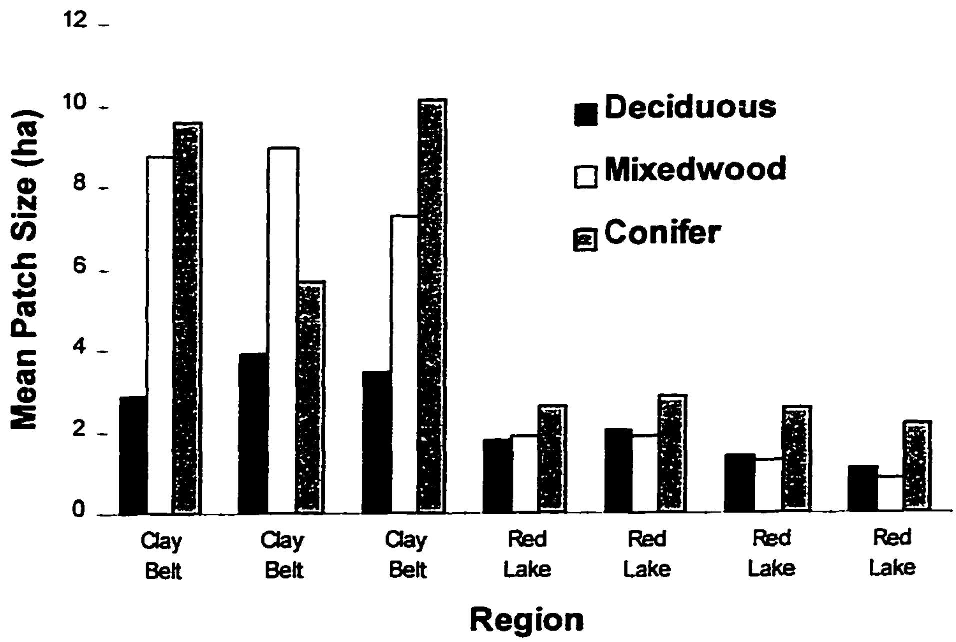


Figure 21. Mean patch size of deciduous, mixedwood and conifer in three 5,625 km^2 sample plots in the Clay Belt area, and four sample plots in the Red Lake area.

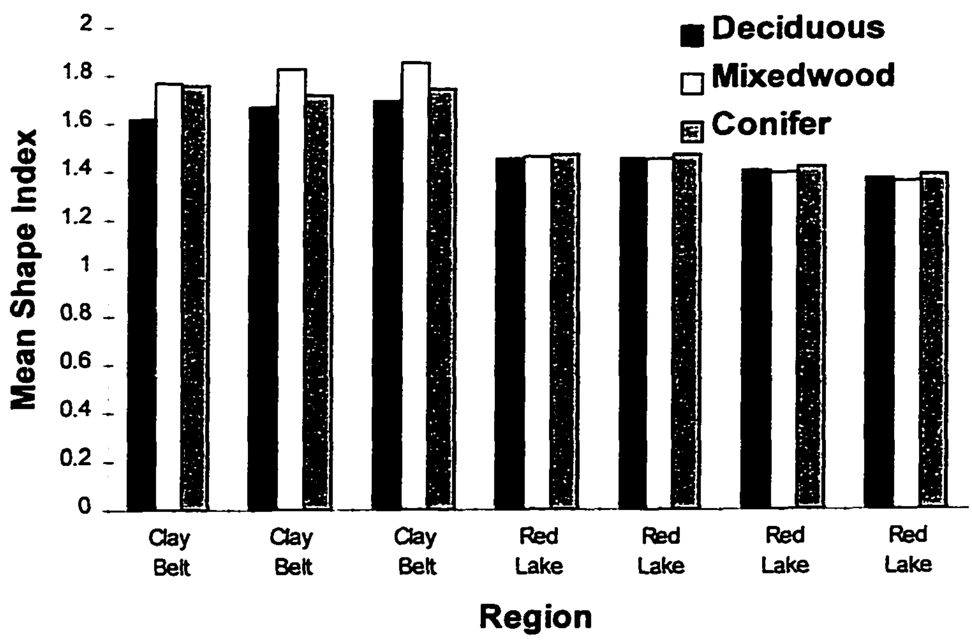


Figure 22. Mean shape index of deciduous, mixedwood and conifer patches in three 5,625 km^2 sample plots in the Clay Belt area, and four sample plots in the Red Lake area.

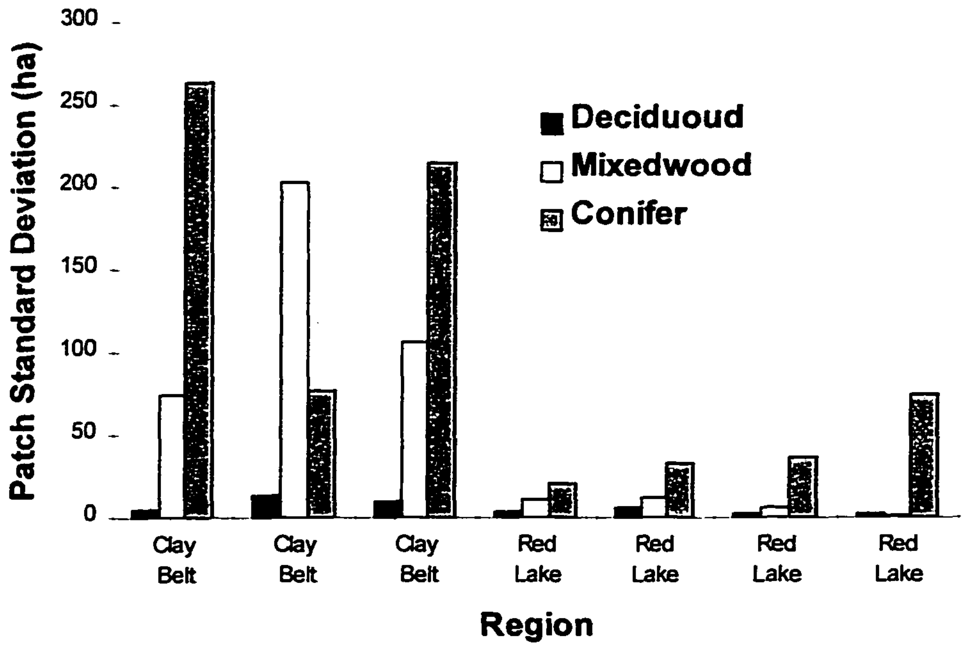


Figure 23. Patch size standard deviation of patches of deciduous, mixedwood and conifer in three 5,625 km^2 sample plots in the Clay Belt area, and four sample plots in the Red Lake area.

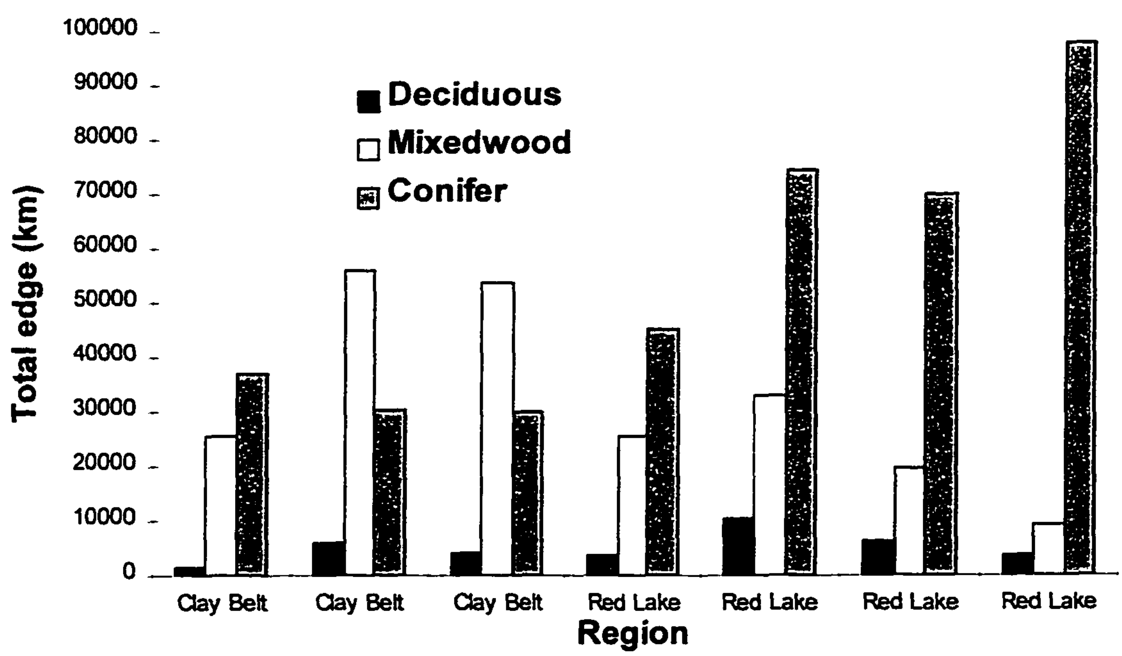


Figure 24. Total edge of deciduous, mixedwood and conifer in three 5,625 km^2 sample plots in the Clay Belt area, and four sample plots in the Red Lake area.

The trends in landscape statistics are similar to the individual class statistics providing further evidence that the hierarchical characteristics in Red Lake are a result of clumps of patches, and the ELO in the Clay Belt result from larger homogeneous patches. For instance, the NP in Red Lake are greater than the Clay Belt, and the MPS is lower (Figures 25 and 26). The PSSD and TE results contrast less between areas (Figures 27 and 28).

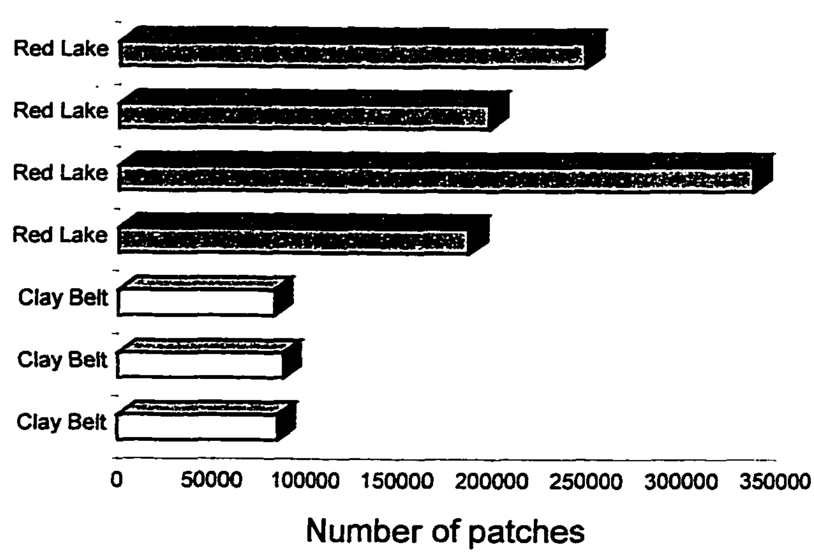


Figure 25. Total number of landscape patches per plot in the Red Lake and Clay Belt areas.

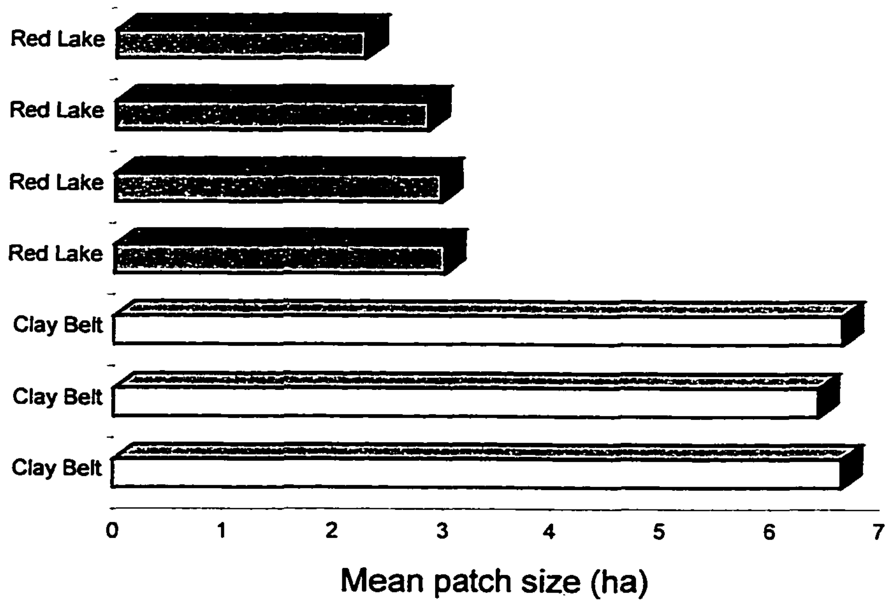


Figure 26. Mean size of all landscape patches in the Red Lake and Clay Belt areas.

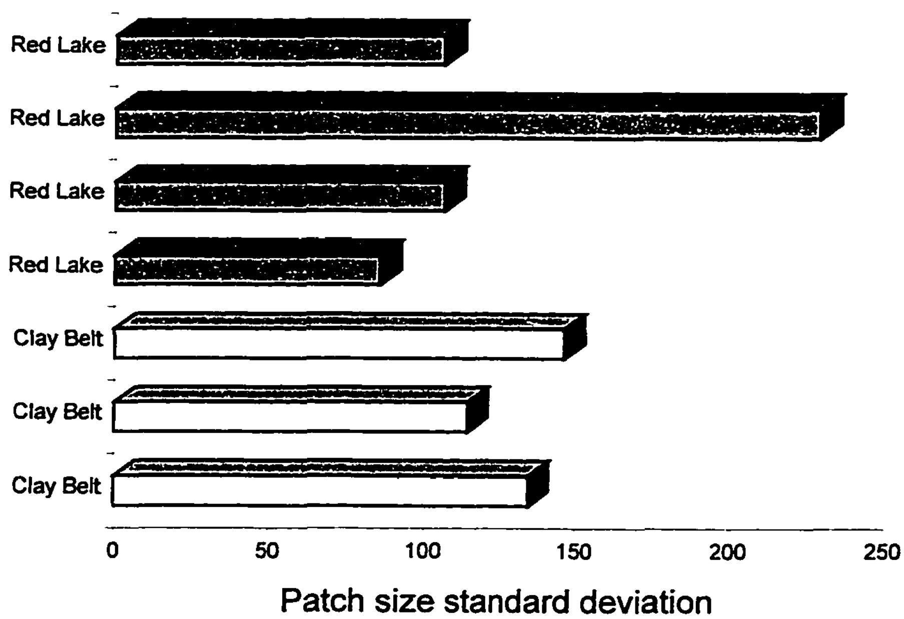


Figure 27. Patch size standard deviation of all landscape patches in the Red Lake and Clay Belt areas.

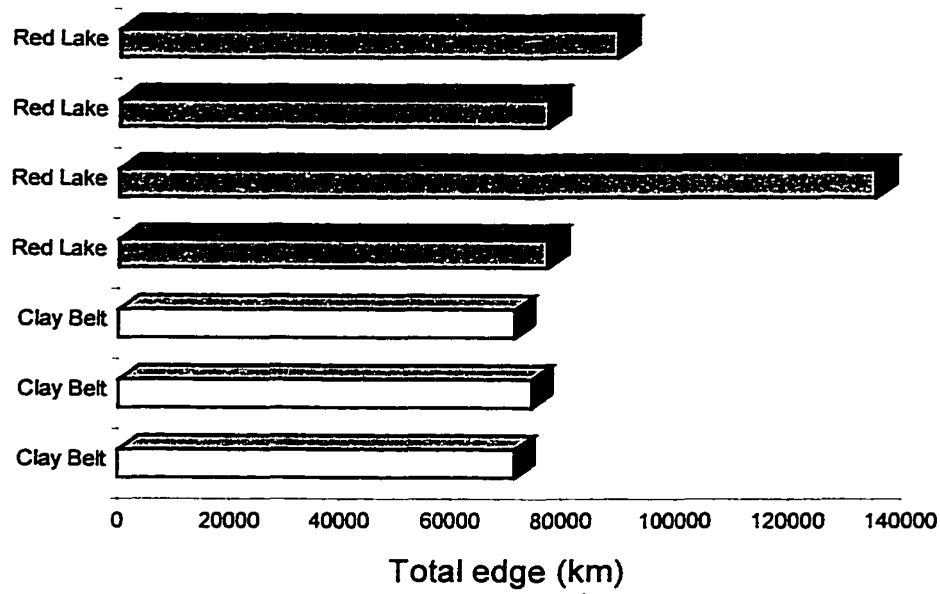


Figure 28. Total edge of all landscape patches in the Red Lake and Clay Belt areas.

DISCUSSION

These results suggest the existence of a hierarchical structure because multiple levels of organization occur. Results are variable though, and in most cases an ELO was detected in only 50% of sample plots. Detected ELO from the fine-scale approach are below 50% in all scale intervals for both conifer and mixedwood with the exception of conifer, interval A, Regions W and S (Figures 17 and 18). Logistic regression discriminated Region E from Regions S and W based on conifer at interval A, and the 95% confidence levels support the discrimination. Similarly, logistic regression discriminated Region E from Regions S and W in mixedwood at interval C, and is supported by the 95% confidence levels. Therefore, although there is no evidence of hierarchical patterning in either mixedwood or conifer, there is strong evidence that there are differences between Region E and Regions W and S in conifer at interval A. The lacunarity and landscape metric analyses from the fine-scale approach did not provide evidence to reject the null hypothesis that differences in hierarchical characteristics among regions existed. However, there is strong evidence that there are differences in ELO between Region E and Regions W and S in conifer below scales of 1,376 ha. The characteristics of landscape texture that make up these differences are unclear, but the landscape and class metrics indicate that the ELO are characterized by patches that are more complex in Region E.

Considering the broad-scale approach, lacunarity results and landcover class statistics from the Red Lake area provide strong evidence of hierarchical characteristics in the form of multiple ELO in conifer, mixedwood, and recent burns. For instance, the NP and TE of conifer is greater in Red Lake than in the Clay Belt, but the MPS, MSI, and PSSD is lower. This indicates that the ELO are not the result of large contiguous patches, but rather small clumps of patches. The PSSD is greater in the Clay Belt indicating that the MPS are a result of greater patch sizes. Although Red Lake had lower %LAND with mixedwood, three of the four sample plots had greater mixedwood NP. The results of the landscape statistics are similar, where Red Lake sample plots have relatively more patches, smaller patches, and greater TE. The landscape and class statistics provide further evidence that the multiple ELO in Red Lake are real and not the result of large contiguous patches.

The stratification of the 400 km^2 sample plots based on humid regions is appropriate; however, because the boundaries are abstract in nature, differences among regions might not be detected. For instance, sample plots located within several kilometres of either side of a region boundary can have similar forest cover and scale-dependent landscape patterns. Humid boundaries are not discrete identities and can change over time with changing climatic conditions. Even if this is the case, I expected to see explicit hierarchical characteristics in at least one of the Regions, but I did not.

Most of the 400 km^2 sample plots are in areas where some anthroprogenic intervention has occurred, mostly in the form of timber harvesting, community establishment, and road establishment. Although I located sample plots in areas where these interventions were reduced as much as possible, a bias could have been introduced and the detected ELO could partly be a remnant of human activity.

The evidence that natural hierarchical characteristics exist in the form of multiple ELO in the Red Lake area is robust. The amount of human activity in the Region is relatively low and more recent than in southern parts of the study area. Although the total number of 5,625 km^2 sample plots is less than the number of 400 km^2 sample plots (i.e., 7 vs. 97, respectively), the total area analyzed is slightly greater (i.e., 39,373 km^2 vs. 38,000 km^2, respectively). Further, the stratification between Red Lake and the Clay Belt based on broad-scale climatic boundaries is less subtle than the stratification between humid regions. This gives further strength to the conclusion that there are real differences between the two areas.

Given the broad thematic classification of the landcover maps (e.g., conifer, mixedwood, deciduous, disturbance +/- 30 years and younger), I expected to see differences between the hierarchical characteristics of fire disturbance and mature forest in the Red Lake area. I expected to see differences because the age range of the mature forest classification above 30 years is broader than the 20-30 year maximum of the fire/disturbance class (i.e., 31 years up to +/-130 years). If fires are the main disturbance events and the end results are mature forests, both recent fire and mature forest should have similar scale-dependent patterns. However, the age class range for mature forest is broader than the age class for fire. The classification of mature forest into mixedwood, conifer, and deciduous could compensate for the broader age classification of mature forest. For instance, if I assume that succession occurs and most stands undergo a series of changes after disturbance (e.g., young deciduous - mixedwood - conifer - etc.), then the differences in age class ranges will be reduced, if not eliminated.

The absence of detected hierarchical characteristics in the Clay Belt area is somewhat expected. When Rowe (1972) subdivided the Boreal Forest region into classes based on spatial extent and distribution of flora, he included the Northern Forest Clay Region as an area with homogeneous flora characteristics. Unlike the 400 km^2 sample plot comparisons, where ELO might be higher than the extent of the sample plots analyzed, the 5,625 km^2 sample plots are large and occupy an area in the magnitude of one quarter of the Clay Belt of Ontario. The next higher level of organization would most likely be the extent of the Clay Belt, or at the level already described by Rowe (1972), the Northern Forest Clay Region.

Differences between the landcover maps produced by contractors A and B could introduce some error into the analysis. However, because I used mature overstory forest landcover classes, and most of the confusion was between sparse and mature overstory forest and wetlands and young classes, the errors are reduced. When matching landcover map 6 with maps produced by contractor A, a distinct line is present on the east side of map 6 (Figure 10). The line is due to the differences in classification primarily between sparse and mature forest. However, when matching map 6 with the maps directly to the south, the contrast is lower. Although the accuracy assessment indicates general differences between the maps, the biggest differences seem to be concentrated at the east side of map 6 and west side of map 8 (Figure 10).

The multiple sample-plot lacunarity analysis at several scale intervals is robust and appropriate for detecting multiple ELO, but only if landscape patch statistics are also used to verify that the detected ELO are not the result of large contiguous patches. The size of sample plots limits the scale of ELO detected. Fine ELO can be a single clump of pixels or multiple clumps of pixels and the relative lacunar values are indications of this. However, at broad scales, the ELO detected are generally based on clumps of pixels and the relative lacunar values are less informative.

Spatial patterning of landcovers on landscapes is non-random. The probability that an individual cell belongs to a particular class is influenced by neighbouring cells. Patterns are created by events and processes such as wildfire, insect attack, and climate. Landforms and soil are other variables that contribute to the structuring of landcovers. The differences between the Clay Belt and Red Lake areas are most likely due to the differences in fire periodicity and size. The fire cycle in northeastern Ontario is greater, both temporally and spatially (Maclean and Bedell, 1955). However, attributing the differences to wildfire would be an over simplification. Wildfires generally occur due to favourable weather conditions (i.e., lightning). The behaviour of a fire depends on past and present weather conditions (i.e., moisture content of fuels), topography (i.e., hills and valleys), geology (i.e., shape, number, and size of lakes) etc. Therefore, to presume that the differences in landscape patterns are due to a single variable would be incorrect. Fire is the most obvious structuring event that is different between areas analyzed. However, a series of processes and events, each influencing the other, contribute to the structuring of the landscapes and differences in ELO between the areas.

In the fine-scale approach the 3 ecoregions differ little in how they are structured, although the subhumid region differs most. All of the plots from S had ELO in conifer at scale interval A. I suspect that this because the Great Lakes St. Lawrence Forest

Region borders S to the south. The higher content of deciduous species contributes to a more fragmented conifer class and this is supported by lower percentages of mixedwood and conifer in Region S (Table 13).

Both fire and man-caused disturbance have ELO at the 6,000 ha scales which is not present in either mature forest land cover classes. I believe the reason that the mature forest classes do not have strong evidence of ELO at similar spatial scales is because the definition of disturbance classes is temporally finer. For example, the disturbance class is from 30 year interval (i.e., 0 - 30 years) and the mature forest landcover class is from a broader class (i.e., 31 - 100 +/-). This might have the effect of allowing detection of spatial patterns at finer scales in the disturbance classes. Given the temporal differences in classification, the detected ELO are still significant. If I classified the forests to finer classes based on narrower age classes the detected ELO would still exist. However, a broader classification might mask ELO.

Band *et al.* (1997) estimate the distribution of ecosystem productivity including nested patterns as controlled by geoclimatic variables in the province of Ontario. Similar conclusions to this multi-scale analysis were made:

a) geoclimatic controls of productivity explain a large part of the variance of productivity over the province (i.e., geology and climate shape ecosystems),

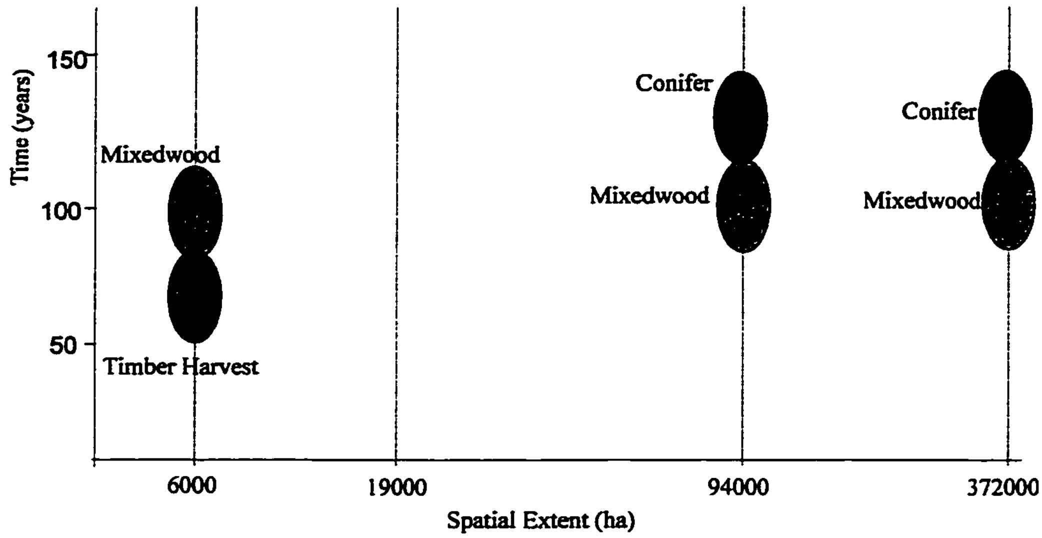
b) local effects such as lakes, topography etc., effect landcover patterning,

c) continuous high gradient edges do not exist (e.g., ecoregion boundaries are abstract - can similar have patterning with different geoclimatic conditions).

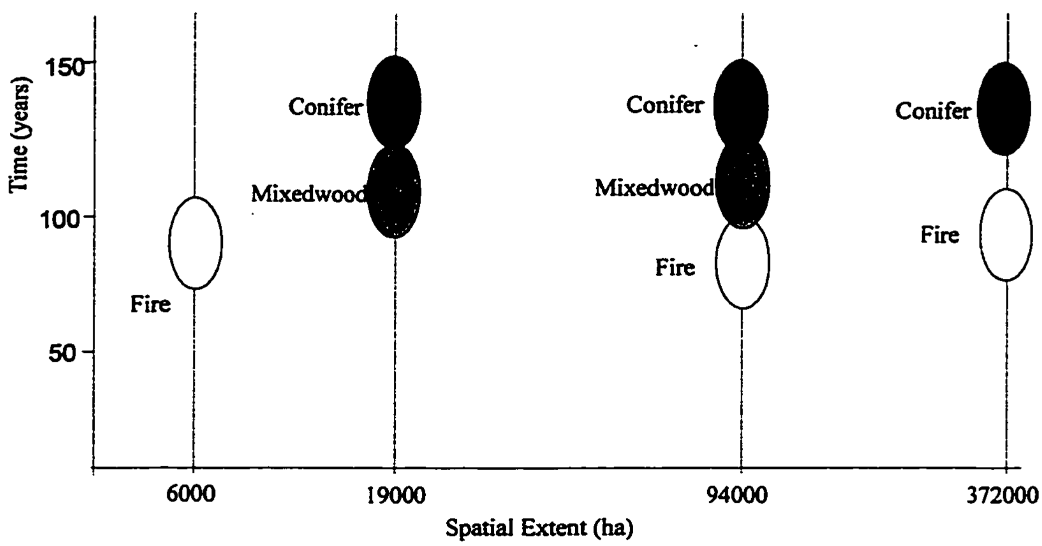
Holling (1992) identifies discrete body mass clump categories and suggests that boreal ungulates, such as white tailed deer (*Odocoileus virginianus*) and moose (*Alces*

alces), are in one grouping and predators, such as wolves (*Canus lupus*), are in another. Further he shows that in a multi-level hierarchy, at the finest level of organization, changes in spatial patterning can occur and are obvious, but at the same time spatial patterning at broader levels remains unchanged. He suggests that animals that fit into different body mass clump categories can be affected by different scales of disturbance in different ways. Althought I do not compare body size clumps with the detected ELO, I have identified specific scales at which ELO occur. Altering boreal landscapes at fine scales without consideration of broad-scale spatial patterning could be detrimental to some species and vice-versa.

Based on my findings I have attempted to build a model (Figure 29) which is similar to King's (1991) nested hierarchical carbon/biomass model (Figure 2). I have included both temporal and spatial scales, where the spatial scales are taken directly from the broad-scale lacunarity analysis. I use 80-100 years as an approximation of fire frequency for northwestern Ontario (Woods and Day, 1977). For an approximation of temporal scales of the mature forest landcover classes, I use stand growth decrease age for mixedwood stands (i.e., +/- 100 years) and conifer stands (i.e., +/- 125 years) from Plonski's Normal Yield Tables (Plonski 1981). Stand growth decrease age is the approximate age of a stand when the mean annual increment curve begins to decline. The model shows that fires occur at temporal scales finer than the estimated stand growth decrease age for conifer and mixedwood (Figure 29 B). In contrast, both mature forest and fire exhibit hierarchical patterning and ELO at similar scales in the Red Lake area. The differences in temporal scales are to be expected because fire is a random process which can occur in the same



(A) Clay Belt



(B) Red Lake Area

Figure 29. A model of forest landcovers for the Clay Belt (A) and Red Lake (B) areas of Ontario, including spatial scales of detected emergent levels of organizations, estimates of fire frequencies (B), estimates of disturbance frequencies (A), and estimates of mature stand ages derived from Plonski's Normal Yield Tables (Plonski 1981).

stand at both short and long intervals. In contrast, a stand that is not disturbed by fire can follow a successional trajectory undergoing a series of changes, the result often being a mature conifer dominated stand.

The scales of detected ELO in mature forest landcovers in the Clay Belt area do not correspond with fire patterns. The fire cycle in the Clay Belt is broader both temporally and spatially than in Northwestern Ontario (Maclean and Bedell, 1955). Therefore, the detected ELO could be from a series of disturbance events such as, timber harvesting, insect attack, and blow down. Similarly, forty years of fire suppression could have the effect of creating forest landcover patterns that are different from natural patterning formed by wildfires. In any case, from the forest landcover model (Figure 29 A), spatial scales of timber harvest in the Clay Belt are finer than mature forests, they do not have similar hierarchical patterning as mature forests, and I estimate the frequency of timber harvest (+/- 60 - 80 years) to be much finer than fire (>130 years).

MANAGEMENT IMPLICATIONS

Managing the spatial and temporal distribution of clearcuts with the intention of emulating natural disturbance and landscape patterns is an approach the Ontario government is adopting and is required by the CFSA (OMNR 1995). The approach includes measuring landscape indices of fire sizes, residual patches within fires, results of burning on different topographical features, different fire intensities etc., and attempting to use these results to guide the layout of cutblocks through forest management planning. The approach is to ensure that landscape patterns created by timber harvest are similar to those created by natural disturbance.

Results of my analyses indicate that in the Red Lake area, scale dependent landscape patterns resulting from natural disturbance are similar to mature overstoy forest landscape patterns. The obvious conclusion is that if timber harvest occurs in landscapes following similar spatial and temporal characteristics to wildfire, the end results should be mature forests with landscape structure characteristics that are close to natural. Although I did not detect wildfire landscape patterns in the Clay Belt area, the results indicate that mature overstory forest patterns exhibit no distinct ELO below 75,162 ha. In contrast, the disturbance landcover class, caused primarily by forest harvest, only had ELO detected below 10,172 ha. This indicates that the landscape patterns formed by timber harvest are not the same as mature overstory forest patterns. If I use the analysis from the Red Lake area to conclude that hierarchical characteristics of mature overstory forest are similar to hierarchical characteristics of natural disturbance, then it appears that in the Clay Belt area, scale-dependent patterns of landscapes created from forest harvest are not closely emulating natural disturbance.

The new Forest Management Planning Manual for Ontario's Crown Forests lists biodiversity as a criterion for sustainability planning (OMNR 1995). Under the criterion, acceptable levels of measurable indicators are listed. These include: i) the frequency distribution of clearcut sizes should show movement towards the frequency distribution of natural disturbance size, and ii) forest diversity should be maintained within bounds of natural variation (OMNR 1995). Further, the Canadian Standards

Association Sustainable Forest Management System lists conservation of biological diversity as a criterion for reaching sustainable forest ecosystems (Canadian Standards Association 1996). Maintaining natural conditions of landscape patterns is not a new concept in the ecological literature, but is new in management and policy initiatives. If we accept ecological hierarchy theory, we should assume that broad scale-landscape disturbances that do not emulate natural disturbances in temporal or spatial frequencies will change biological components at low levels in hierarchies and movements away from natural conditions, including changes in biological diversity. Given Holling's (1992) premise that body mass clumps of birds and mammals are entrained and defined by these textural discontinuities, I can only conclude that if we fail to develop and implement forest policy that focuses on maintaining the natural texture discontinuities of landscapes, the results will be changes in site, regional, and provincial biological diversity.

Forest management models are currently being tested and used in the province. For instance, the Strategic Forest Management Model (SFMM) system is an aspatial model which aids in the prediction of wood supply and habitat suitability. The need for spatial models to predict habitat, wood supply, and future forest conditions is great. Spatial analysis of variables such as patch size, core area, patch density, edge density etc., assist in planning and comparing present and future forest conditions. Multiple scale analyses comparing current and future forest conditions could be used in unison with the current single scale comparisons. For instance, detecting ELO by generating lacunarity values over a series of scales on current forest landcover and forest resource inventory maps, and then generating lacunarity values over the same scales for differing forest planning scenarios, would allow forest management planning teams to make comparisons and decisions that would aid in emulating recent historical disturbance landscape patterns.

I have shown that differences in ELO are subtle and in some cases non-existent at the 400 km^2 level, and differences are more pronounced at the 5,625 km^2 level. Forest management units in northern Ontario are between 160 km^2 and 21,480 km^2 (Northeast $\mu = 3{,}937$ km^2, $n = 57$, Northwest $\mu = 3{,}832$ km^2, $n = 69$), ecodistricts are between 240 km^2 and 58,360 km^2, and ecoregions are between 18,480 km^2 and 117,480 km^2. Detected ELO in the east were at 100 km^2, 1500 km^2, and 4000 km^2, and in the east at 220 km^2, 1500 km^2, and 4000 km^2. This indicates that within forest management units multiple ELO at fine-scales can be detected, planned, and managed. However, at broad-scales multiple ELO has to be managed for within and across several management units.

An example of a fine-scale management strategy is the Timber Management Guidelines for the Provision of Moose Habitat (OMNR, 1988). The guidelines prescribe cut-block sizes (+/- 120 ha), distance between cuts, leave blocks etc. The guidelines may be appropriate when managing for a single species, such as moose. However, sustainable ecosystem management is a more holistic approach that demands more rigorous and complex strategies, such as multi-scale forest habitat management.

LITERATURE CITED

Allain, C. and M. Cloitre. 1991. Characterizing lacunarity of random and deterministic fractal sets. Physical Review A 44:3552-3558.

Allen, T.F.H., R.V. O'Neill,, and T.W. Hoekstra. 1987. Interlevel relations in ecological research and management: some working principles from hierarchy theory. J. Appl. Sys. Analy. 14:63-79.

Baker, W.L. 1993. Spatially heterogeneous multi-scale response of landscapes to fire suppression. Oikos 66:66-71.

Band, L.E., F. Csillag, A.H. Perera, and J.A. Baker. 1997. Estimation of net ecosystem productivity in Ontario: Derivation of ecoprovines. (in press) 18 pp.

Burger, D. 1993. Revised site regions of Ontario: Concepts, methodology and utility. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Research Report No.129. Sault Ste. Marie, Ont. 29 pp.

Canadian Standards Association. 1996. A sustainable forest management system: guidance document. CAN/CSA-Z808-96. Canadian Standards Association, Etobicoke, Ontario. 32 pp. + apps.

Congalton, R.G. 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing Environ. 37:35-46.

Forman, R.T.T. and M. Godron. 1986. Landscape ecology. John Wiley and Sons, N.Y. 486 pp.

Gefen, Y., Y. Meir and A. Aharony. 1983. Geometric implementation of hypercubic lattices with noninteger dimensionality by use of low lacunarity fractal lattices. Physical Review Letters. 50:145-148.

Gluck, M.J., R. Rempel and P. Uhlig. 1996. An evaluation of remote sensing for regional wetland mapping applications. Ontario Ministry of Natural Resources, Forest Research Report No. 137, Sault Ste. Marie, Ont. 33 pp.

Hills, G.A. 1952. The classification and evaluation of site for forestry. Ontario Department of Lands and Forest Research Division Research Report 24. Sault Ste. Marie, Ont. 22pp.

Hills, G.A. 1959. A ready reference to the description of the land of Ontario and its productivity. Queens Printer for Ontario. Toronto, Ontario. 29 pp.

Hills, G.A. 1960. Regional Site Research. For. Chron. 36:401-423.

Hills, G.A. 1976. Mapping the site regions and landscape districts of Ontario 1944-1975. Introducing the 1975 version. Ontario Ministry of Natural Resources., Ontario Forest Research Institute, Archives OFRI, Sault Ste. Marie, Ont. 25 pp.

Holling, C.S. 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. Eco. Mono. 62(4):447-502.

Johnson, E.A. 1992. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge University press. G.B. 128 pp.

Jones, R.K., G. Pierpoint, G.M. Wickware, J.K. Jeglum, R.W. Arnup,, and J.M. Bowles. 1983. Field guide to forest ecosystem classification for the clay belt, site region 3E. Ontario Ministry of Natural Resources, Queen's Printer for Ontario. Toronto, Ont. 121 pp.

King, A.W. 1991. Translating models across scales. In: Quantitative methods in landscape ecology. Editors: M.G. Turner, R.H. Gardner. Springer-Verlag N.Y. 479-517.

Klijn, F., and H.A. Udo de Haes. 1994. A hierarchical approach to ecosystems and its implications for ecological land classification. Landscape ecology 9(2):89-104.

Kolasa, J. 1989. Ecological systems in hierarchical perspective: Breaks in community structure and other consequences. Ecology 70(1):36-47.

Kotlair, N.B. and J.A. Wiens. 1990. Multiple scales of patchiness and patch structure: A hierarchial framework for the study of heterogeneity. Oikos 59:253-260.

Krummel, J.R., R.H. Gardner, G. Sugihara, R.V. O'Neill and P.R. Coleman. 1987. Landscape patterns in a disturbed environment. Oikos 48:321-324.

LaGro, J. 1991. Assessing patch shape in landscape mosaics. Photo. Eng. & Rem. Sen. 57(3):285-293.

Lillesand T.M. and R.L. Kiefer. 1987. Remote sensing and image interpretation. John Wiley and Sons. Totonto, Ont. 621 pp.

Legislative Assembly of Ontario. 1994. The Crown Forest Sustainability Act. Chapter 25, Statutes of Ontario.

Legislative Assembly of Ontario. 1995. Environmental Bill of Rights. Chapter 28, Statutes of Ontario.

Mandelbrot, B.B. 1983. The fractal geometry of nature. W.H. Freeman. N.Y. 486 pp.

MacLean, D.W. and G.D. Bedell. 1955. Northern clay belt growth and yield survey. Canada department of Northern Affairs and National Resources, Forestry Branch. Forest Research Division. Technical Note No. 20 31 pp.

McGarigal, K. and B.J. Marks. 1993. Fragstats: Spatial pattern analysis program for quantifying landscape structure. Reference manual. For. Sci. Dep. Oregon State University. Corvallis Oregon. 62 pp.

Menard. S. 1995. Applied logistic regression. In: Series; Quantative applications in the social sciences. (ed) Michael S. Lewis-Beck. 97 pp.

Nellis, M.D. and J.M. Briggs. 1989. The effect of spatial scale on Konza landscape classification using textural analysis. Landscape Ecology. 2(2):93-100.

Odum, E.P. 1977. Fundamentals of Ecology. 3rd Ed. Saunders. Philadelphia, 574 pp.

OMNR. 1988. Timber management guidelines for the provision of moose habitat. Ontario Ministry of Natural Resources. Toronto, Ontario. 31 pp.

OMNR. 1994. Policy Framework for Sustainable Forests. Ontario Ministry of Natural Resources, Toronto, Ontario

OMNR. 1995. Forest Management Planning Manual for Ontario's Crown Forests. Ontario Ministry of Natural Resources. 343 pp.

OMNR. 1997. Lands for life: a land use planning system for Ontario's natural resources. Ontario Ministry of Natural Resources. 15 pp.

O'Neill R.V., R.H. Gardner and M.G. Turner. 1992. A hierarchical neutral model for landscape analysis. Landscape ecology. 7:53-61.

Ontario Environmental Assessment Board. 1994. Reasons for decision and decision: Class environmental assessment by the Ministry of Natural Resources for timber management on Crown lands in Ontario. Queen's Printer for Ontario, Toronto, Ontario. 561 pp.

Ontario Forest Policy Panel. 1993. Diversity: Forests, people, communities. Report of the Ontario Forest Policy Panel. Queen's Printer for Ontario, Toronto, Ontario. 147 pp.

Plonski, W.L. 1981. Normal Yield Tables (Metric) Ontario Ministry of Natural Resources. 40 pp.

Plotnick, R.E., R.H. Gardner, and Robert V. O'Neill. 1993. Lacunarity indices as measures of landscape texture. Landscape Ecology. 8(3):210-211.

Plowright, R.C. and C.Galen. 1985. Landmarks or obstacles: the effects of spatial heterogeneity on bumble bee foraging behaviour. Oikos. 44(3):459-464.

Rempel, R.S., P.C. Elkie, A.R. Rodgers, and M.J. Gluck. 1997. Timber-management and natural disturbance effects on moose habitat: Landscape evaluation. J. Wildl. Manage.61(2):516-524.

Rowe, J.S. 1972. Forest regions of Canada. Canadian Forestry Service. Department of the environment. Info. Can. Cat. No. 47-1300. 172 pp.

Rudd, W.G., D.C. Herzog, and L.D. Newsom. 1984. Hierarchical models of ecosystems. Environ. Entomol. 13:584-587.

Spies, T.A., W.J. Ripple, and G.A. Bradshaw. 1994. Dynamics and pattern of a managed coniferous forest landscape in Oregon. Ecological Applications 4(3):555-568.

SPSS. 1994. SPSS Advanced statistics 6.1, Users manual. SPSS inc. Chicago, Illinois 606 pp.

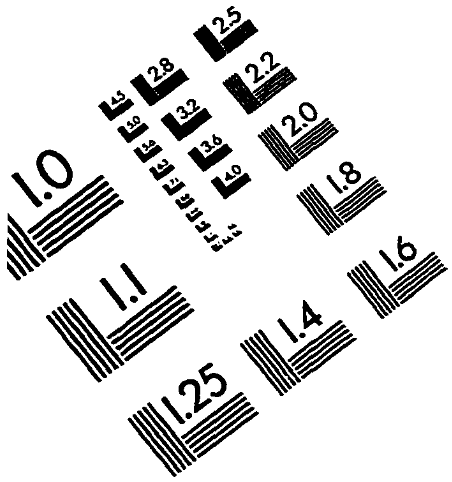
Story, M., and R.G. Congalton. 1986. Accuracy assessment: A user's perspective. Photogramm. Eng. Remote Sensing 52:397-399.

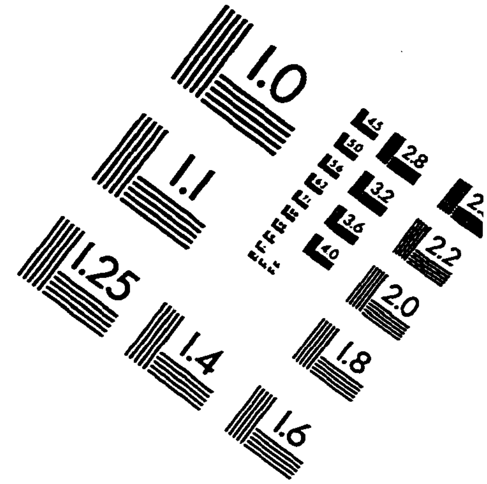
Turner, M.G. 1989. Landscape Ecology: The effect of pattern on process. Annu. Rev. Ecol. Syst. 20:171-197.

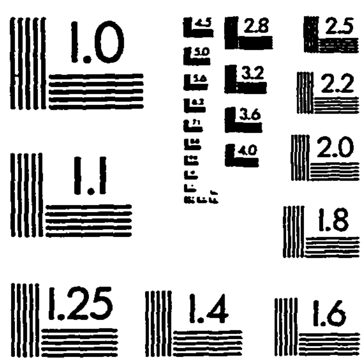
Turner, M.G. and R.H. Gardner. 1991. Quantitative methods in landscape ecology. pp 3-14. In: M. Turner and Gardner, R.H. (eds) Quantitative methods in landscape ecology. Springer-Verlag. N.Y.

Woods, G.T. and R.J. Day. 1977. A summary of the fire ecology of Quetico Provincial Park. Ontario Ministry of Natural Resources. Report No. 8, Fire Ecology Study. 39 pp.

IMAGE EVALUATION TEST TARGET (QA-3)

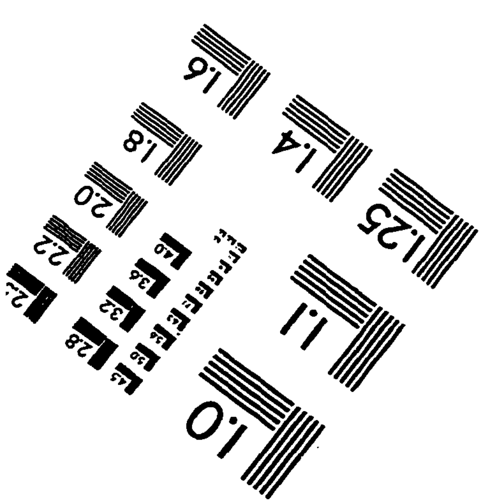


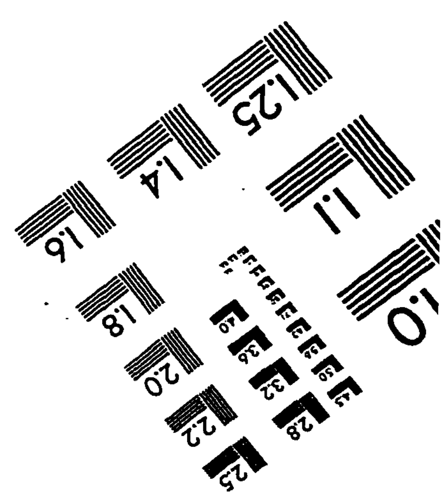




150mm

6"





APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989