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Natural disturbance and land cover patterns in a mountainous, sub-Arctic environment (Yukon)

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Abstract

The dynamics of landscape pattern and disturbance were studied in the 'green belt' area of Kluane National Park, Yukon. White spruce montane forests and various sub-alpine and alpine vegetation communities dominate the study area, adjoining the Kluane Ranges of the St. Elias Mountains. Combining theory on landscape structure and function, the relationships of disturbance regimes and landscape pattern are examined. The landscape mosaic was mapped from classification of multispectral Landsat Thematic Mapper imagery. Landscape pattern was measured using quantitative indices of patch, class, and landscape attributes. Natural disturbance regimes, important to land cover development in the region, include fire, insect infestation, and geomorphological processes. The impact of these disturbances on landscape pattern is governed by the frequency, intensity, distribution, size, and synergism of their occurrence. The landscape of the Kluane region experiences infrequent, large-scale fire and insect disturbances and frequent, smaller-scale fluvial disturbances. Heterogeneity of landscape types is maintained through the cycles of repeating disturbance; however, the long return interval of catastrophic disturbance allows some homogeneity to establish in the montane forests. The high landscape diversity is also a function of highly variable topographic and micro-climatic conditions.

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TABLE OF CONTENTS

List of Tables

LIST OF MAPS AND FIGURES

CHAPTER 1: INTRODUCTION

Background

The earth's surface displays varying degrees of environmental heterogeneity (Pearson 1994). Heterogeneity in landscapes is created by two elements of vegetation patterns: the differential distribution of species along environmental gradients and the stage of recovery from disturbance (Romme 1982). Knowledge of spatial and temporal heterogeneity is essential to understanding population, community, and ecosystem processes (Johnson and Gutsell 1994).

Traditionally, diversity was investigated at the species, population, and community levels, and only in the last two decades have diversity concepts been seriously examined at the landscape scale (Suffling 1988). This recognition was motivated by the need to understand regional and global processes. Landscape pattern refers to the composition and configuration of different ecosystems across a region, and is a function of the distribution of species and environmental conditions (Baker *et. al.* 1991). Disturbance regimes (eg. fire, insect outbreaks, windfalls) affect the spatial and temporal heterogeneity of ecosystems (Denslow 1985, Kamada and Nakagoshi 1996, Johnson and Gutsell 1994). Landscape pattern also influences the behaviour of disturbance regimes (Turner *et. al.* 1989, Baker *et. al.* 1991). These effects, either synergistic or antagonistic, create a complex set of relationships governing the interactions between disturbances and landscape pattern.

Research Question

The basic premise supporting this research is that landscapes are differentiated spatially and temporally, and that our understanding of landscape heterogeneity is incomplete. This research aims to characterize landscape pattern in the Kluane Ranges of southwest Yukon (Map 2) and to explore links between natural disturbance regimes and landscape pattern. Also, the dynamics that significant topographic relief add to the natural disturbance-landscape pattern system are examined. Specifically, this analysis measures the variation of standard landscape pattern indices over time and space. Particular emphasis is placed on the role of natural disturbances as causes or factors in the variation of landscape pattern. Knowledge of natural variations in landscape pattern is important to understand how landscapes evolve, develop, and react to disturbances. The analytical portion of this research addresses these questions, albeit over a relatively short period of time. Using two snapshots of landscape pattern and research from the literature, the dynamics of landscape pattern and disturbances are explored. This research is not limited to one or more hypotheses, but rather takes a broad approach to the topic of landscape pattern and disturbance. As no previous research on landscape pattern has been conducted in the study area, this comprehensive approach is well suited to open the field of research for the study area.

Landscape Pattern and Disturbances

Broad scale landscape structure, function, and change are the fundamental components of landscape ecology (Forman and Godron 1986). As a measure of structure, indices have been developed to quantify landscape pattern (O'Neil *et. al.* 1988). Through the application of these indices, changes in landscape pattern will be measured for a portion of the Kluane Ranges in Kluane National Park Reserve. Changing landscape pattern will be placed in the context of natural disturbances regimes, including insect infestation, forest fire, and geomorphological disturbances. Kluane National Park Reserve is situated in the St. Elias Mountains, and is characterized by changing vegetation communities along climatic and topographic gradients. The spatial configuration of these communities is established and influenced by climatic, edaphic, and environmental conditions and continually modified by disturbance regimes. Knowledge of landscape patterns, and associated links with disturbances, will contribute to the understanding of ecological processes in mountainous environments. Natural resource managers also benefit from knowledge of the impact of disturbance regimes on landscape structure. There is increasing focus on understanding the impact of forest harvesting on landscape pattern (Mladenoff *et. al.* 1993) and managing these activities to more closely resemble natural disturbances (Frelich and Reich 1998, Bergeron *et. al.* 1998). For example, sections of the Crown Forests Sustainability Act (CFSA) in Ontario stipulate that forest harvesting must simulate patterns created by natural disturbance regimes, most notably fire (CFSA 1994).

Measurements of landscape pattern, as well as providing necessary information for studies of landscape functioning, allow monitoring of regional ecological changes (Turner and Gardner 1991). Changes in landscape structure are regulated by the cumulative history of all disturbances in a region. The response of species and populations to disturbances creates a mosaic of communities, each at a different stage of recovery (Johnson 1992). Landscape patterns are also affected by the variable physical conditions in alpine areas, which determine the distribution of species. Changes in altitude, aspect, and slope further influence the behaviour of disturbance regimes (Pearson 1994). The physical and environmental constraints and the history of large scale disturbances are factors which add complexity to the study of relationships between disturbance regimes and landscape pattern.

The study of landscape structural characteristics, including spatial and temporal variations, in the Kluane region will address the deficiency of research on landscape pattern in high relief areas. Studies linking landscape structure and topographic relief are rare in the literature, and those that have been published are not current (Romme 1982, Romme and Knight 1981). There has been some work on landscape pattern and disturbances in mountainous regions (Trabaud and Galtié 1996), however the role of topographic relief is seldom fully explored. The linking of natural disturbance regimes and changes in landscape pattern also represents an important contribution, and one that has only recently been explored (Turner and Dale 1991). Many studies have explored diversity-disturbance relationships, however few have researched the impact of disturbance on other aspects of landscape pattern (*e.g.* patch shape). Finally, it is important for long term studies to establish a baseline of present landscape pattern from which the impact of future disturbances can be measured.

Study Area

Kluane National Park Reserve (KNPR) occupies the southwestern corner of Yukon Territory within the St. Elias Mountains. The study area (46 km by 54 km) is located in the Kluane Ranges southwest of Haines Junction and is almost completely contained within the park. Steep, narrow mountains dominate the landscape, which includes glacial and non-glacial lakes and rivers (Environment Canada 1987). The Alsek River flows through the study area and forms a broad valley supporting open stands of white spruce. On higher elevation slopes and valleys grow various sub-alpine and alpine tundra, meadow, and shrub communities (Environment Canada 1987). West of the study area, in the park interior, exists a vast glaciated landscape devoid of vegetation. Long valley glaciers link the interior icefields with the 'green belt' region. Strong winds continually blow down the valley glaciers. The St. Elias mountains create a rain-shadow in the study area whose climate is generally classified as semi-arid continental with long cold winters and short warm summers (Beaver 1997). The Kluane region, as a relatively undisturbed landscape, lends itself well to studies of landscape patterns and natural disturbances.

Chapter Outline

Chapter 1 provides the required background and introduction to the research objective and study area. The supporting literature and theory is reviewed in Chapter 2. Beginning with a discussion of the theoretical framework and contributions of the thesis, this chapter lays the theoretical groundwork for the research. The interrelated principles of disturbance and the landscape mosaic are presented and examined in the greater context of landscape development. As the principal supporting discipline, landscape ecology is reviewed before focussing on the methods and applications of landscape pattern analysis. The methods used to complete the technical portion of the research are documented in Chapter 3. Steps include a description of the study area, land cover classification, landscape pattern analysis, and sensitivity analysis. Chapter 4 reviews the results of the quantitative landscape pattern analysis. This includes a presentation of the results at class and landscape scales, temporally, and altitudinally. Chapter 5 forms the link between natural disturbances and landscape pattern and reviews three principal acting disturbances – forest fire, insect infestation, and geomorphological processes – and their impact on landscape pattern. Chapter 6 closes the discussion and summarizes the main findings of the research.

CHAPTER 2: LITERATURE REVIEW

The landscape as a focus of study originated early in the 19^{th} century when A. von Humbolt introduced the scientific-geographic term 'landscape' (Naveh and Lieberman 1994). Defined then simply as a region of the earth (Naveh and Lieberman 1994), the word also has artistic, cultural, economic, physical, and ecological connotations. Despite naming a relatively new and growing discipline, the definition of the word has not changed significantly from its nineteenth century origins. Landscapes are defined with varying sizes and boundaries in the literature, often dependent on the scale of investigation. Other broad scale units such as watersheds (very precisely spatially defined) and ecosystems (less precisely defined) are subsumed within *the* landscape.

Originating in central Europe (Naveh and Lieberman 1994), research on landscapes and landscape ecology has gained importance in North America, especially in the last decade (Kupfer 1995). The landscape formed a central theme in geography from the 1880s to 1930s (Dobson 1993). Carl Sauer introduced the term 'landscape' to American geography in 1925 (Bailey 1996). Several influential texts have been published on landscape ecology (Forman and Godron 1986, Naveh and Lieberman 1994). An international journal was established in 1987, and significant publication of pattern-related research has occurred in ecology, forestry, geography, and planning journals. Introducing the new journal *Landscape Ecology*, Golley (1987) described the contributions of landscape as setting the scale and orientation, and the contributions of ecology as indicating the breadth and holistic approach for the new discipline. Troll (1971) described the new Landschaft geography, or landscape ecology, as the regional differentiation of the earth's surface, examining the spatial interplay of natural phenomena , a relatively 'horizontal' approach, and the functional interrelationships from a 'vertical' view point, the interplay of phenomena at a given site (ecotope) studied as an ecological system (44).

New technology has provided researchers with instruments to study the whole landscape. Troll (1971) was especially motivated by the use of aerial photography for the interpretation of landscapes and their constituent patches. Beyond aerial photography, satellite imagery and geographic information systems allowed the precise delineation and quantitative analysis of landscapes (Riitters *et. al.* 1995). However, more important to the development of landscape ecology was interest in broad scale processes affecting the earth's surface – from ecological to climatological systems.

Ecosystems and Landscape Evolution

Much ecosystem theory can be extended to landscapes simply by increasing the scale of the concepts. Elements in the hierarchy of systems from species to populations, communities, ecosystems, and landscapes share many of the same attributes at different scales. The four definitions presented in Table 1 describe systems comprising biotic and abiotic components and their interactions. The scale of the system is normally large, but distinguishing between ecosystems and landscapes is often only accomplished with superlatives. Defining landscapes, or other large systems, requires consideration of two critical points: a) landscapes consist of both parts (structure) and processes (function); and b) scale is crucial to the definition of the whole system and its parts. Table 2 lists several definitions of the term landscape. Fundamentally, this thesis explores the interrelationships between landscape pattern (structure) and natural disturbances (function/process). Moreover, to analyse landscape pattern, the scale used to define the landscape and its classes and patches must be chosen carefully and rationally.

Table 1. Ecosystem definitions.

Source	Definition
Miller (1990)	... combination of a community and the chemical and physical factors making up its non-living environment. It is an ever-changing (dynamic) network of biological, chemical, and physical interactions that sustain a community and allow it to respond to changes in environmental conditions. [p.80]
Forman and Godron (1986)	...all of the organisms in a given place in interaction with their nonliving environment. [p.592]
Raven et. al (1992)	A major interacting system that involves both living organisms and their environment. [p.744]
Bailey (1996)	... an area of any size with an association of physical and biological components so organized that a change in any one component will bring about a change in the other components and the operation of the whole system. [p.167]
Rowe (1961)	A topographic unit, a volume of land and air plus organic contents extended areally over a particular part of the earth's surface for a certain time. [p.422]

Table 2. Landscape definitions.

Source	Definition
Forman and Godron (1986)	...a heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in similar form throughout. [p.11]
Bailey (1996)	...spatially contiguous sites distinguished by material and energy exchange between them. [p.25]
Naveh and Lieberman (1994)	...physiographic, geological, and geomorphological features of the earth's crust (Western geography, geology, and earth science) [p.4] The total character of an Earth region (A. Von Humbolt) [p.4] ...the total spatial and visual entity of human living space, integrating the geosphere with the biosphere and its noospheric man-made artifacts. (Troll, 1971) [p.4]
Funk and Wagnalls Standard Dictionary (1980)	A stretch of inland natural scenery as seen from a single point. [p.444]

Abstracting a landscape for quantitative pattern analysis requires delineation of its components. The literature is replete with methods for mapping and classifying landscapes and their elements (Bailey 1996, Davidson 1992, Sample 1994). The definition of landscape elements by land cover is common, although European sources often refer to the hierarchical system of ecotope, land facet, and land system to define elements holistically rather than thematically (Naveh and Lieberman 1994, Davidson 1992, Troll 1971). The holistic approach to land evaluation may incorporate patterns of climate, geology, soils, vegetation, and fauna to define landscape elements (*e.g.* Canadian Ecological Land Classification system, Table 3), whereas the thematic approach utilizes only one information layer (eg. vegetation or land cover). The mosaic model of landscapes is the dominant view for landscape pattern analyses (Wickham and Norton 1994), but alternate interpretations of the land as gradients, networks of corridors, or as boundaries in a mosaic also exist (Forman and Moore 1992). Constituent patches of a landscape mosaic may be defined either holistically or thematically. When defined by land cover, mosaics are well suited to analytical and disturbance studies. Many disturbances have direct impacts which create new patches or affect patch shape, hence creating the landscape mosaic.

Table 3. Land units in the Canadian Ecological Land Classification. (Davidson 1992, 32)
Note: the scale varies according to the diversity of the landscape under survey.

Land Unit	Definition	Scale
Ecoprovince	An area of the earth's surface characterized by major assemblages of structural or surface forms, faunal realms, vegetation, hydrological, soil, and climatic zones.	1:5,000,000
Ecoregion	A part of an ecoprovince characterized by distinctive ecological responses to climate as expressed by the development of soils, water, fauna, etc...	1:1,000,000 - 1:5,000,000
Ecodistrict	A part of an ecoregion throughout which there is a recurring assemblage of terrain, soils, and vegetation.	1:250,000 - 1:1,000,000
Ecosection	A part of an ecodistrict throughout which there is a recurring assemblage of terrain, soils, and vegetation.	1:50,000 - 1:250,000
Ecosite	A part of an ecosection in which there is a relative uniformity of parent material, soil, hydrology, and vegetation.	1:10,000 - 1:50,000
Ecoelement	A part of an ecosite displaying uniform soil, topographical, vegetative, and hydrological characteristics.	1:10,000

Landscapes develop through five natural processes: geomorphology, climate, plant and animal establishment, soil development, and natural disturbance (Forman and Godron 1986). A region's landforms form the physical substrate for ecosystems and landscapes. The processes that create the earth's geomorphic features and continue to disturb landscapes include plate tectonics, volcanism, erosion, deposition, and glaciation (Forman and Godron 1986, Bailey 1996). Climate may influence these processes as well as significantly predetermine which communities of plants and animals colonize a region (Bailey 1996). Climatological parameters, such as precipitation and temperature gradients, are used to define ecological zones in Ontario (Hills 1959). Plant and animal communities, while forming essential components of a natural landscape, may exert continued influence on its development. Even in the absence of disturbance events, the composition and configuration of ecological systems may change due to plant succession and faunal activities. Soils develop according to climatological conditions, underlying landforms, and plant communities. Acting as a landscape's surficial substrate, they also in turn influence the establishment of plant and animal communities. Finally, natural disturbance is arguably the most tangible method of landscape change. Varying in scale from large, catastrophic forest fire to a gap opening windfall, disturbances continually produce distinct patches within a landscape.

Landscape composition and configuration is determined by these mechanisms (geomorphology, climate, plant and animal establishment, soil development, and natural disturbance). Continued change is especially linked to disturbance events. Disturbances tend to be spatially explicit in their influence and affect localized areas. Their application is therefore uneven, rather than even, across the landscape. The area disturbed and the spatial distribution may vary widely, but the result is often a network of patches, forming a landscape mosaic. Patches are areas of relative homogeneity whose areal extent is defined by the phenomenon under consideration (McGarigal and Marks 1994).

Investigations of land cover pattern would define patch boundaries where land cover varies significantly. Habitat studies may delineate patches differently, based on significant variation in habitat conditions for a particular species. Patches are consolidated according to their composition into patch types or classes. A general, reconnaissance classification scheme may define a dozen patch types, although detailed studies frequently consider many more classes. The scale and resolution of the study determines the detail required in defining the patches and classes comprising the landscape mosaic.

The delineation of patches, as elemental landscape units, is fundamentally scale reliant. When defined as an area of relative homogeneity, the scale at which the patch is defined must be explicitly stated. Scale may be stated quantitatively (*e.g.* 1:1,000,000) or qualitatively (*e.g.* regional or local). Heterogeneity may always be found within a patch by increasing the resolution or scale of investigation (Hunter 1990, Frelich and Reich 1995).

This research involves the mapping of the landscape mosaic for a portion of Kluane National Park Reserve. Due to the resolution of the data used for this exercise, some generalization was introduced. Given data with a finer spatial resolution, patches previously considered homogeneous, might in fact be divided into several different patches belonging to different classes. Small-scale studies (*e.g.* a continent) define broad patches, whereas a larger scale study (*e.g.* a field) within the same landscape would subdivide those broad patches to finer ones. The classification of patches and classes in a landscape is scale reliant and contingent on subject focus. The scale of study in this research would be considered meso-scale based on the area under consideration and the detail at which it is being considered and classified (Bailey 1996).

The literature commonly views landscape patterns and structure synonymously with vegetation patterns (Suffling 1988, Kamada and Nagagoshi 1996, Romme 1982). Alternate models may use ecosystems, climate, or soils to define the landscape matrix and structure. There is convention and simplicity to defining landscapes through land cover. Also, disturbances tend to operate on landscape patches defined by land cover or vegetation. They create new land cover patches and produce changes in existing ones. Change is also frequently caused by successional mechanisms operating within land cover patches. Plant communities, especially forest systems, may change predictably from one community to another. Bailey (1996) discourages the use of vegetation alone for defining ecosystem boundaries since plant communities respond to disturbances. Ecosystems cannot be solely defined and delineated by vegetation or land cover. They include physical, chemical, and biological components *and* processes. This research aims to map and analyse land cover patterns, rather than ecosystem patterns.

Stability, Resilience, and Landscape Change

The behaviour of ecological systems can be characterized by their stability and resilience to disturbances (Holling 1974). Catastrophic disturbances, such as fire, commonly occur in the boreal forest, creating an interesting pattern of stability and resilience. The boreal forest is a resilient system in light of the catastrophic modifications resulting from natural disturbances (Denslow 1985). A review of the concepts of stability and resilience is relevant to the discussion of disturbances and long-term fluctuations in landscape pattern.

Stability is a concept that describes two characteristics of system behaviour: fluctuation and sensitivity. It represents the "ability of a system to return to an equilibrium state after a temporary disturbance" (Holling 1974, 17) and it measures the number and degree of fluctuations that occur in a system (Denslow 1985). Stable systems fluctuate very little, or when they do they can rapidly return to their pre-disturbance state. Feedback processes operating in the system impose stability (Berryman 1986). An exotic disturbance will often result in the shift to a new state or structure (Denslow 1985). Unstable communities may have a high degree of resilience if they contain species and communities adapted to variable environmental conditions (Denslow 1985, Holling 1974). The sensitivity of these species and communities to disturbances will affect the stability of the ecosystem. Stability estimation is also sensitive to scale. Communities may appear unstable if their structure is changing, but long term fluctuations may actually constitute a stable system (Romme 1982).

Resilience is a measure of the "persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling 1974, 17). In contrast to stability, the resilience of a system is not related to the sensitivity to disturbance, but is concerned with the ability of the system to undergo change, and still function as before (Denslow 1985). A system disturbed beyond the limits of its resilience will change to a new structure characterized by a different composition and interactions of species (Denslow 1985).

The recognition that change may be a normal part of a landscape's history has important implications for measurements of landscape pattern. Delcourt and Delcourt

(1987) describe the difficulty, but importance, of understanding long-term vegetational change. Oscillations in the state of a landscape (occurring normally due to disturbance, but also due to other mechanisms of change) enhance the difficulty of analyzing temporal variations of landscape pattern. Observations made during peaks or troughs of the oscillatory cycle must not be interpreted as changes in the mean state of the landscape (*e.g.* Figure 1, A versus B). Knowledge of the frequency of mechanisms of landscape change (*e.g.* disturbance) is critical to properly measure change.

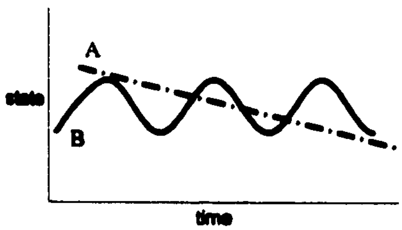

Figure 1. Temporal patterns of landscape change (A - linear change; B - oscillating stability).

Natural Disturbance

Disturbances are defined as discrete events which disrupt or change "ecosystem, community, or population structure and change resources, substrate availability, or the physical environment" (White and Pickett 1985, 7). A disturbance event modifies the communities and spatial configuration of landscapes. New patches are created and form a patchwork mosaic. In mountainous regions, disturbance responses are greatly affected by topography, or altitude, aspect, and slope (Pearson 1994). White and Picket (1985) describe two general kinds of disturbance: destructive events and environmental fluctuations. Forman and Godron (1986) further distinguish between frequent disruptive events (to which communities adapt and evolve) and true, infrequent disturbances. The mechanisms may be similar, yet the landscape response differs.

Studies have shown that some landscapes which experience frequent disturbance become resilient through species and community adaptation (Frelich and Reich 1995, Denslow 1985). Over the long term, disturbances may be a normal part of the functioning of an ecological system. While systems may be resilient to natural disturbances, anthropogenic or foreign disturbances may exceed the resilience of a system. Disturbances may or may not be considered stresses to a system. Stresses, defined as factors that disturb the normal functioning of a system, imply change beyond normal thresholds of tolerance (Auerbach 1981, Ivanovici and Wiebe 1981). In this sense, exotic and especially anthropogenic disturbances are more likely to present a stress to a system.

Knowledge of disturbances attributes is essential to understand their combined effect on landscape pattern and ecosystem functioning. Turner and Bratton (1987) describe disturbances as biotic and abiotic vectors. Vectors are defined as physical forces or animals that move materials or energy in the landscape, and can be distinguished by their origins, either internal or external (Turner and Bratton 1987). From these definitions, disturbances can be physical in nature and originate from outside an ecosystem (eg. fire) or biological and originate from within an ecosystem (eg. insect infestations). Different associations, such as external biological disturbances, are also possible (*e.g.* exotic species). Disturbances with external (exogenous) and internal (endogenous) origins (Kamada and Nakagoshi 1996) can also be considered extremes on a continuum (White and Pickett 1985).

Disturbances change the structure of the ecosystem by reorganizing materials and energy in the landscape (Hendee *et. al.* 1990). Homogeneity normally enhances the spread of disturbances across landscapes since edges or patch boundaries increase resistance (Forman and Godron 1986). Turner and Bratton (1987) outline some cases where heterogeneity may increase dispersal rates of disturbances. The effect of landscape pattern on the spread of disturbances is dependent on the scale of the disturbance and the spatial arrangement and similarity of landscape elements (Turner and Bratton 1987). The behaviour of disturbance regimes involves the following characteristics: distribution, frequency, return interval, rotation period, predictability, area, intensity, severity, and synergy (Table 4) . Consideration of these factors leads to a better understanding of the dynamics of disturbance regimes and their relationship with landscape pattern. For example, a fire regime consisting of infrequent and intense fires will affect landscape pattern differently than one of frequent and less severe fires.

Table 4. Disturbance attributes and descriptions (White and Pickett 1985, Methven and Feunekes 1988).

Disturbance Attribute	Description
distribution	spatial distribution in the landscape
frequency	mean number of events per time period
return interval	mean time between disturbances
rotation period	mean time needed to disturb an area equivalent to the study area
predictability	scaled inverse function of variance in the return interval
area or size	area disturbed
intensity	physical force of the event per area per time
severity	impact on the organism, community, or ecosystem
synergism	effects of occurrence of other disturbances

Fire

Fire is one of the most important abiotic disturbances that influences the structure of the boreal forest ecosystem (Mushinsky and Gibson 1991, Hunter 1990, Forman and Godron 1986). As a disturbance, the impacts of fire on landscape patterns have been studied more than any other disturbance regime (Knight 1987). Large, stand-destroying fires create a 'shifting mosaic' of disturbance patches on the landscape (Baker *et. al.* 1991). The elements of the landscape mosaic can be defined by their last disturbance, as shown on 'stand origin maps' (Johnson 1992). Disturbance regimes vary spatially in complex terrain because of the spatial variation of the environmental conditions that affect disturbance initiation and spread (Baker *et. al.* 1991). Estimation of fire behaviour in mountainous forests can be complicated by the erratic, often weather driven nature of these fires (Agee 1993).

The impact of fire on the boreal forest ecosystem is governed by fire mechanics and the ecological response or strategy of boreal species. The effect of fire on landscape structure does not follow general conventions, but shows specific responses in different vegetation communities (Mushinsky and Gibson 1991). By examining the disturbance characteristics of fire in boreal forest, some insight can be gained into the relationships of landscape pattern and fire. The Kluane case is supplemented with examples from other boreal or alpine forest regions, notably Yellowstone National Park (YNP), where there has been significant forest fire research and interest (Romme 1982, Christensen *et. al.* 1989).

Two scales of landscape pattern are produced by forest fires: a smaller scale partial-fire pattern driven by intensity and severity, and a larger scale whole-fire pattern controlled by fire size and frequency (Methven and Feunekes 1988). Size and spatial distribution of forest fires are fundamental characteristics of the disturbance when considering landscape pattern. The influence of fire on the creation of landscape mosaics is significant (Hawkes 1983a, Baker *et. al.* 1991), but additional information on shape, size, and spatial distribution of fire dynamics are also important considerations. The behaviour of a fire is not only dependent on the ambient temperature, wind speed, and humidity, but also by the spatial distribution of fuels and the structural variation (type, density, and height) of the vegetation community (Mushinsky and Gibson 1991). The distribution of the forest itself affects the spread and extent of the fire (Agee 1993). Fires in mountainous areas tend to be limited to lower elevation forests since they support greater fuel accumulation. At very higher elevation, plant productivity is reduced, fuels are scarce, and hence fires are infrequent (Agee 1993).

In the boreal zone, fires tend to burn large areas mainly because of the available coniferous fuels (Johnson 1992). Even prior to the significant 1988 fires in Yellowstone National Park (Christensen *et. al.* 1989), large fires in YNP were found to have a significant impact on landscape dynamics (Romme 1982). The effect of fire disturbance on landscape pattern is dependent on the severity and impact of the fire on the forest community. A cycle of large, stand-destroying fires will create a shifting mosaic of forest patches, each created by a specific disturbance event (Baker *et. al.* 1991). Alternatively, lower intensity fires will not completely destroy the stand but may open the canopy thereby altering community structure. In this case, disturbance patches are less clearly defined spatially and are also structured by numerous disturbance events. The stand destroying fires create even-aged forest patches whereas the lower intensity fires contribute to an uneven-aged forest (Hunter 1990). In practice, these two scenarios are extremes of the behaviour of fire disturbances. Many forests experience infrequent large scale fires and also more frequent small scale treefall or geomorphic disturbances. Scale plays an important role in identifying patterns of heterogeneity and disturbances. In greater detail, every uneven-aged forest is made up of many even-aged stands (Hunter 1990) and a fine-scale mosaic may be identified in seemingly homogeneous forests (Frelich and Reich 1995).

Altered community structure (size, age, and spatial distribution of trees) is produced by forest fires (Mushinsky and Gibson 1991) and increased diversity of this structure is represented by higher heterogeneity. Supporting disturbance created landscape heterogeneity, Frelich and Reich (1995) rule out biotic interactions among tree species as causes of patch formation in the boreal forest. Understory-overstory relationships are weak in this region in contrast to other forest types. For example, the hemlock/sugar maple forests of the Great Lakes region have significant overstory-understory relationships, where the overstory species influence the composition of understory species and understory species often replace overstory trees (Frelich and Reich 1995). The absence of such successional relationships in the boreal forest suggest that disturbance regimes are more responsible for the creation of the landscape mosaic.

In Yellowstone National Park, Romme (1982) found that landscape richness, evenness, and patchiness were highest under the natural fire regime of large, infrequent fire events. During this period, natural fires burned significant proportions of the landscape. When fire suppression policies were implemented, the overall landscape diversity remained relatively constant in the region, whereas under the natural fire regime landscape composition and diversity fluctuated greatly (Romme 1982).

Studies have identified specific relationships of landscape diversity and levels of disturbance. Suffling (1988) notes that in the boreal forest of northwestern Ontario, landscape diversity is highest with intermediate levels of fire disturbance. At the intermediate level of disturbance, any change in the disturbance rate will decrease landscape diversity (Suffling 1988). When the disturbance rate is low, large homogeneous forested areas can develop, but if fires are frequent and the rotation period is also short, then homogeneity is similarly introduced.

Restoration of heterogeneity in forested landscapes is desired in some cases where fire suppression has limited the occurrence of natural disturbances. Simulation modelling in the Boundary Waters Canoe Area (BWCA) of northern Minnesota has revealed that landscape measures related to the number of patches (*e.g.* mean age and richness) require much more time to restore than do measures of the spatial attributes of patches (eg. shape and size) (Baker 1994). The time required to restore the compositional attributes of landscape patches (150-250 years) was calculated as longer than the period of alteration which degraded them (82 years of fire suppression). This suggests that landscape change occurs over relatively long time periods.

Insect Infestation

Similar to fire, insect outbreaks can have significant impact on forest communities. An insect infestation occurs when populations of an insect reach epidemic proportions and tree mortality or damage is significant. Spruce beetles normally inhabit dead, fallen, and mature trees and are therefore a secondary disturbance agent (Garbutt 1994). When population levels increase sufficiently, spruce beetle move to healthy trees and an infestation occurs (Garbutt 1994). Spruce beetle normally exhibit a two-year life cycle which includes overwintering twice in the inner bark (Savaria 1994). The effect on the tree is the reduction of its conductive capacity and its eventual death. This process of drying is most evident in the needles as they turn from green (current attacks) to red (attacked the previous year) to grey (attacked two years previous). Under favourable conditions, a spruce beetle infestation can cause 100% mortality of mature spruce trees in a stand (Savaria 1994). Some events which permit an outbreak of spruce beetle include floods, blowdown, and right-of-way clearing (Garbutt 1994). These events increase the availability of susceptible trees. Clearcut slash is also known to provide suitable conditions for spruce beetle inhabitation (Berryman 1986). The outbreak can also result from the influx of spruce beetle from outside the ecosystem. This scenario is thought to have occurred in the Kluane region in southwest Yukon (Garbutt 1994). In contrast to fire disturbances, insect infestations normally originate from within the system (under non-outbreak conditions). Exotic pests have external origins and therefore different (usually more severe) impacts on the ecosystem.

The frequency of insect infestation disturbances is related to the population dynamics of the particular insect. Population densities are affected by biotic (host abundance, host quality, competition), physical (landscape, soil, climate), and disturbance (weather, human activities) factors (Berryman 1986, 53). The duration of insect outbreaks is also an important factor in the disturbance regime. At high latitudes, the lifespan of a spruce beetle individual is 2 years and infestations of standing timber normally decline after a few generations (Garbutt 1994). Insect infestations do not have the same intensity as fire disturbances. Very intense insect infestations cause heavy tree mortality over large areas. Less intense outbreaks may only kill a small percentage of trees, thereby thinning the stand and reducing the competition for light, water, and nutrients (Berryman 1986). Since insects will normally infest stressed trees before healthy ones, they serve to regulate the productivity of the stand (Berryman 1986). Insect disturbances are not as severe as forest fire in the sense that they do not destroy the entire vegetative community. Insects are host specific and any understory shrub or grass populations are not damaged to the same degree as with fire disturbances. However, many forest communities have evolved to depend on the post-fire environment of limited competition for establishment and growth. Forest stands may have more competition when regenerating from insect infestation mortality, but there is also an increased likelihood of seed survival, unless they are dependent on fire for regeneration (*e.g.* serotinous cones).

Disturbance Synergy

Ecosystems are not often affected by only one disturbance regime. Several disturbances will often affect an ecosystem, either simultaneously or in very quick succession, and conditions created by one disturbance can impact another. Synergy in the impact of disturbance regimes is not uncommon and it is gaining importance as a concept as holistic, landscape approaches to studying ecosystems are adopted. Multiple disturbances can also have antagonistic (less than additive) effects (Turner and Bratton 1987). The nature of the combined effect of two or more disturbance regimes is governed by the characteristics of each disturbance and the relationships between them (Turner and Bratton 1987).

While most examples of multiple disturbances involve synergy in their occurrence, antagonistic examples also occur. Turner and Bratton (1987) describe an antagonistic relationship on a Georgia barrier island where grazing reduces fire frequency by removing available fuel (fire intensity is also reduced). Spruce beetle activity, under non-outbreak conditions, may also have an antagonistic effect with fire disturbances since they inhabit dead and down trees, thereby increasing the decomposition and removal of potential fuel (Berryman 1986). Susceptibility of insect infested stands to windstorm is another commonly cited synergy in multiple disturbances (White and Pickett 1985). Turner and Bratton (1987) conclude that increased landscape heterogeneity enhances the potential for non-additive, either synergistic or antagonistic, effects of multiple disturbances.

Landscape Pattern Analysis: methods and applications

A landscape mosaic has many measurable attributes related to the configuration and composition of its patches. Collectively, these attributes are called pattern. There is ongoing research exploring the effect of heterogeneous land surfaces on global and regional processes. (Schinel *et. al.* 1991, Lafleur *et. al.* 1997). Some landscape mosaic attributes are relatively simple in concept and measurement, while others are more complex. The composition of a landscape can be characterized by the number and distribution of patches and patch types found within. Configuration describes the arrangement of these patches in the landscape. The landscape ecological literature contains many references to methods and algorithms that measure these landscape pattern characteristics (Baker and Cai, 1992; Cullinan and Thomas, 1992; Hulsshoff, 1995; Ritters *et. al.* 1995). Methods for measurement of composition, heterogeneity, diversity, connectivity and texture have been developed in the last two decades and have benefited from advances in computer technology. Patch level attributes, such as perimeter, area, shape, complexity, and adjacency are also frequently measured. O'Neill *et. al.* (1988) devised equations for measuring dominance, contagion, and fractal dimension of 94 different landscapes covering the majority of the eastern USA. This important study demonstrated the practicality of measuring landscape patterns over large areas with remotely sensed data. In their conclusions, they justify the measurement of landscape pattern with a small set of indices and point to the recognition of different scales in the results of the various metrics. For example, dominance and fractal dimension were found to capture broad patterns, while contagion was sensitive to the fine-grained texture of the landscapes. Hargis *et. al.* (1998) found a high degree of correlation between indices of landscape pattern. A challenge exists for the landscape ecologist to measure indices of pattern that uniquely measure landscape structure and eliminate repetition of results.

Indices of landscape pattern may be classified according to the component being measured and the type of structure evaluated: composition or configuration. Table 5 lists

Table 5. Types of metrics calculated by Fragstats 2.0.

Group	Number of metrics	Aspect of Structure Measured
Area	6	composition
Patch density, patch size and variability	5	configuration
Edge	8	configuration
Shape	8	configuration
Core area	15	composition/configuration
Nearest-neighbour	6	configuration
Diversity	9	composition
Contagion and interspersion	2	configuration

the types and number of metrics calculated by Fragstats 2.0, a popular spatial pattern analysis program developed by Kevin Marks and Barbara McGarigal at Oregon State University. These metrics are applicable at one or more scales (patch, class, and landscape) and quantify either landscape composition or configuration. Metrics measuring landscape configuration are normally spatially explicit, whereas those measuring landscape composition are not.

Although simple, area metrics describe fundamental information regarding landscape composition. Patch and class areas form the statistical basis for the calculation of many other metrics. Patch density, size and variability metrics quantify elements of landscape configuration. Describing the number and mean size of patches in a landscape provides a measure of fragmentation or spatial heterogeneity. Edge metrics measure landscape configuration and are significant to boundary-related phenomena and landscape resistance to plant, animal, and disturbance movement. Shape metrics quantify landscape configuration by measuring patch complexity using a perimeter-area calculation. Core area is defined as the interior area beyond a given distance from the patch edge. Describing both landscape composition and configuration, core area metrics are most significant to studies with a specific focus (*e.g.* avifauna) (McGarigal and McComb 1995). Nearest neighbour metrics quantify landscape configuration by measuring the distance to the nearest patch of the same type. Diversity metrics evaluate landscape composition by considering the richness and evenness of patch types. Finally, contagion and interspersion metrics, measuring landscape configuration, regard the evenness with which patches are spatially distributed throughout the landscape. Individual metrics are discussed in detail in Chapter 4.

The metrics discussed above assess landscape structure based on the patch base unit. Image analysis measurements of landscape pattern employ an alternate method of calculation by measuring pattern in a geometric neighbourhood surrounding a pixel in a raster grid. This differs from the patch-based approach and produces different results that require different interpretation. Texture measurements, for example, would be considered an image analysis method that has no consideration for patches and classes, but still may reveal significant information on landscape pattern (Musick and Grover, 1990). In fact, the contagion index calculated in Fragstats 2.0 is considered an image technique since it calculates 'cell' adjacencies rather than 'patch' adjacencies (McGarigal and Marks, 1994). Some image techniques have incorporated patch shape into their analysis by using geographic instead of geometric neighbourhoods (Dillworth *et. al.* 1994). Image analysis methods rely strictly on the raster data model, whereas landscape based methods may use either the vector or raster models. The distinction lies in the base unit of analysis — the patch (vector/raster) for landscape based methods and the pixel (raster) for image analysis methods. This research employs image analysis of satellite imagery for landscape mosaic definition and patch-based measurements of landscape pattern.

Geographic Information Systems and Remote Sensing

The role of geographic information systems (GIS) in the development of landscape pattern research cannot be understated. Dobson (1993) defines GIS as 'allowing the digital representation of the landscape of a place structured to support analysis' (434). Many of the metrics measuring landscape composition can be calculated without a GIS.

However, calculating basic statistics (area, number) of patches is more rapid and accurate using computer software. This convenience of speed translates to an ability to evaluate more complex and larger landscapes. Metrics describing landscape configuration are even more dependent on systems that can store and manipulate spatially referenced information. Beyond the ability to calculate indices of landscape pattern, the use of GIS for capturing, storing, and measuring change in landscapes is significant. Abstracting landscapes digitally allows quick analysis of change from one date to another and efficient storage of extensive information on individual patches and classes. Remote sensing, as a method of data collection and body of technique and theory, has been tremendously beneficial to landscape ecological studies. Building on the use of aerial photography for landscape mapping, satellite remote sensing allows repeated mapping of land cover over broad areas. The spatial and spectral resolution of modern earth observation satellites is steadily improving. This is creating new challenges and opportunities for research.

The algorithms used to calculate indices of landscape pattern may be simple (*e.g.* number of patches, or edge density: edge/area) or complex (*e.g.* fractal dimension). Simple indices are easily calculated in a geographic information system. User defined routines can be developed to calculate the more complex metrics. However, there are several common software programs (*e.g.* Fragstats, r.le for Grass) that have been written to meet this need. These programs, developed in the research and academic communities, allow the rapid evaluation of dozens of landscape pattern metrics. They have passed the scrutiny of scientific review and have resulted in a proliferation of research using a standard measurement technique. Fragstats is arguably the most popular software for landscape pattern analysis. It was used for this research due its widespread use and stand-alone application. The raster version will accept as input many common image formats and will run on any desktop computer without the need for expensive additional software. The vector version of Fragstats requires Arc/Info and as such is available to a smaller audience.

Kluane National Park has been the subject of several studies on remote sensing of mountainous regions (Franklin 1991, Franklin and Wilson 1991, Franklin and Wilson 1992, Franklin and Moulton 1990). While none of these studies examined the Alsek River region[1], the vegetation patterns of the studied areas are very similar to those of the Alsek. The landscape classes (~10) used in this previous work were considered when developing the classification scheme for this study. An interesting focus of these works was the use of topographic variables for land cover classification. Franklin and co-authors report significant improvement in classification accuracies when topographic variables (elevation, slope, aspect) were used in addition to spectral information. The vegetation in the study area exhibits a distinct altitudinal distribution which accounts for the significance of topographic ancillary data to improved classification.

In a related research project (Wurtele and Slocombe 1997a), various approaches to classifying infested stands using Landsat TM imagery were tested. The methods involved comparing the spectral signature of areas of known infestation severity (eg. healthy, light, moderate, or severe infestation). The report showed poor statistical discrimination

[1]Most of this research was located in the Slims River valley, west of the Alsek River.

between the infestation levels for all variables (TM bands, combinations, ratios) tested due primarily to inadequate reference data[2]. However, significant results have been shown in numerous remote sensing studies of forest defoliation (Ekstrand 1994, Brockhaus *et. al.* 1993, Franklin *et. al.* 1995). Successful application of satellite or aerial imagery to mapping of insect infestations would facilitate temporal studies linking disturbances and changes in landscape pattern. Other geomatics applications to disturbance studies include fire mapping with global positioning systems and fire behaviour modelling.

Landscape Pattern in Mountainous Regions

Topographic relief of any magnitude affects the five guiding forces of landscape development (geomorphology, climate, plant and animal establishment, soil development, and natural disturbance) and in turn landscape pattern. This impact is magnified in mountainous regions with significant and variable topographic relief. Certain soil, slope, or micro-climatic conditions prevent vegetation establishment altogether. In the early eighteenth century, A. Von Humbolt associated vegetation belts surrounding mountains to variable micro-climate, thus initiating the field of biogeography (Forman and Godron 1986). Hydrological patterns can be complex in mountainous regions. In the Kluane region, glacial activity, erosion, and deposition are important relief-influenced factors impacting land cover patterns and landscape processes. Soils develop differentially along topographic gradients and vegetation pattern can be affected by these soil catenas.

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[2]Broad areas of insect infestation delineated from aerial surveys proved inadequate to correlate with the satellite imagery. Field plots or detailed rather than reconnaissance aerial surveys might have provided better results. However, detection could still be hampered by the open canopy which produced a mixed spectral signature of infested spruce trees and understory vegetation and healthy spruce saplings.

Varying rates of snowmelt have been shown to affect the distribution of plant communities above and below the tree-line (Billing and Bliss 1959).

Above all, it is the landform itself that defines much of the landscape pattern in mountainous areas. Bailey (1996) attributes microscale variation to edaphic-topoclimatic differentiation and provides examples of complex mosaics created by differences in aspect and exposure. High relief can also influence the movement and magnitude of disturbances through increased heterogeneity (Turner *et. al.* 1989) and physical barriers. In Kluane, strong winds frequently blow down mountain valleys off glaciers and impact fire direction and slope (Beaver 1997, Hawkes 1983a).

There has been much published research on landscape pattern analysis, yet relatively few have regarded mountainous landscapes (Ripple et. al 1991, Romme 1982, Kamada and Nakagoshi 1996). Seldom is the entire landscape from valley bottom to mountain peak considered or the role of high relief in determining pattern.

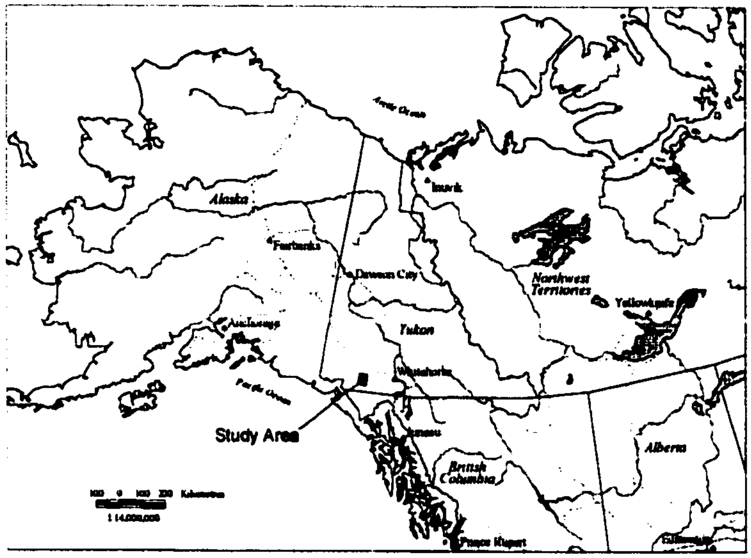
CHAPTER 3: METHODS

The research method to investigate landscape pattern involved two principal phases. The first phase identified the landscape mosaic through a land cover classification of multispectral satellite imagery. This stage included steps to define the landscape (number of classes, scale of study), acquire and prepare data, and construct a digital elevation model (DEM). The landscape pattern analysis was conducted in the second phase for the entire landscape and for the three broad elevation zones (montane, sub-alpine, and alpine). To assess temporal variation in landscape pattern, the method was repeated for datasets from 1989 and 1996. These dates surround a period of intense spruce beetle (*Dendroctonus rufipennis*) infestation in the study area that in the long term will affect landscape pattern.

Study Area

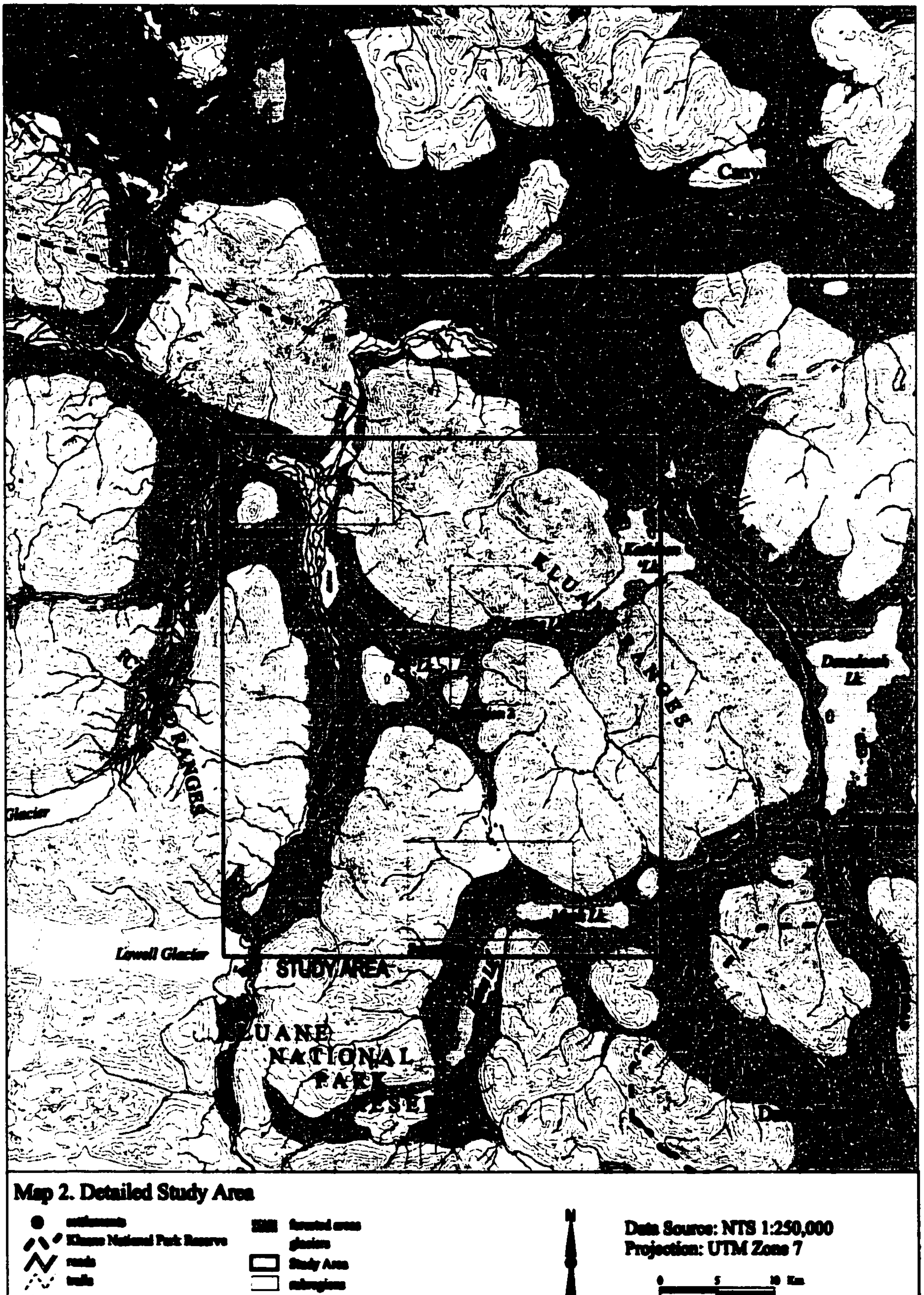
The study area lies on the eastern flank of the St. Elias Mountains in southwest Yukon (Map 1) (60°45'10"N, 137°30'25"W). This mountainous landscape is young geologically (mid-tertiary) and has been significantly shaped by recent and continuing glacial and glaciofluvial actions (Environment Canada 1987). The Alsek River valley roughly divides the Icefield Ranges (3000-5000 metres) from the Kluane Ranges (~2000 metres) (Map 2). To the west is a vast icefield created by the proximity of this high latitude mountain range to the Pacific Ocean. East of the study area, across the Shakwak Trench, is the Kluane Plateau. It is a geologically older landscape of still significant relief interspersed with large lakes and rivers.

The Alsek River figures prominently in the study area. Flowing south from the



Map 1. Continental setting of study area.

confluence of the Kaskawulsh and Dezadeash rivers, it is a silt-laden river running along a heavily braided channel. The river valley supports extensive, open white spruce forests. Deciduous shrub communities border the river and are also abundant in the sub-alpine. High elevation slopes support tundra and meadow communities (Douglas 1974). The area is characterized by steep, narrow mountains, interrupted by distinct valleys (Environment Canada 1987). A distinct pattern results where vegetated land cover communities envelop mountain clusters and extend up their valleys and slopes. This dendritic pattern is typical of geologically young mountainous terrain whereas older landscapes may have more subdued patterns. The patterns are illustrated well in the digital elevation model created for this research. Another artifact of mountainous landscapes is patches extending over broad areas through valleys and alongside mountain slopes. Patches occupying linear bands on slopes and through valleys increase significantly the amount of edge between land cover classes.



Map 2. Detailed Study Area

Disturbances

Geomorphology and climatic variations are significant contributors to land cover development in the Kluane region (Franklin 1991). Other notable influences are permafrost and poor soil development (Environment Canada 1987). Forest fires and insect infestations are the prominent natural disturbances occurring in the montane forests of southwest Yukon (Hawkes 1983a). Fire history has been well documented for Kluane National Park Reserve. The fire regime includes infrequent, variable sized fires (Hawkes 1983a). Shapes of burned areas in high relief regions are highly variable and influenced by wind, topography, fuel, and moisture conditions (Johnson 1992). Insect infestations occur at shorter intervals in the Kluane region (Ferris 1991). A recent spruce beetle infestation (1992-1996) in southwest Yukon has caused significant mortality of white spruce forests. In time, this will influence landscape pattern and affect other natural disturbances. In July 1997, a severe fire directly north of the study area was linked to fuel loading from the spruce beetle infestation (Beaver 1997). Chapter 5 discusses fire, insect, and geomorphological disturbances occurring in the study area.

Human activities are minimal in the study area due to its protected status and wilderness character. Since 1976, the area has been designated Kluane National Park Reserve (22,000 km^2) (Theberge 1980). Less than one quarter of the park is significantly vegetated (Environment Canada 1987) – the remaining portions are non-vegetated or glaciated. The study area lies within this 'green-belt' along the northeastern periphery of the national park. Visitor access to the park is mostly restricted to Alaska and Haines highways along the northern and eastern borders. South of KNPR in British Columbia is the Tatshenshini-Alsek Wilderness Park and to the west is the Wrangell-St. Elias National Park in Alaska. These protected areas form an immense contiguous reserve. Human disturbances include historical mining activity[3], limited visitor access (hiking and rafting on the Alsek) and park management (mostly research). These are currently small scale impacts, however pressures for development of more visitor facilities could constitute greater disturbance. The Alsek River is designated a special preservation zone in the park management plan and is a Canadian Heritage River (Environment Canada 1990).

Land Cover Classes

Review of previous land cover classification studies in the Kluane region (Douglas

Table 6. Land cover classes.

Code	Class	Species/Description
1	spruce forest	white spruce forests
2	rock	exposed rock and gravel
3	alpine meadows	grasses/sedges
4	alpine barrens	exposed soil, some mosses, lichens, grasses/sedges
5	alluvial deposits	unstable, river channels
6	alpine tundra	mosses and lichens
7	mixed forest	classes 1 and 8
8	deciduous shrub	willow, balsam, poplar, some grasses/sedges
9	lake	lake water
10	river	river water (higher sediment load)
12	snow/ice	glaciers/snow pack

[3]There is ample evidence of placer mining, dating to the 1890s and the Klondike Gold Rush. Prior to regulation of Kluane as a national park, portions of the Kluane Game Sanctuary were omitted from the park boundary due to high mineral potential, reflecting continued mineral interests in the area (Theberge 1978).

1974, Franklin and Wilson 1991) led to the development of the classification scheme outlined in Table 6 (see Appendices K and L for the classification schemes of Douglas, 1974 and Franklin and Wilson, 1991 respectively). Without intensive field work, the land cover classes were general in nature resulting in a reconnaissance level classification. A criterion for definition of the land cover classes was detection ability using multispectral satellite imagery. Refinements to the classification scheme were made mid-process to reflect the spectral separability of some classes. For example, water was subdivided to lake and river classes to reflect the distinct spectral and pattern differences between these features.

The landscape matrix in the study area is white spruce forest. Covering extensive areas at lower elevation, this community has variable canopy closure. The predominant community type has an open canopy with a healthy understory of deciduous shrubs (willow, soapberry). Douglas (1974) surveyed stands up to 220 years old, most showing some fire history. This highly-mature forest community is especially susceptible to spruce beetle infestation (Savaria 1994).

The mixed forest class has a lower stem density of white spruce (Douglas 1974) and an abundance of deciduous shrubs (willow, shrub birch). Located generally at higher elevation than the white spruce forests, mixed forests grow adjacent to the landscape matrix along a gradient from full coniferous forest to alpine tundra. The true deciduous shrub community exists at still higher elevation or on slopes with south or south-east aspects. Forest stands with a dominant deciduous component are not generally found within the limits of the study area. However, the KNPR biophysical inventory identifies a small deciduous forest community along the south shore of the Dezadeash River at the northern end of the study area. Deciduous forest was omitted as a land cover class due to its scarcity.

The deciduous shrub communities give way to a collection of sub-alpine and alpine vegetation classes. Alpine tundra and alpine meadow differ in their distribution due to micro-climatic and soil conditions. The tundra community, composed of mosses and lichens, occupies dry sites with poorly developed soils. Alpine meadow, comprising grasses and sedges, prefer mesic to wet sites with more developed soils (Douglas 1974). Based on these characteristics, tundra communities are found at higher elevations than alpine meadows. Alpine barrens are also found at higher elevations and contain species from both tundra and meadow communities, although with a high percentage of exposed soil.

Mountain peaks, ridges, and steep slopes were assigned to the rock class. These features are found predominantly in high alpine areas. Exposed rock and gravel along mountain streams and rivers was also included in this class. These include smaller streams in the sub-alpine and montane and the Alsek River. Alluvial deposits are also found in significant area along the Alsek River and some mountain streams. Consisting of fine particles, and thus a different spectral signature from gravel and rock, these were assigned a separate land cover class. In the summer months, snow and ice are found mostly at high elevation in the study area. The peaks in the Front Ranges are roughly 2,000 metres and therefore contain small snowcaps year-round. Also, the terminus of the Lowell Glacier enters the study area in the southwest corner where it meets the Alsek

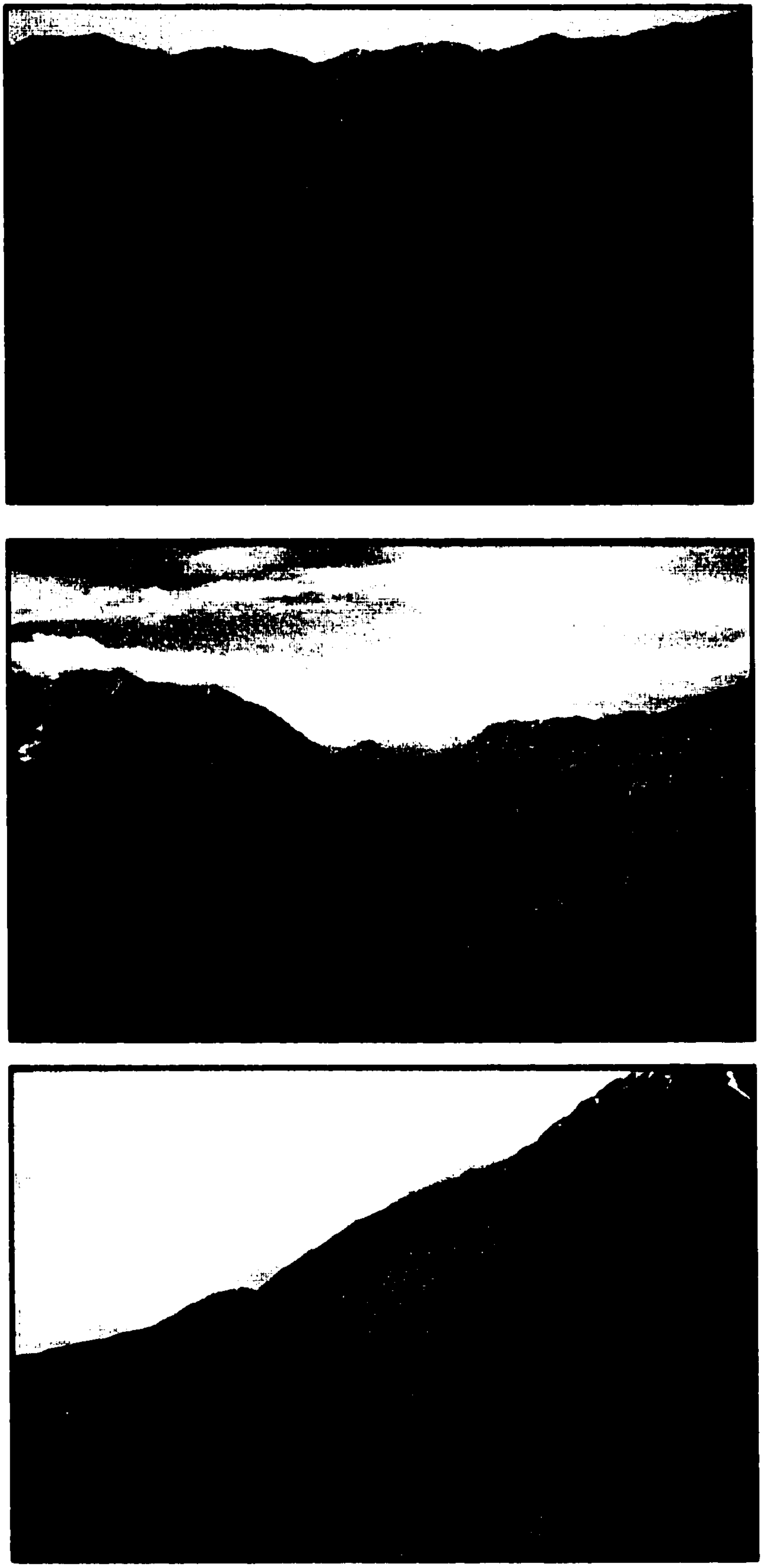


Figure 2. Photographs from 1996 field work.
Top - south of Louise Lake; Centre - Dezadeash River near confluence with Alsek; Bottom - slope west of Dezadeash River.

River.

The spectral signature of lakes and rivers was noticeably different. Rivers[4] in the study area are mostly glacier fed and therefore contain significant amounts of suspended sediments. None of the lakes in the study area are glacier fed. They are clear and deep and absorb a high percentage of incoming solar radiation. Due to their different spectral signatures and their dissimilar shapes, lakes and rivers comprise two land cover classes.

Defining the Landscape Mosaic

Representation of landscapes as mosaics is the dominant model for pattern analyses (Wickham and Norton 1994). Mosaics are suitable for quantitative measurement and emphasize landscape structure versus other models that stress landscape function. However, the process of reducing a landscape to a digital representation has important implications for subsequent pattern analysis. For example, the number of classes in a chosen classification scheme significantly affects indices of landscape diversity.

Factors such as the grain, resolution, scale, and extent of the landscape must be considered carefully both when defining the landscape and when interpreting results of pattern analysis. To simplify interpretation, the landscape should be represented with equal detail between general land classes and spatially within the landscape (*e.g.* between elevation zones). Factors that influence the choice of landscape grain include scale and resolution of source data used for landscape classification (satellite imagery), grain of previous classifications, and the focus of investigation. Available reference data for

[4]The Dezadeash River does not have a glacial source and therefore its spectral signature is very distinct from that of the Kaskawulsh and Alsek rivers. High contrast was observed at the confluence of the Kaskawulsh and Dezadeash rivers on the Landsat imagery.

landscape classification may also predetermine the ability to have equivalent detail throughout the study area. In the Kluane region, few detailed investigations of the alpine and subalpine regions have been completed (KNPR Biophysical Map Series 1:50,000). These regions may have more classes than are currently represented. Such assumptions and conditions related to the landscape definition should be considered when interpreting the extensive results of pattern analyses.

Data Acquisition and Preparation

Image interpretation, DEM creation, and classification were performed in PCI EASI/PACE Version 6.0. This image processing software uses a multi-component file format, whereby many data types are stored within a single file. These types include images, vectors, graphic masks, and signatures. For this research, all data were reprojected to Universal Transverse Mercator (UTM), Zone 7 (metres). The study area selected for analysis comprised approximately 2,500 km^2 and was represented by an image matrix of 1,520 by 1,800 pixels (30 metre pixel size). There were two Landsat Thematic Mapper images in the multi-temporal dataset (1989 and 1996). Appendix I lists the specifications for each image. The 1989 image is much larger and covers a significant portion of eastern KNPR. It was acquired by Parks Canada with a 1990 image that covers the western icefields. The 1996 image is a quarter scene of the eastern greenbelt portion of KNPR. The research method was repeated for the 1989 and 1996 images.

Issues concerning the use of satellite imagery for land cover classification include the cost and availability of images and the time required for processing and field work. The Landsat 5 satellite has a sixteen day repeat cycle. This significantly restricts the 'window of opportunity' for finding cloud free scenes. For example, there were no suitable scenes acquired in 1995 for the study area and this significantly delayed the research. Additional constraints are imposed by the presence of snow from early fall to late spring.

After importing the images to PCI EASI/PACE, geometric and radiometric corrections were applied to enable comparative analysis. The remoteness of the study area precluded detailed field observations for absolute corrections. A relative procedure was therefore used to geometrically and radiometrically register the images. The 1989 image, obtained from Kluane National Park Reserve under a cooperative project, was georeferenced to UTM Zone 7 when delivered. The 1996 image was corrected to the 1989 image using seventeen pairs of ground control points identified on each image. GCPs were distributed throughout the image. A widespread distribution (located around the edges and throughout the body) was not possible due to the difficulty of locating suitable targets. The lack of roads or human development and the shifting nature of the Alsek River made GCP selection difficult. For the selected GCPs, pixel coordinates of the input image (1996) were transformed to determine their corresponding location on the coordinate system of the target image (1989). The 1996 image was registered to the 1989 master image using a 3rd order polynomial mapping function and a nearest neighbour resampling algorithm. The image correction was applied to all bands of the 1996 image (RMS error: 1.31).

Radiometric corrections were applied in a similar fashion with the objective of reducing the effects of different atmospheric conditions of each image capture. For the geometric corrections the 1996 image was corrected to the 1989 image since the 1989 image had been previously georeferenced. Neither image had been processed for radiometric corrections (excluding systemic corrections). The 1996 image was selected as the radiometric control since it contained all seven TM bands, whereas the 1989 image contained only three. Absolute radiometric accuracy was unnecessary for this project – only relative radiometric equivalency between the images was desired to facilitate comparable land cover classifications. Using the 1996 image as a master, the 1989 image was corrected using a linear transformation and radiometric control sets of dark and light objects (Hall *et. al.* 1991). Table 7 shows the mean pixel values and number of pixels in each radiometric control set for each image. Pixels chosen for the control set represent areas with stable reflectance characteristics. Shadows and snow/ice were typical features for dark and bright objects respectively. Equations 2 and 3 were used to generate the transform coefficients (shown in Table 8). The new corrected pixel value was generated from Equation 1.

Table 7. Radiometric control sets.

1989	Band 3		Band 4		Band 5	
Target	Bright	Dark	Bright	Dark	Bright	Dark
Mean Pixel Value	251.02	10.05	183.48	5.49	162.71	2.01
Number of Pixels	44	182	44	182	21	182

1996	Band 3		Band 4		Band 5	
Target	Bright	Dark	Bright	Dark	Bright	Dark
Mean Pixel Value	254.86	12.05	201.7	5.53	157.85	4.47
Number of Pixels	44	182	44	182	20	182

Spatial and non-spatial ancillary data were used in the research method as reference information for land cover classification and for elevation zone partitioning. Spatially referenced data sources included a digital elevation model, vegetation and aerial spruce beetle survey coverages. All spatial ancillary information was imported to the main EASI/PACE file and reprojected to a common standard. Other non-spatial ancillary information was used for land cover classification. This information consisted of aerial

Table 8. Radiometric transformation coefficients.

	Band 3	Band 4	Band 5
m_i	1.01	1.10	0.95
b_i	1.92	-0.50	2.55

$$x_i^* = m_i x_i + b_i \quad (1)$$
$$b_i = (D_{Ri} - D_{Si}B_{Ri})/(B_{Si} - D_{Si}) \quad (2)$$
$$m_i = (B_{Ri} - D_{Ri})/(B_{Si} - D_{Si}) \quad (3)$$

where x_i^* is the corrected pixel value, m_i and b_i are the transform coefficients, B_{Ri}, B_{Si}, D_{Ri}, and D_{Si} are the mean pixel values of the bright and dark control sets respectively for the i^{th} band of the reference (R) and subject (S) images.

photographs of the Alsek River valley, airborne photographs, and field observations from limited ground access to the study area. It provided valuable reference during land cover classification, described below.

A digital elevation model (DEM) was interpolated from 1:250,000 scale NTS contours. The vector data (interval: 150 metres) was imported to EASI/PACE and reprojected to the common standard. The PACE program GRDINT was used to interpolate the vector contour data to develop the DEM. A 30 metre cell size was chosen to match the spatial resolution of the Landsat imagery. GRDINT uses a morphology dependent interpolation algorithm that uses neighbourhood functions to classify regions as peaks, depressions, or slopes (PCI EASI/PACE Users Manual). When completed the DEM was represented by a raster grid of elevation values in a 32 bit real channel.

Additional reference information was sought to aid the land cover classification. Spatial coverages of spruce beetle surveys for 1994, 1995, and 1996 were obtained from the Pacific Forestry Centre in Victoria, BC. These are generated annually from aerial surveys of the insect infestation and classify intensity as light, moderate, severe, or dead. The vegetation component of the Kluane National Park Reserve biophysical inventory was also obtained. It is based on work done by Douglas (1974) and shows more than 60 classes of vegetative cover. The distribution of study sites shown in Douglas (1974) is clustered around roads, rivers, and points with good access. Franklin and Moulton (1990) have identified internal inconsistencies in the biophysical inventory and the need for its improvement. The methodology defined here does not address this need, but instead aims to develop a general land cover classification suitable for landscape level pattern analysis.

The aerial photographs (Line 13-N: A23793-207 and A23793-178), ordered from the National Air Photo Library in Ottawa, were flown in 1974. This series is the most recent for the study area. An assortment of personal photographs was also taken in July 1996 from various ground and air vantage points. The location and direction of each photograph was recorded and aided considerably during land cover classification. Field observations were also made during one helicopter flight through the study area, including two landings (July, 1997).

Land Cover Classification

The landscape was represented digitally by classifying the multispectral Landsat

TM imagery of the study area. Review of previous vegetation classification studies (Franklin and Wilson 1991, Douglas 1974, Franklin and Moulton 1990) led to the development of the classification scheme outlined above. The entire landscape is represented (as in Franklin and Moulton 1990, Franklin and Wilson 1991), whereas some earlier studies focussed on only montane vegetation (Douglas 1974) or geomorphic surfaces (Franklin 1991). Refinements to the classification scheme were made mid-process to reflect the spectral separability of some classes. For example, water was subdivided to lake and river classes to reflect the distinct spectral and pattern differences between these features.

The classification process relies on spectral differences between landscape classes that are quantitatively identified from the imagery. Additional reference data (Table 9) were used to assign spectral clusters an informational label (Table 6). The success of the classification relies heavily on the accuracy of this additional data. When this information is used depends on the type of classification being performed. Unsupervised classification typically uses reference data to assign informational labels to spectral classes or clusters identified in the imagery. Supervised classification employs reference data to train the classifier to recognize the spectral patterns of informational classes pre-determined by the user.

Table 9. Inputs to land cover classification.

Classification Inputs	Format
TM imagery (1989, 1996)	digital raster
vegetation coverage	digital vector
aerial photographs	print
miscellaneous photographs	print
field observations	textual
bispectral plots of class means (red versus NIR)	chart
topographical maps	paper
pattern recognition	-
location recognition	-

An unsupervised/supervised hybrid approach was used in this research method. Due to the remoteness of the study area, suitable reference data for a straightforward supervised classification was not available. Therefore, an unsupervised classification was first performed. The resulting spectral classes identified from this step were assigned to one of the informational classes in Table 6. The reference data were critically important for this labelling. One or more of these inputs was used to make the assignment. All of the class signatures assigned to an informational class were merged. These signatures were then passed to a supervised classifier to generate the land cover image. The unsupervised classification and subsequent labelling provided the training to the supervised classifier.

This unsupervised/supervised hybrid classification benefits from the unbiased detection of spectral clusters in the data and from operator knowledge of informational classes. The full classification methodology is described in detail in Richards (1993). The initial unsupervised classification and signature generation is done on sub-regions instead of the entire image. This reduces computation time and allows better discrimination of spectral class boundaries. Three sub-regions (candidate clustering areas) were chosen across the image (Map 2). These representative regions each contained the complete cross-section of classes. The same regions are used to test the sensitivity of the landscape pattern metrics to different classification schemes. By choosing areas with a good representation of all land cover types, the initial unsupervised classification will recognize boundary pixels as legitimate spectral classes so they can be properly added to adjacent classes (Richards 1993).

A KMEANS unsupervised classifier was selected for the initial clustering (PACE program 'ISOCLUS'). Richards (1993) suggests that three to four spectral classes exist per informational class. Accordingly, the classification parameters included: thirty-five classes for output; ten iterations; and processing of bands 3, 4, and five. The number of classes output from the classifier varied between the sub-regions from 24 to 39 classes. This variation is dependent on the complexity of the region and the inherent range and clustering of spectral classes. An informational label was assigned to each spectral class in each of the sub-regions. In consultation with the reference data, certain classes were easily assigned. Others required more detailed investigation with numerous data sources. The bi-spectral plots proved extremely useful for the labelling procedure. The near infrared and red (bands 4 and 3 respectively) class means were plotted for each sub-region. Each class was grouped with adjacent classes using all appropriate reference data (vegetation maps, photographs) and general knowledge of the relative difference in spectral signature between land cover classes. The trend of lower near infrared reflection for non-vegetated cover types and higher reflection for vegetated cover types is the general principle that guided the distinction of class boundaries on the bi-spectral plots. Additionally, the matching of spectral classes with informational classes from reference data aided in the labelling. Occasionally, density slicing of merged spectral classes was done interactively to ensure that resulting merged classes formed reasonable classes spatially on the landscape. The final grouping of spectral classes was consistently done on the bi-spectral plots to ensure that no class was multi-modal. The maximum likelihood classifier assumes a normal distribution of signatures. Therefore all spectral groups were contiguous in feature space (bi-spectral plot) and had elliptical or circular boundaries delineating their constituent spectral classes.

Signatures of all spectral classes in a group were merged together. Consisting of mean vectors and covariance matrices, signatures could not be merged manually and were processed using the PACE program 'MERGESIG'. Once all of the signatures within regions were merged, the signatures between regions were merged to produce one signature per informational class for all regions. These eleven signatures were passed to the maximum likelihood classification (MLC) and a land cover image was generated. Each pixel in the image was classified according to a maximum likelihood decision rule where class assignment is based on the highest probability of membership.

The use of topographic variables from the DEM was explored for this classification, as outlined in Franklin and Wilson (1991). Early tests produced unsatisfactory results when elevation, slope, and aspect were included as variables with spectral bands in an unsupervised classification. These variables contributed heavily to the classifier, as evidenced by altitudinal banding in the output image. Franklin and Moulton (1990) note their use of discriminant analysis over maximum likelihood methods due to its lower sensitivity to the number of variables and normal distribution assumptions. Without independent data to assess classification accuracies, topographic variables were not used in this study to aid classification, although their successful application is recognized.

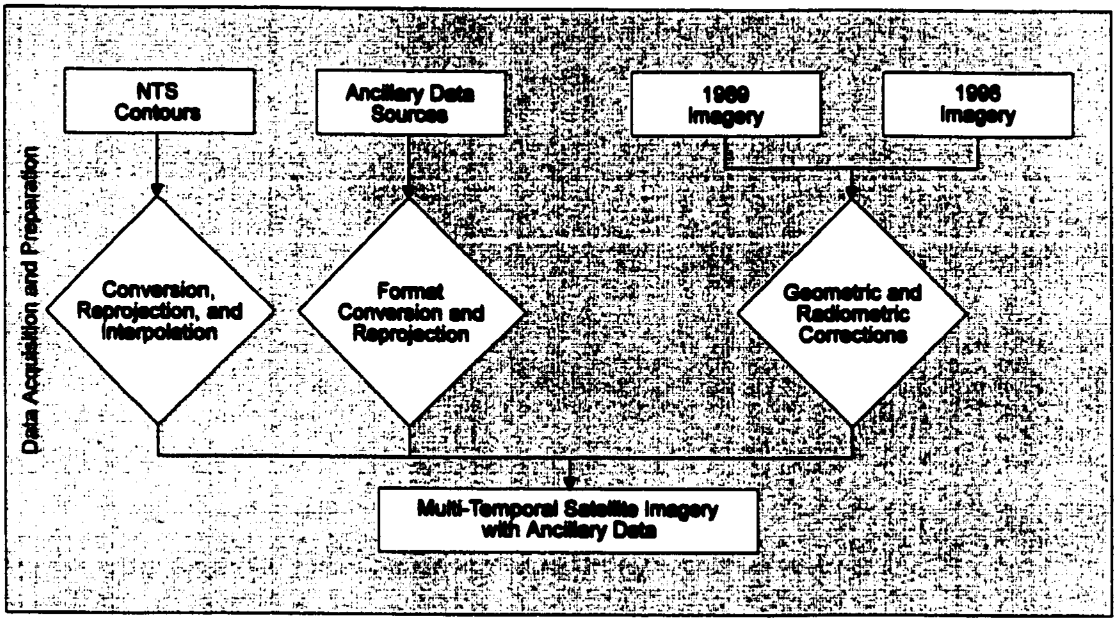


Figure 3. Flow chart of data acquisition and preparation phase.

Table 10. Decision rules employed in knowledge-based reclassification.

Class	Decision Rule	New Class
lake & river	elevation > 1,300 metres or slope > 10 degrees	shadow (background)
alluvial deposits	elevation > 1,000	rock

Two passes of a 3x3 window mode filter were made to smooth the classified image. This filter changes each pixel to the most common value in a nine pixel window centred on the cell. Designed to reduce heterogeneity introduced by systematic noise during image capture, post classification filtering increases the minimum patch size by introducing some spatial context to the classification. The loss of extremely small patches is justifiable given the large extent of the landscape. A larger scale investigation may omit this filtering to preserve fine detail in the landscape mosaic.

The final processing step aimed to correct wrongly classified pixels. Using a simplified knowledge-based reclassification procedure, classes were reclassified if they met established decision rules (Table 10). For example, shadows generated by mountain peaks were labelled as lakes by the classifier. Using an elevation-based decision rule, all high elevation 'lake' pixels were reclassified to shadow. This process enables the discrimination of classes that are spectrally similar, yet exhibit spatially explicit differences. Any pixels not meeting a decision rule remained unchanged. Since this procedure was run post-classification and there were few decision rules, not all pixels were processed (*i.e.* some were unchanged). Typically, more complex expert systems for land cover classification combine the spectral and knowledge-based classifiers and process all pixels (Wharton 1987, Kartikeyan *et. al.* 1995). High elevation alluvial pixels were reclassified to gravel/rock. The decision rules were established after careful examination of the spatial distribution of land cover classes. Above 1,300 metres a.s.l., no lakes were found in the study area from examination of topographic maps. Lower elevation shadows were captured by a slope-based decision rule. All water with a slope greater than 10 degrees was reclassified to shadow. Below 1,300 metres at the confluence of the Kaskawulsh and Dezadeash River (on the east side), there is a steep sloped area that generated a large shadow. The alluvial reclassification relied on a similar elevation based rule. Any pixels classified to alluvial above 1,000 metres were revised to gravel/rock. This is based on the assumption that at higher elevation and slope in the study area, no significant fluvial deposition occurs. This assumption is valid within the precise study area, since the major alluvial feature is the braided channel of the Alsek River.

Typically the final step in image classification is an assessment of classification accuracy[5]. The lack of suitable, independent ground observations did not allow an empirical assessment of classification accuracy. However, the research method was applied consistently and equally to the 1989 and 1996 images. The entire method, detailed thus far, was repeated for the 1989 and 1996 images. The procedure was conducted independently for each of the iterations. Preceding the classification of each image, new signatures were created and clustered on bispectral plots. The same reference data were used to label spectral classes. Reference information from the year of image capture would have been desirable for classification, however the utility of the available information was not diminished by its absence.

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[5]An estimation of the percentage of pixels correctly labelled by the classifier is obtained using independent reference data (ground truth) and commonly expressed in tabular form (confusion or error matrix) (Richards 1993).

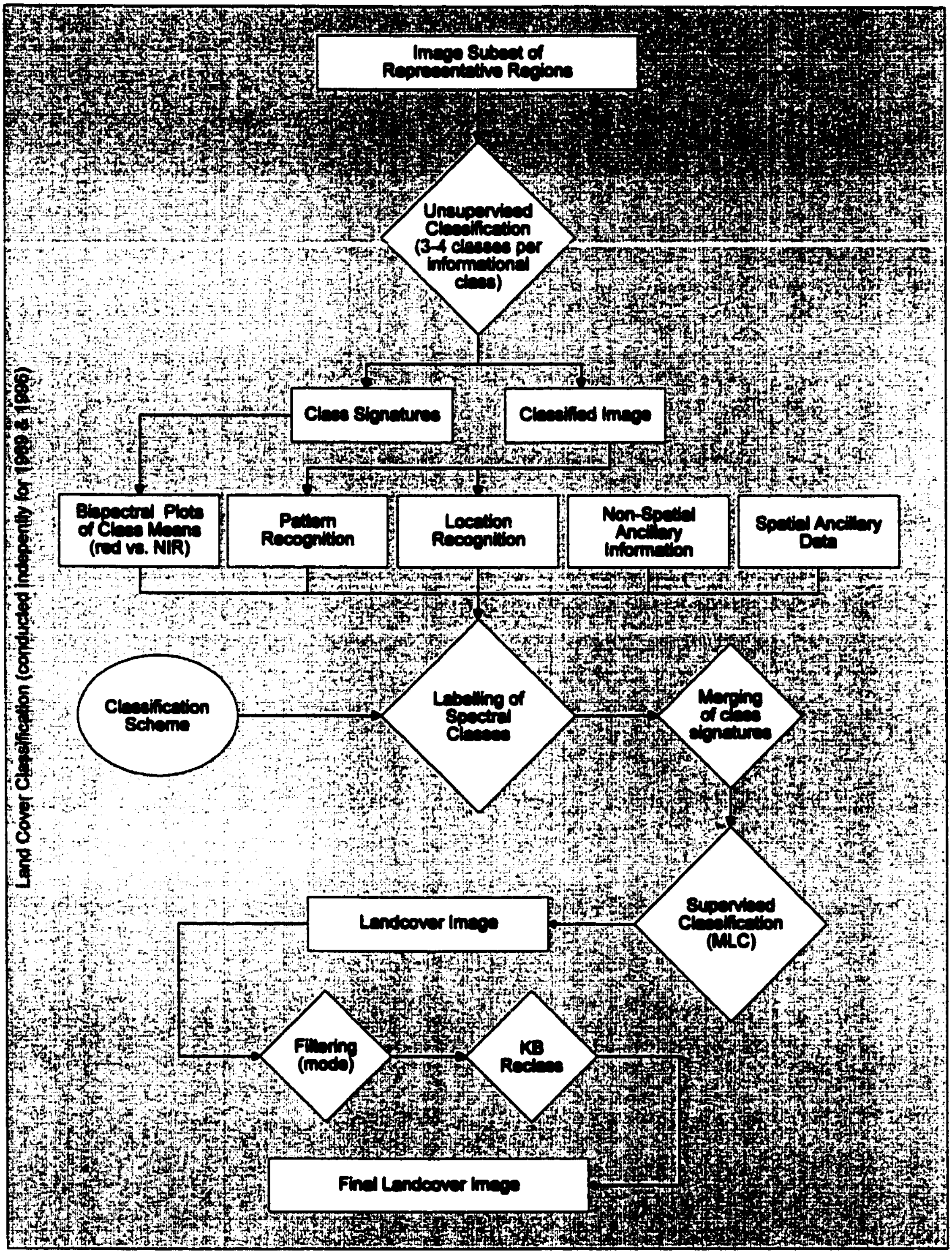

Figure 4. Flow chart of land cover classification.

Landscape Pattern Analysis

Measuring changes in landscape pattern involves examining the changing configuration and composition of the landscape mosaic. The research method quantified change by assessing landscape pattern for two dates. The deliverables from the land cover classification consisted of two raster images, one from each 1989 and 1996. These images are digital representations of the study area landscape in their respective years. They delineate the extent and shape of eleven land cover classes that comprise the Kluane landscape. Each class consists of many individual patches. At three scales (landscape, class, and patch), pattern was measured. Additionally, the landscape was partitioned to three elevation zones: montane, sub-alpine, and alpine.

Douglas (1974) describes the zonation of elevation bands as: montane (less than 1,300 metres), sub-alpine (1,300-1,750 metres), and alpine (greater than 1,750 metres). The rationale for partitioning the landscape on altitudinal ranges is based on the distribution of vegetation communities. Landscape pattern was measured for these zones to quantify altitudinal changes. The DEM was used to reclassify the land cover image from each year to three new images, one for each elevation zone. Therefore, eight images were processed.

All measurements of landscape pattern used the software package Fragstats 2.0 (McGarigal and Marks 1994). Appendix J lists the parameters input to the PC raster version of Fragstats. The land cover images for each year were exported from EASI/PACE to a 16-bit binary format. Likewise, the three elevation zones were analysed independently for each year. Areas outside the zone of interest were classified as background and excluded from the analysis.

Landscape pattern was analysed principally at the landscape and class scales. There are tens of thousands of individual patches in the study area and therefore examination of individual patch statistics was not practical. There is greater utility for patch statistics in landscapes with few patches – either large scale studies (*e.g.* a field) or very small scale studies using a general classification scheme (*e.g.* a continent).

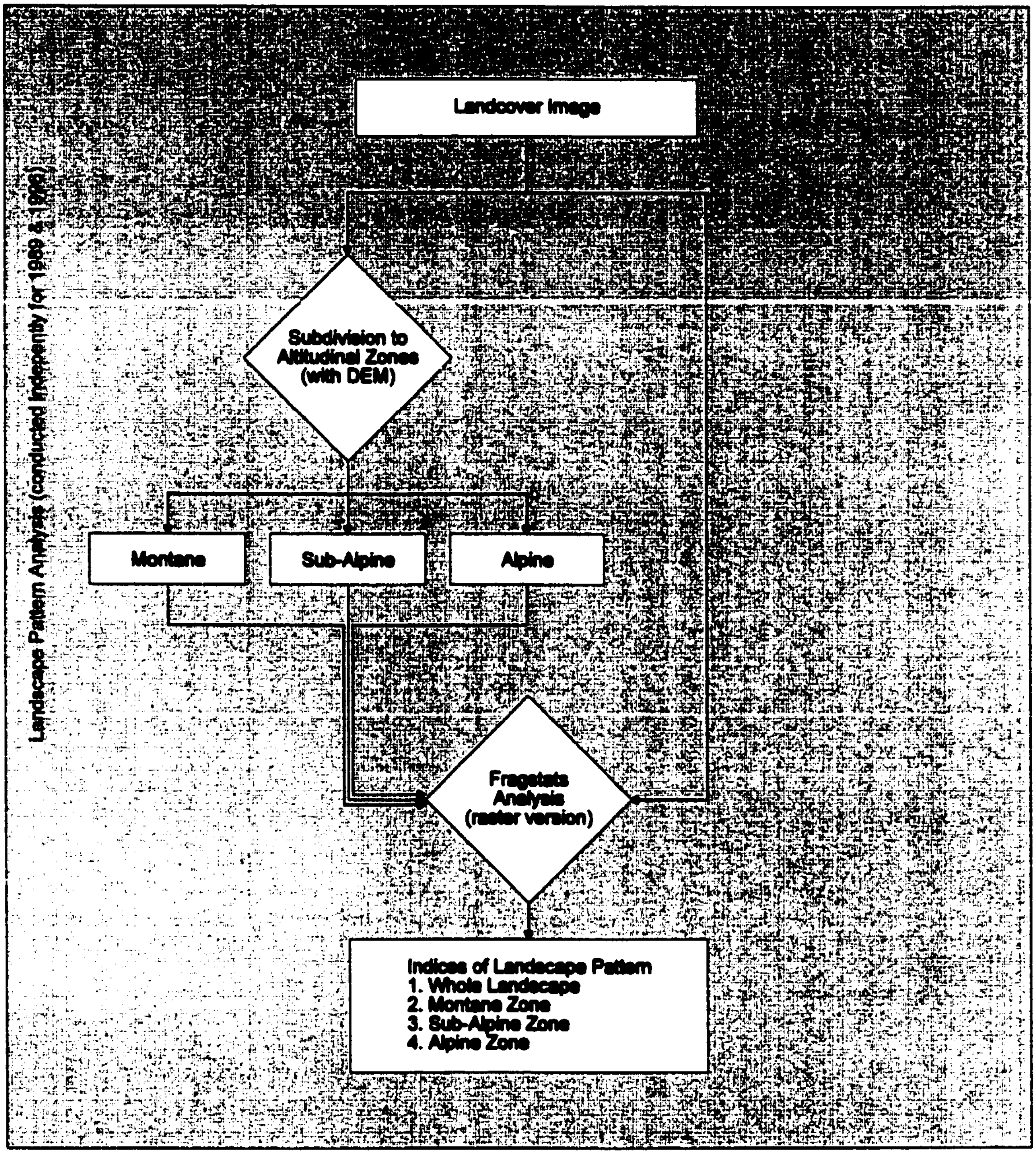

Figure 5. Flow chart of landscape pattern analysis.

Figure 6a. 1989 Land Cover Image.

Figure 6b. 1996 Land Cover Image.

Chapter 4: Quantitative Assessment of Landscape Pattern

An exhaustive set of metrics is available to the landscape pattern researcher. These are comprehensive and address many aspects of landscape pattern. This research aims to investigate disturbance-pattern links and establish a baseline for future landscape pattern analyses in the Kluane region. Therefore, metrics reflecting disturbance impacts are presented: area, edge, diversity, shape, contagion. None of the eleven core area metrics calculated by Fragstats were reviewed since these are more applicable to wildlife habitat studies. Also, nearest-neighbour calculations were not performed due to software and/or hardware limitations related to the size and complexity of the dataset for the study area.

The quantitative results of landscape pattern analysis are presented at the landscape and class scales for both the 1989 and 1996 landscapes. As well, montane, sub-alpine, and alpine sub-landscapes were analyzed for each year. Full results of all indices calculated by Fragstats 2.0 are listed in Appendices C through G. Further information and algorithms for the landscape pattern indices calculated by Fragstats can be found in McGarigal and Marks (1994).

Interpretation of quantitative landscape pattern results should consider several issues related to the initial land cover classification. Classification errors in the landscape mosaic can significantly affect indices of landscape pattern (Hess 1994). In addition, the chosen classification scheme will greatly affect results of pattern analysis. A landscape mapped to a detail of twenty classes will generate higher diversity values than the same landscape mapped to only ten classes. The classification scheme and classification errors must be carefully considered when interpreting results of pattern analysis. Future studies would be more easily comparable if the same study area was chosen. Class area and proportion would vary for a different study area. However, many of the proportional indices should not be significantly affected by varying study area size and extent.

Table 11 shows the basic summary statistics for the 1989 and 1996 landscapes. The study area is 246,240 hectares. Since shadows precluded classification of certain high elevation areas, the landscape sizes for 1989 and 1996 were less than the total study area. These unclassified areas are considered background in the landscape pattern analysis. As a reference, the study area is approximately one third the size of Ontario's Algonquin

Table 11. Summary results for 1989 and 1996 landscapes.

Index	1989 Landscape	1996 Landscape
Total Area (ha)	233,646	222,728
Number of Patches	19,047	19,484
Patch Density (# / 100 ha)	8.15	8.80
Mean Patch Size (ha)	12.27	11.40
Largest Patch Index (%)	11.14	9.90
Patch Richness	11	11
Edge Density (m / ha)	60.03	61.30
Total Edge (m)	14,026,020	13,653,030

Provincial Park. Nearly half of the study area is considered montane, and one quarter each is sub-alpine and alpine (Figure 10). The 1996 image was captured nearly two weeks later in the year than the 1989 image, and therefore contained more shadows. Shadows were observed on steep slopes with a northwest aspect. The differing landscape sizes for 1989 and 1996 demanded more careful consideration of the landscape metrics. For comparative purposes, the proportional indices (*e.g.* edge density, m/ha) are more meaningful than absolute indices (*e.g.* total edge, m). However, since shadow/background areas are mainly restricted to the high elevation alpine zone, the comparison of absolute indices for montane and sub-alpine land cover classes is appropriate.

The 1989 and 1996 images were classified using the same scheme (class list) and as such have identical patch richness. However, the number of patches is slightly higher in the 1996 landscape, despite its smaller total size. The higher patch density (8.80 per 100 ha) reflects the smaller mean patch size (11.40 ha) in the 1996 landscape. There was significant variation in patch size for both the 1989 and 1996 landscapes. The patch size standard deviation was 254.1 and 225.8 for the 1989 and 1996 landscapes respectively. Patches ranged in size from 0.09 hectares (1 pixel) to 26,032 hectares (289,249 pixels) in 1989 or 22,050 hectares (245,001 pixels) in 1996. Caution must be exercised when considering these basic patch statistics since patch size is not normally distributed. Examining the 1989 and 1996 landscapes more closely reveals that nearly 99% of patches were less than 100 hectares and more than 85% of patches were smaller than 5 hectares. Only 28 patches (0.1%) were larger than 1,000 hectares.

Large patches are found in three varieties: rock/gravel at high altitude, deciduous shrub communities banding across mountain slopes in the sub-alpine, and spruce forest along the Alsek River valley floor in the montane zone. The large rock patches may be somewhat of an anomaly. Due to varying slope, aspect, general relief and micro-climate, these patches should be considered conglomerations of many distinct patches. However, they appear relatively homogeneous on satellite imagery and are classified as single units. The resistance in these patches to physical and biological vectors is significant and few organisms would interact with them as single patches. The large spruce forest and deciduous shrub patches are more plausible in their existence. More gentle relief allows these land cover types to extend across large areas. In practice, not all organisms would consider them single patches due to finer scale heterogeneity. However, many species and natural disturbances do interact with these large patches as single units as evidenced by widespread insect and fire impacts in montane forests.

Edge, defined as the boundary between two land cover classes, is an important facet of landscape pattern. McGarigal and Marks (1994) report that few species are indifferent to edge habitat, some prefer it and others avoid it. Disturbances also react significantly to edge since it represents a contrast in the landscape mosaic and may influence landscape resistance. The 1989 landscape contains 14,026 kilometres of edge whereas the 1996 landscape contains 13,653 kilometres. Considering the differing landscape sizes, the edge density (m/ha) is higher in 1996 (61.30) than 1989 (60.03). The ecological significance of 1.27 metres per hectare is difficult to assess. Other metrics, such as shape and diversity indices, that are not measured in physical units require even more detailed interpretation. To test the scale of variation in all metrics, a sensitivity analysis was done using landscapes classified to varying number of classes.

Sensitivity Analysis

The sensitivity analysis was conducted to provide significance to the scale of variation of the calculated indices, but also to relate the classification scheme to the landscape pattern results. Meaningful interpretation of landscape pattern indices is aided by information on the ranges of metrics and their response to landscape characteristics

(Hargis et. al 1998). It is important to know how classification errors might influence results and how the classification scheme itself might affect the indices (Hess 1994). Also, certain metrics may be more sensitive to changing landscape definition. The edge complexity of a landscape with 5 classes may not differ much from that of the same landscape classified to 15 classes. However, the diversity of these two mosaics would be significantly different. Also, considering subsequent studies may not use the same land cover classes, the sensitivity analysis will hopefully provide some basis for comparison.

Five different land cover images were produced for two of the regional subsets using methods that varied the number of resulting classes (Table 12). For each subregion, three unsupervised classifications and two supervised classifications were performed. The two supervised classifications used the maximum likelihood classifier and signatures from the whole scene or the regional subset. Post-classification processing was repeated for each landscape using the method described in Chapter 4. The three unsupervised

Table 12. Sensitivity analysis landscapes.

Landscape	Classification Method	Number of Classes	
		Subregion 1	Subregion 4
1	Supervised (clipped from main image, equivalent to using original signatures)	11	9
2	Supervised (using regional signatures)	10	9
3	Unsupervised	24	39
4	Unsupervised	11	10
5	Unsupervised	5	5

classifications differed only in the number of classes requested (40, 11, and 5). The number of classes returned by the classifier varied between the subregions based on the distribution of spectral values. Only the post-classification filtering was done on the three unsupervised classified landscapes. Since the classes were not labelled, the knowledge-based reclassification was not applicable.

Landscape pattern was measured for each of the landscapes. Results from subregion 1 (listed in Appendix H) show predictable variation in some of the metrics. The diversity metrics decrease in those landscapes with fewer classes. There are fewer patches in those landscapes with lower patch richness. Interestingly, the edge density (m/ha) is higher for landscape #5 than for both landscape #1 or #2 despite its lower patch richness. The complexity of this subregion accounts for the high edge length in landscape #5. Some of the added edge length in landscape #5 can be attributed to the larger size of #5 over #1 and #2. Landscapes #1 and #2 vary slightly in size from the others due to the background (shadow) class. Landscape #3 contains almost double the amount of edge found in landscape #5.

Shape indices appear inversely related to patch density. Those landscapes with fewer classes tend to have fewer and larger patches. As patches become larger, their shape complexity also increases, mainly due to topographic relief. The 'landscape shape index' (LSI) responds differently from the 'mean shape index' (MSI) since it is calculated as a perimeter-area ratio for the whole landscape instead of the mean of perimeter-area ratios of all patches in the landscape. The LSI varies similarly to edge density. There was little variation in all three of the fractal dimension indices. These consider the logarithm of the perimeter-area ratio in their formula and have a smaller range than the limitless shape indices.

Temporal Results (1989 - 1996)

In the absence of significant natural or human disturbance, landscape pattern was not expected to exhibit appreciable change over a period of seven years. In the Kluane region, disturbances such as fire have extremely long (~200 years) return intervals (Hawkes 1983a). While disturbance events may occur relatively quickly (days to years), their impact on landscape pattern (as measured by quantitative indices) may not be realized for several decades. Results from the landscape pattern analysis of 1989 and 1996 confirm little change over this period. Even though a major disturbance event (spruce beetle infestation) occurred between these dates, its impact was not noticeable in the quantitative results. The chosen classification scheme does not distinguish between infested white spruce stands and healthy ones. Therefore, only if the forest communities impacted by the infestation change significantly in species composition (*e.g.* to mixed forest) would the quantitative analysis observe a change in pattern. Over the long term the cumulative impact of this and other disturbances (*i.e.* forest fires) may result in changing composition and configuration of vegetation communities.

The classification scheme does not include classes related to the level of spruce beetle infestation for a number of reasons. A classification scheme should describe the landscape *or* land cover without reference to the disturbances acting upon it. To do otherwise might skew results of landscape pattern analysis to highlight disturbed land cover patches that may not have different pattern from the landscape perspective. Secondly, the methods used to abstract or define the landscape were not generally capable of detecting spruce beetle infested forests.

Assuming negligible change occurred between 1989 and 1996 in overall landscape pattern, these temporal results further add significance to the level of variation observed in quantitative metrics. For example, the variation in metrics measured from 1989 to 1996 may be attributable to random variation introduced by the method of analysis (most likely spectral or classification differences resulting from the satellite imagery).

The summary pattern statistics were reviewed above for the 1989 and 1996 landscapes. Notable changes were also observed in the shape indices. The landscape shape index varied widely between the 1989 and 1996 landscapes due to higher edge density in 1996, whereas the mean shape index was stable. The area-weighted mean shape index deviated from 8.90 to 9.25 from 1989 to 1996 – influenced by larger patches in the 1989 landscape. As observed in the sensitivity analysis, the fractal dimension indices varied little between 1989 and 1996, either for the whole landscape or the elevation zones. The diversity and evenness indices were extremely stable since the landscape area and patch richness did not vary significantly between 1989 and 1996. Only slight variation was observed in the interspersion and contagion indices, indicating the landscape configuration was relatively stable over the 7 year study period. The temporal analysis generally shows little change in landscape pattern between 1989 and 1996 and provides invaluable information on the variation of indices under stable conditions.

Class Results

The class results show many of the same metrics used at the landscape scale. These are presented for the 1996 landscape, as it is more current. The full results for both 1989 and 1996 are listed in Appendices D to G. Landscape pattern results between classes are fundamentally affected by classification errors. Erroneously classifying land cover types will alter metrics measuring composition and configuration. The size and extent of the study area pre-determines the proportion of area by class — altering the extent of the study area would change the class area proportions. The study area was defined to capture a broad range of land cover types at different elevation. Nevertheless, class area is an appropriate descriptor of basic landscape composition. Over one quarter of the study area is gravel/rock. Much of this is at high elevation, but many exposed rock areas also exist in the sub-alpine and montane zones. More than twenty percent of the landscape is white spruce forest, highlighting the concern expressed during the recent spruce beetle infestation. Occupying just over ten percent of the landscape each are mixed forest, deciduous shrub, and alpine meadow land cover types. The remaining classes cover less than five percent each of the total landscape area. Therefore, the study area is approximately sixty percent vegetated and forty percent non-vegetated. This ratio would be much smaller west of the study area in the Icefield Ranges and larger to the north and east.

Basic patch statistics vary widely between the classes. The meadow land cover type exceeded all others in number of patches, with nearly one quarter of all patches in the landscape. However, its mean patch size was only 5.2 hectares. At the other extreme, there were only 51 river patches, yet their mean size was 63.1 hectares. The rock land cover type numbered 2,554 patches (13.1%) and also had a relatively high mean patch size of 23.2 hectares. White spruce forests (spruce forest class) were found in 1,902 patches with a mean size of 25.1 hectares. As noted above, there is great variation in patch size. The full indices show large values for both the patch size standard deviation and patch size coefficient of variation indices.

Shape indices are perhaps more intuitively related to landscape development and direct disturbance impacts than any other metrics. Disturbance events often directly

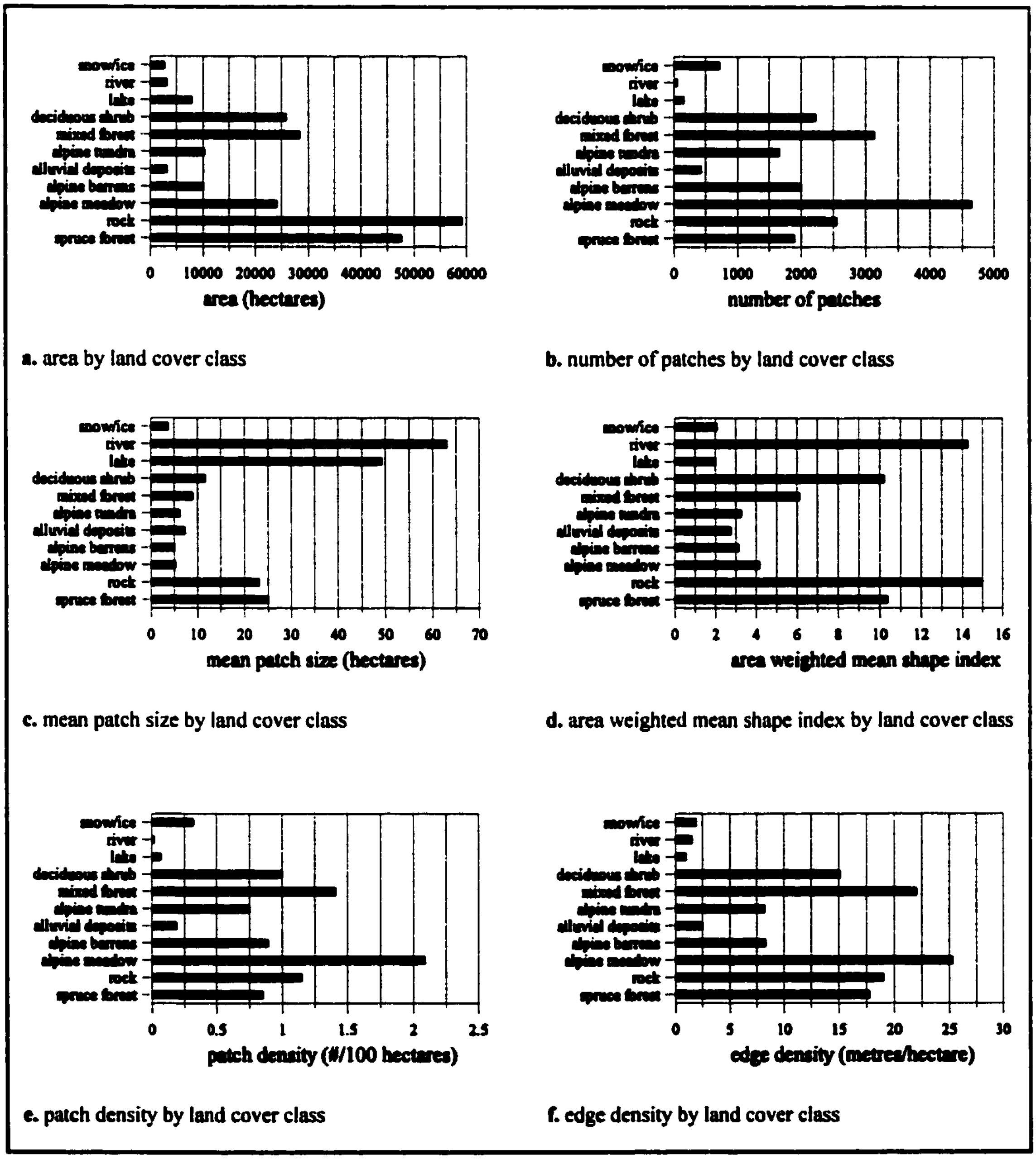

Figure 7. 1996 Landscape - selected indices by class.

influence resulting patch shape. The area-weighted mean shape index considers increasing patch size as a beneficial attribute and correspondingly increases the calculated metric. The mean shape index has no consideration for patch size. It is the mean for all patches of a perimeter-area calculation adjusted to a square standard (for raster analysis). Figure 8 shows how the shape index varies for patches with different edge complexity. The alpine tundra patch (A) lies on an even slope in the south end of the study area. Its shape index is 1.5, while the more complex shrub patch has a shape index of 5.45. This deciduous shrub patch covers a small mountain valley reaching up Mount Worthington and exhibits a typical dendritic pattern found in high relief areas.

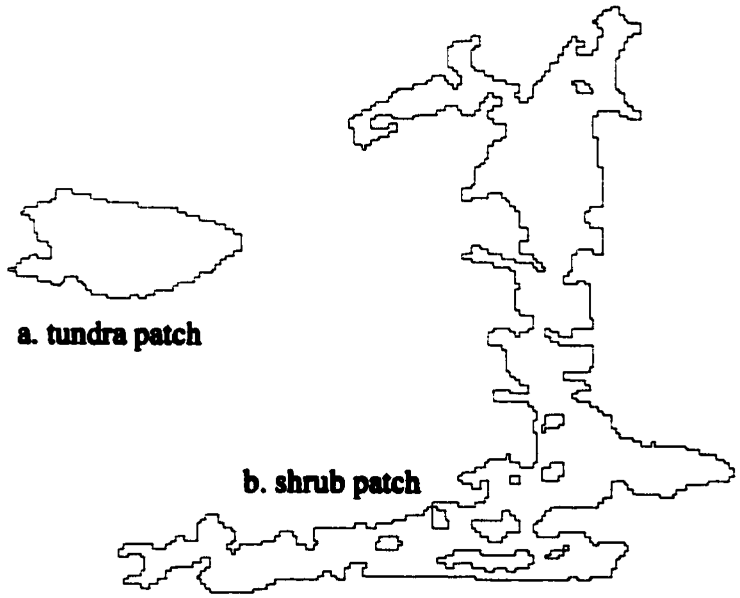

Figure 8. Selected patches from the 1996 landscape.
A: alpine tundra patch on a south-facing slope north of Goatherd Mountain (shape index: 1.5).
B: deciduous shrub patch lining a narrow mountain valley north of Louise Lake (shape index: 5.45).

The lake land cover type exhibited the lowest MSI and AWMSI due to its close resemblance to the square standard. Although in many cases singular pixels classified as water may have skewed this result. Rivers (long, linear, braided patches) showed the highest MSI and AWMSI values due to their complex shape and large mean patch size. An earlier analysis (Wurtele and Slocombe 1997b) using the biophysical inventory of Kluane National Park Reserve showed a very high edge density for the gravel class (defined as gravel creek beds). The current classification scheme regards gravel and rock as one class (due to spectral similarity) and the pattern results of these linear features are lost with the influence of large, alpine exposed rock patches. However, some creeks were classified as alluvial deposits and contributed to the linear nature (and high shape indices) of this class found predominantly along river channels.

Interestingly, the mixed forest and spruce forest classes showed similar MSI values (1.43 and 1.42 respectively) yet much different AWMSI results (6.13 and 10.37 respectively). The mean size of forest patches is over double that of mixed forest patches. White spruce forests may be considered the landscape matrix and as such their patches share an edge with many other land cover classes and cover large areas.

Altitudinal Results

Topographic relief defines mountainous landscapes and greatly influences processes occurring within them. To further explore the dynamics of landscape pattern and altitude, the quantitative metrics were calculated for three distinct altitudinal zones: montane, sub-alpine, and alpine (Figure 10). These results are presented at the landscape and class scales. The study area is roughly one half montane and one quarter each sub-alpine and alpine. The montane and sub-alpine zones each have nearly twice as many patches as the alpine zone (Figure 10). However, the mean patch size of the alpine and montane zones is nearly twice that of the sub-alpine zone. In the sub-alpine zone, patches are smaller but more numerous per hectare (resulting in a higher patch density). Also, due to the smaller patch size, shape complexity is reduced in this zone. When measured at the same scale, larger patches are more likely to have higher shape indices. This results from an artifact of the analysis method and data. The minimum patch size in raster analysis is the size of one pixel. The shape index for a patch represented by one pixel is equal to that of the square standard – the least complex shape. Larger patches can potentially vary more from this square standard. Patches represented by one pixel may in fact have more complex shapes, but only detectable at finer scales of resolution.

The maximum Simpson's diversity index for a landscape with 11 land cover types is 0.91. The Simpson's diversity index for the 1996 landscape measures 0.84 while the montane, sub-alpine, and alpine zones are 0.80, 0.80, and 0.50 respectively. The alpine zone is lacking patch richness (8 land cover types) compared to the sub-alpine and montane zones (10 and 11 respectively) and an equitable distribution of area among these types. The rock class dominates (over 70%) the alpine zone. The sub-alpine, with a smaller mean patch size, has very high evenness values. It is not dominated by any one class, rather the alpine meadow, deciduous shrub, and rock land cover types are roughly equal in proportional abundance. The alpine and montane zones contain land cover types (rock and spruce forest respectively) that clearly dominate and may be considered the landscape matrix.

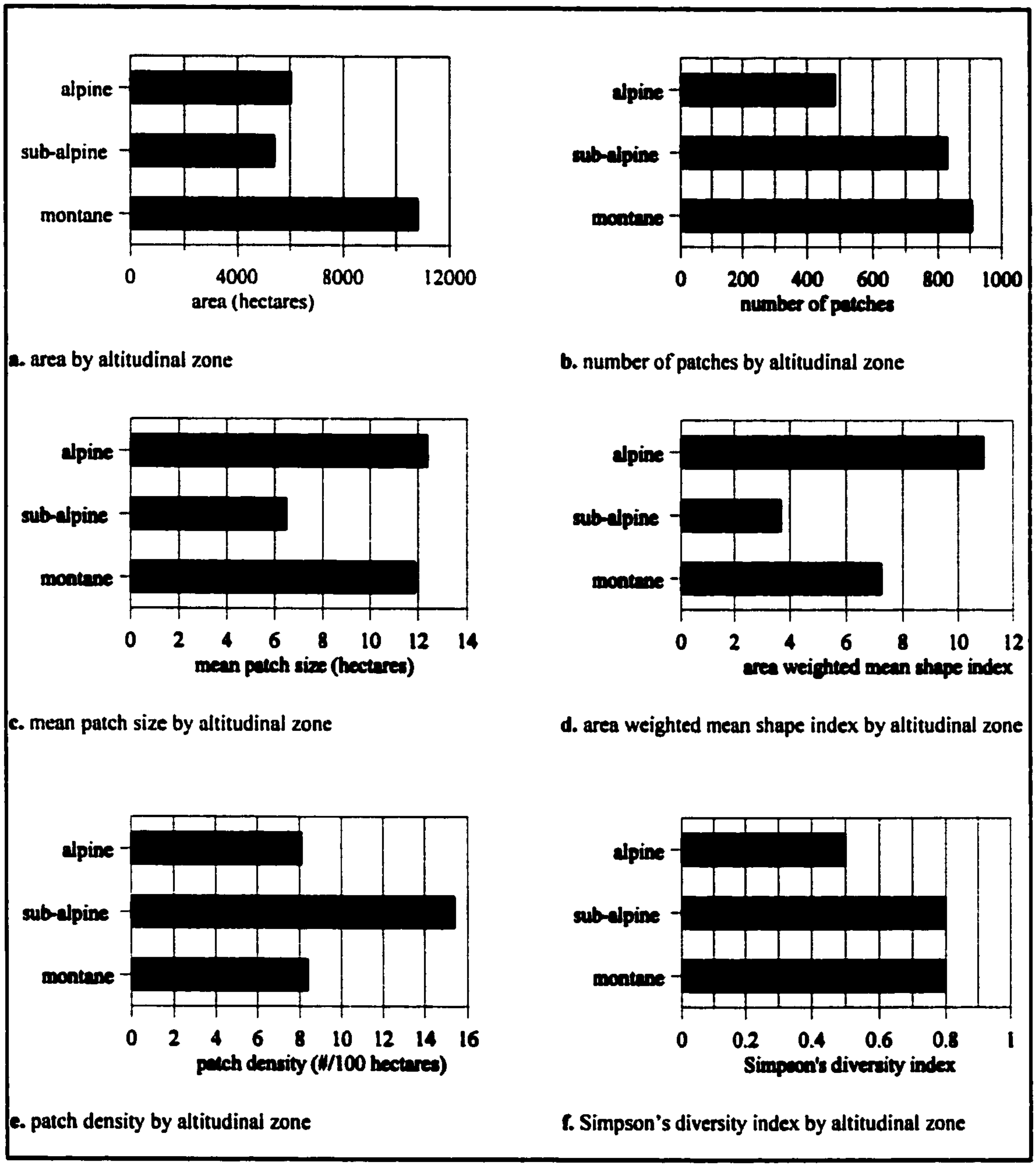

Figure 9. 1996 Landscape - selected indices by altitudinal zone.

At the class scale, some noticeable variations in pattern metrics can be observed between altitudinal zones. Land cover types exhibit uneven distribution of area among the altitudinal zones. While most land cover types belong in majority to one zone (Table 13), all types (excluding lake, river, and alluvial deposits) can be found in each zone.

Interestingly, the snow/ice class is found throughout all three altitudinal zones (even in late summer) owing to the terminus of the Lowell Glacier at the Alsek River in the southwest corner of the study area.

As noted above, larger patches exhibit more complex shapes. The edge density of individual land cover types is correspondingly higher in that altitudinal zone where its area is greatest. The landscape shape index (LSI) varies similarly to edge density. Deviating slightly from the pattern of edge density and landscape shape index, the mean shape index (MSI) is also maximized in the altitudinal zone with greatest area. These trends are not followed by the shrub class. The area of deciduous shrub in the montane and sub-alpine zones is reasonably similar – nearly 14,000 and 12,000 respectively – however patch shape varies significantly between these altitudinal zones. Deciduous shrub edge density is much higher in the sub-alpine (28.41 m/ha) than the montane (15.96). The mean shape index is also higher in the sub-alpine zone. This is explained by the prevalence of deciduous shrub land cover in sub-alpine mountain gulleys that have highly irregular, dendritic shapes. In the montane zone, in the valley bottom, there is less variable relief and deciduous shrub patches have less complex shapes.

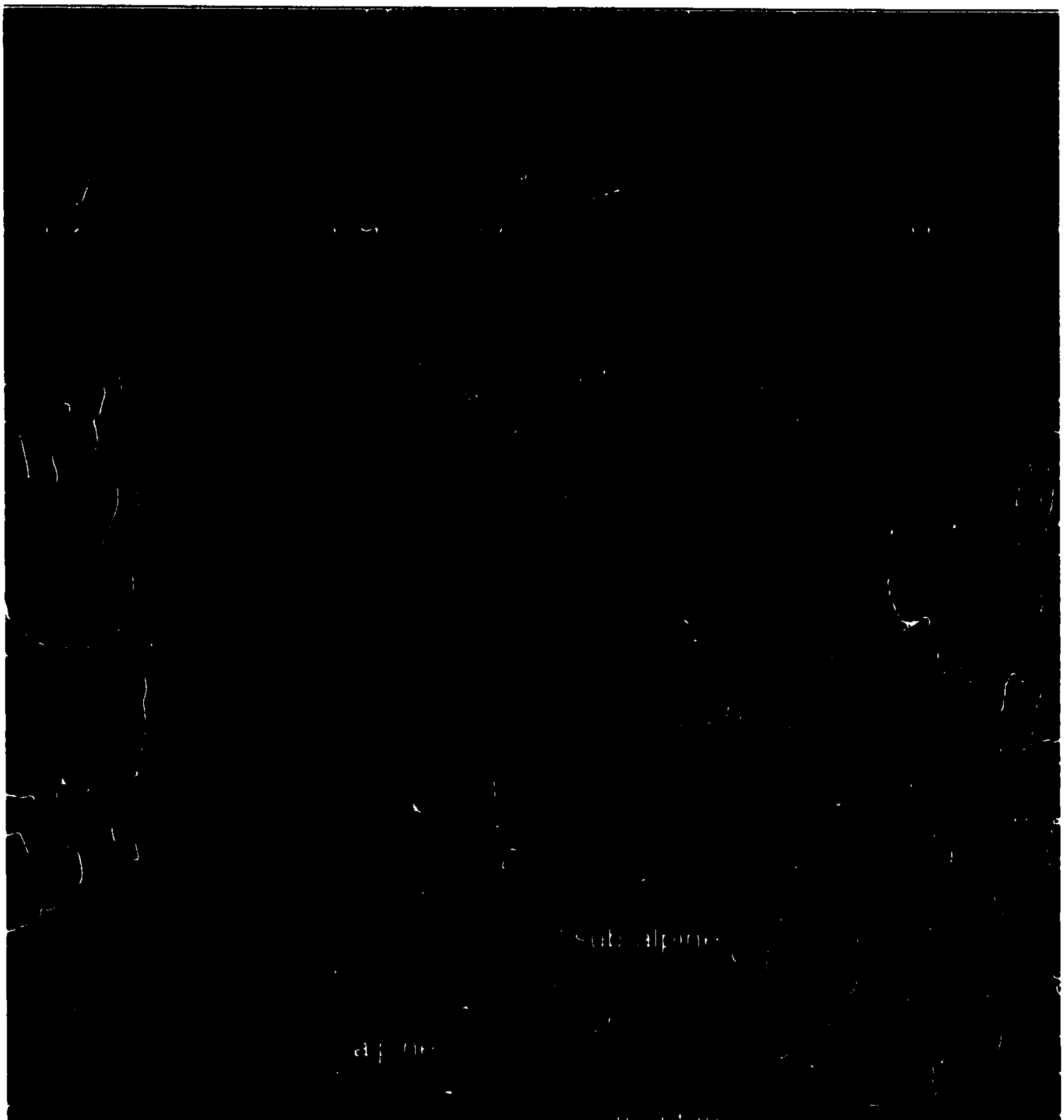

Figure 9. Altitudinal Zones

Table 13. Dominant altitudinal zone occurrence by area.

Land Cover	Altitudinal Zone
alpine barrens	alpine
alluvial deposits	montane
alpine tundra	sub-alpine
mixed forest	montane
deciduous shrub	montane/sub-alpine
lake	montane
spruce forest	montane
rock	alpine
alpine meadow	sub-alpine
river	montane
snow/ice	alpine

Chapter 5: Natural Disturbance and Landscape Pattern in Kluane

Natural disturbances play a significant role in the creation of landscape mosaics, especially in the boreal forest (Frelich and Reich 1995). However, knowledge of the temporal fluctuations of landscape structure and the effect of disturbances on these variations is incomplete (Baker 1994). The previous chapter reviewed the results of the quantitative analysis of landscape pattern in the Kluane region. This chapter reviews the principal disturbance regimes acting on the Kluane landscape and examines their role in determining variations in pattern. Most disturbances produce heterogeneous, patchy effects and tend to increase the diversity of landscapes (White and Pickett 1985, Kamada and Nakagoshi 1996), however in some cases may increase homogeneity when they are very severe and impact large areas (Trabaud and Galtie 1996).

Aspects of landscape configuration are influenced by the distinct characteristics of disturbance regimes. Individual disturbance characteristics (Table 4) must be examined to understand the impact of a disturbance regime on landscape structure. These attributes impact landscape pattern in specific and different ways. For example, the size and shape of very intense disturbance events are often directly related to the size and shape of resulting landscape patches. However, if a disturbance event is less intense this relationship may be less prominent. The frequency of disturbance is also significant since it will determine the stage of regeneration possible and may also affect disturbance specific properties, such as fuel loading in the case of fire or the availability of host material in the case of insect pests.

Synergy between disturbance regimes can alter the expected impact of any one disturbance. The most notable synergistic disturbance dynamic in Kluane is that of insect infestations and fire fuel loading. Whereas the size, shape, and spatial distribution of disturbance events are spatially explicit attributes, intensity and synergy describe additional biological and physical factors.

Three principal natural disturbances in the boreal forest – fire, insect infestation, and geomorphological processes – are reviewed with particular emphasis on their role in forming landscape patterns. The scale of investigation is at the landscape level, however, species and community processes are important since their cumulative and combined effects influence the larger scale landscape responses. Therefore, elements of fire and insect ecology are presented to study disturbance mechanics from species, community, and landscape perspectives. Finally, the quantitative results are placed in context of the disturbance-landscape pattern review.

Fire

Disturbance characteristics of fire and its behaviour in the boreal forest ecosystem are summarized in Table 14. The frequency of fire events is perhaps one of the most important characteristics of the disturbance regime. The interval between catastrophic fires generally determines the available fuel loads and stage of succession or regeneration possible. Frequent fires will consume fuel, affect the possible severity of subsequent fires and may prevent climax stages of succession from establishing. Hawkes (1983a) calculated the average fire interval in Kluane National Park Reserve at 179 years, with a range from 113 to 238 years. He identified a general trend of increasing mean fire interval from southern to northern climatic regions in Kluane National Park. The current study area comprises sites from Hawkes' (1983) southern and central climatic regions. When human-caused fires are eliminated from the fire history, the interval may be extended to 200-300 years. Also, since study plots were located near fire boundaries, Hawkes (1983a) reports that the mean fire interval would likely increase with randomly distributed plots. Alexander and Dubé (1983) observed that half of the forest zones in Kluane National Park showed evidence of fire within the past 80 years. They also suggest that the wide age distribution and low maximum age of forest stands in Kluane is suggestive of recurring fire and geomorphic events. Fire history studies in Kluane show that fire is a recurring landscape disturbance but that it occurs relatively infrequently due to low incidence of lightning (Greater Kluane Land Use Planning Commission 1991). The low frequency of fire in Kluane has contributed to the extensive coverage of mature forest stands.

To place the low fire frequency of Kluane in perspective, other areas of the boreal forest have significantly shorter fire intervals. An area east of Great Slave Lake, NWT had a measured interval of 40-100 years (Hawkes 1983a). Forests of Yellowstone National Park are characterized by a 300 year major fire cycle, with few large fires occurring between (Romme 1982). An extremely long fire interval (1,000 years) has been identified in high elevation conifer forests of New Brunswick (Hunter 1990) and an extremely short interval (less than fifty years) was found in northwestern Ontario boreal forests (Suffling *pers. comm.*). Romme (1982) reports high geographic variation in the frequency of fires in the sub-alpine zone of the northern Rocky Mountains. Light surface fires have been more frequent in sub-alpine forests of the northern Rockies.

The fire history of Kluane National Park Reserve reveals significant variation in fire size (Hawkes 1983a). Large fires were found to have more elongated shapes, due to strong down valley winds, whereas smaller fires had variable shapes less influenced by wind and more by environmental conditions (Hawkes 1983a). High rates of spread tend to result in large fires and elliptical shapes (Johnson 1992). In addition to wind, steep slopes can affect fire behaviour and increase the movement of fire through the vertical strata of vegetation (Hawkes 1983a). Also, topographic breaks and wide outwash fans provide effective fire control – limiting the size of fires (Hawkes 1983b).

Table 14. Fire characteristics in Kluane.

Fire Characteristic	Behaviour
distribution	influenced by topography, fuel loads, and the distribution of vegetation
frequency	low
return interval	long
rotation period	long
predictability	high
area or size	large
intensity	variable
severity	variable
synergism	affected by all disturbances that influence fuel load and structure

The determination of fire behaviour from available fuel loads generally underestimates the potential of fire in the sub-alpine zone (Agee 1993). Low biological productivity of alpine areas slows fuel accumulation and retards the occurrence of high severity fires, thus resulting in long fire intervals (Romme 1982). The type of fuels and the rate of accumulation have significance for the type, intensity, and frequency of fires in forest ecosystems. Table 15 lists the principal factors causing boreal fires to have high rates of spread (Johnson 1992). The types of fuels in the boreal forest (mostly conifer) allow rapid spreading of fires, resulting in large areas disturbed. The low productivity of alpine forests reduces the rate of production of fuel material (*i.e.* plant growth is slower) but accumulation of these materials is increased due to slower decomposition of material on the forest floor. The high intensity of boreal fires is caused in part by the crown fire regime active in the boreal region (Johnson 1992), which is a function of the vertical continuity of fuels in the forest. These 'ladder' fuels facilitate the spread of the fire from surface fuels into the crown. Once a crown fire is established, large areas of forest can burn and entire stands can be replaced (Agee 1993). However, fires in mountainous regions may not always spread according to fuel loads, since they are additionally constrained by topographic features and micro-climatic influences.

Table 15. Factors responsible for the high rate of spread in conifer fuels (Johnson 1992).

Characteristics of fuels in conifer forests
accumulation of significant forest floor of dead biomass
greater abundance of fine fuels in the form of needles, small twigs, resinous products, and small bark flakes
lichens and mosses common on forest floor
retention of branches of all sizes
crown shape of trees allows easy access of flame from ground to crown
moisture content of conifer foliage is low

In Kluane, the frequency of fire is low and its intensity variable. Therefore, landscape patches may not have a singular disturbance origin. Oswald and Brown (1990) have documented the specific regeneration characteristics following fire in the Kluane region. The distribution of trembling aspen is closely linked to fire disturbance. Healthy regeneration of shrub and deciduous species occurs within the first five years and is followed by a transition to late seral species such as white spruce.

A mosaic pattern of vegetation within burned areas in Kluane National Park Reserve has been reported (Hawkes 1983a). The remnant vegetation in these areas develops from sprouts and individuals that survive fire due to the spatial variation of moisture content of the fuel and soil. The fire severity or impact and subsequent regeneration may vary significantly spatially within a burned area (Delcourt and Delcourt 1983). In simple terms, fire disturbances increase the heterogeneity of forested landscapes (Kamada and Nakagoshi 1996). In Kluane, Hawkes (1983a) suggests that landscape diversity would decrease if human-caused fires are suppressed. However, this change would occur slowly based on the vegetation succession rate. In concurrence, Morrison and Swanson (1990) report significant variation in fire frequency between proximate sites in the Cascade Range of central-western Oregon. This spatial variation of fire frequency in mountainous areas serves to increase the heterogeneity of the forested landscape.

A significant fire occurred in 1924 in the upper Donjeck River, north of Kluane National Park (Hawkes 1983b). The resulting forest patch created by this fire is visible on a 1977 Landsat Multispectral Sensor image of the area. Located between Arch and Wade creeks east of the Donjeck River, the fire patch shows evidence of the combined impact of topography and micro-climatic conditions on fire behaviour. The patch shape is elongated owing to the strong down valley winds and stretches into the subalpine, its spread likely aided by steep slopes. There are no fire patches clearly visible on the Landsat Thematic Mapper imagery used in this research, although the fire history studies conducted by Hawkes (1983a) included field plots within the current study area.

With the exception of small human-caused fires in the southern portion of the study area, there are no known recent fire occurrences in the study area. However, the highly complex patch shapes of the mixed and white spruce forests, especially northwest of

Mush and Bates lakes, are indicative of fire origin. The mixed forest land cover type, consisting of shrub and deciduous species and white spruce, establishes following fire disturbances. Mixed forest patches were observed in abundance adjacent to the dominant forest land cover. The open canopy of the white spruce forests, while a function of climate, may also indicate low intensity fire disturbances (R. Garbutt *pers. comm.*) While disturbance origin patches are visible on the classified land cover maps, a low intensity fire regime may not create clearly defined patches, but will have a more distributed effect over the landscape. These seemingly conflicting impacts represent a complex fire history and suggest that fire influences landscape pattern in two ways: 1) by creating distinct patches and 2) by altering community composition (creating gradients of land cover).

Insect Infestation

Biotic disturbances, such as insect infestations, are also active in the study area and have impacted large areas and influenced landscape pattern. The recent spruce beetle (*Dendroctonus rufipennis*) infestation in southwest Yukon caused significant mortality of white spruce stands. The spruce beetle is common to spruce forests of western Canada and has been labelled one of the most destructive pest of mature stands (Savaria 1994). The relationships and ecology of the forest/insect system are fundamental to understanding impacts on the landscape pattern.

Environmental conditions are known to affect the viability of insect populations. The recent spruce beetle infestation in southwest Yukon is thought to have been enhanced by successive mild winters and warm, dry summers (Garbutt 1994). Warm winter conditions allowed many of the spruce beetle to survive from one season to the next and the warm, dry summer conditions accelerated the development of the population. The other factor involved in this spruce beetle infestation was the enormous supply of mature white spruce stands. The catalyst may have been an influx of spruce beetle from outside the ecosystem (Garbutt 1994). This is a good example of a feedback loop whereby landscape pattern affected the behaviour of the disturbance regime. The draining of a glacial lake[6] in the Alsek valley 150-200 years ago (Clague 1979a) created fertile conditions for the development of white spruce forest, which is now reaching maturity and therefore susceptible to insect infestation (Garbutt 1994). Spatial variations in micro-climatic conditions also affect the development and distribution of insect populations.

The disturbance characteristics of insect infestations are summarized in Table 16. The primary influence on the spatial distribution of insect populations of disturbance regimes is the heterogeneity of the forest. Large, homogeneous stands of susceptible trees will allow the insect population to grow and spread throughout a large area. However, if suitable forest stands for the insect are sparse and disconnected, then the distribution of the infestation will be more limited. Major spruce beetle infestations for the Yukon Territory occur at roughly ten year intervals (Ferris 1991), however the severity of infestations varies. It is reported that the recent infestation in southwest Yukon was the most severe in fifty years (Garbutt 1994). Studies of landscape pattern and insect infestation are not as numerous as those considering the effects of fire. However, many of the same aspects of fire and patterns of landscape diversity and heterogeneity apply

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[6]The upper shoreline of the most recent glacial lake in the Alsek River valley reached 640 metres a.s.l. (Douglas 1974). It was caused by a surge of the Lowell Glacier across the valley. Beach ridges are clearly visible along some slopes.

equally well to insect disturbance regimes. Succession after insect infestation is similar to successional patterns after fire, although specific regeneration is characteristic of a complex mosaic, dependent on disturbance intensity, seed availability, and environmental conditions (Denslow 1985). The intensity and severity of the disturbance plays a significant part in determining impacts on landscape pattern. High tree mortality associated with intense insect outbreaks, resulting in the destruction of the majority of the stand, will create large areas of homogeneous forest cover. The structure of the pre-disturbance landscape determines much of the behaviour of the insect infestation, and therefore also much of the resulting impact on landscape pattern. Landscapes with low diversity and heterogeneity are more susceptible to outbreaks of forest pests (Hunter 1990). Acting as a positive feedback relationship, forests of low diversity will allow more infestation of insects, and thus create more homogeneity. Contrary to this relationship, landscapes with existing heterogeneity are not as sensitive to insect infestation, therefore outbreaks are not as severe, and heterogeneity is maintained.

Table 16. Insect infestation characteristics in Kluane.

Insect Infestation Characteristic	Behaviour
distribution	variable, depends on heterogeneity of forest
frequency	variable, sensitive to age structure of stand
return interval	frequent
rotation period	long
predictability	high, known from studies of population dynamics
area or size	variable, sometimes large
intensity	low
severity	high
synergism	affects fuel loads and susceptibility to wind throw

The impact of insect infestations on landscape pattern in the study area is less significant than that of fire disturbances. Since insect outbreaks target specific tree species, only those communities containing the host species are affected. The impact of insect infestations is directed therefore to the white spruce and mixed forest communities. In these communities the insect disturbance plays a significant role in maintaining heterogeneity.

Geomorphological Processes

The complex geological and glacial history of the Kluane region has had significant impact on land cover development. Glacial movements have exposed new areas for vegetation establishment and caused significant lake formation (Hawkes 1983a). A significant disturbance, such as rapid lake formation, represents a discrete event in time that can be used to establish the maximum age of forest stands in the valley.

Seismic activity, such as earthquakes and volcanoes, is significant in the region, although it occurs relatively infrequently (Clague 1979b). The creation of outwash fans and the deposition of alluvium and loess create landscape patterns with more frequency. Annual and diurnal variations of creek runoff, associated with variable glacial or snowpack melt, impact riparian vegetation throughout the region. Hawkes (1983a) reports that alluvial deposits first support balsam poplar communities, then succeed to coniferous species. White spruce stands that do not show evidence of fire history typically occur on alluvial and lacustrine gravel deposits (Douglas 1974). In many cases, shifting drainage patterns prevent the succession of riparian vegetation to white spruce (Theberge 1972). Debris flows represent a major disturbance to riparian communities and vegetative land cover on steep slopes (Figure 2 - centre) in mountainous areas (Grey and Wilson 1990, Hawkes 1983b).

Notable characteristics of geomorphological disturbances are the scale and frequency of their occurrence. Infrequent disturbances related to seismic and glacial activity impact large areas, while more frequent fluvial disturbances impact relatively smaller areas. Occurring somewhere between these extremes of frequency and scale are events such as slope failures, which retard vegetation establishment, especially at higher elevations.

Geomorphological disturbances, similarly to fire and insect disturbances, are very focussed in their impacts. They affect primarily drainage features and high elevation areas. However in a mountainous landscape such as Kluane, this area impacted is large. Debris flows along mountain creeks and rivers significantly increase patch shape complexity. As mentioned in Chapter 4, the linear creek system has a highly irregular shape, thus increasing edge length. Without fluvial disturbances, mountain streams might not in fact be represented as a land cover type at the landscape scale. In many forest ecosystems, canopy closure over creeks is complete and thus only larger rivers are discernable at the landscape scale. Creeks in mountainous regions develop into complete systems with various land cover types.

Disturbance Synergy

The most commonly cited example of disturbance synergy in Kluane is the impact of insect infestations on fire risk (through increased fuel loading). Romme (1982) attributes accelerated succession and fuel accumulation to the infestation of mountain pine beetle (*Dendroctonus ponderosae*) in Yellowstone National Park. Many of the fuel characteristics in conifer forests that allow boreal forest fires to rapidly spread (Table 15) are enhanced by insect infestation. Tree mortality and defoliation results in the large accumulation of fine fuels. In southwest Yukon, Savaria (1994) describes the increased fuel loads caused by spruce beetle infestation and suggests that forest flammability is maximized in the year following tree mortality. Studies of spruce beetle infestations in Engelmann spruce (*Picea engelmannii*) forests have noted that site flammability increases, especially if large areas are disturbed (Agee 1993). The recent spruce beetle infestation in the Kluane region has significantly increased the risk of fire (Beaver 1997). Increased fuel loading and micro-climatic conditioning of the forest floor and canopy (greater sun penetration) result in higher risk of fire in infested stands (Beaver 1997, Division of Forestry 1998).

The recent spruce beetle infestation in the study area may have been a more extreme than usual disturbance event. However, these outbreaks are normal events in the white spruce forests of the Kluane region, occurring at roughly ten year intervals (Ferris 1991). Therefore the fire interval figures reported by Hawkes (1983a) should not decrease substantially (increase frequency of fire) with the recent insect infestation.

Pattern and Disturbance in Kluane

Fire disturbances occur within the montane zone and to a lesser in the lower sub-alpine. In these zones, fire occurs predominantly within forested land cover types. The high shape index values measured in the forest and mixed forest classes reflects the irregular interface between these two classes and fire origin patches. Generally, the high shape index values for the montane zone are attributable to the complex forest interface, but also to the abundant occurrence of other land cover types adjacent to and within drainage features. The linear nature of rivers and creeks and their shifting nature in the study area creates complex edge shapes with adjacent meadow, shrub, and forested vegetation communities. Similarly, high diversity is a function of these other land cover types, although disturbance-driven successional mechanisms in the forested landscape certainly contribute. In the absence of fire disturbance, landscape diversity would likely remain high due to the presence of other land cover types. At a finer scale of investigation, diversity within forested ecosystems (considering individual forest stands as patches) would decrease in the absence of fire disturbance.

The low fire frequency within the study area has allowed the establishment of large areas of mature forest communities. More frequent fire disturbances would create a mosaic of early to mid-successional communities (Delcourt and Delcourt 1983). However, the large expanse of mature white spruce has allowed significant infestation by spruce beetle. The impact of this disturbance has created gaps in the canopy where re-growth may occur. The average age of the spruce forest community has decreased as a result of the recent insect infestation – any stimulated re-growth will not significantly alter species composition since healthy young spruce saplings are plentiful. The abundance of dead, standing trees (snags) will affect pattern in a number of ways. It may, for several decades, increase fire occurrence and as some dead, standing trees fall, gaps will be created in the forest thereby altering the fine texture of the canopy surface.

Geomorphological disturbances play a critical role in determining landscape patterns, especially at higher elevation. High diversity values are related to complex land cover patterns surrounding drainage features in the montane, but in the sub-alpine and alpine, debris flows (visible in Figure 2) are significant causes of high diversity. They create large gravel/rock (tallus) patches where vegetative land cover would have otherwise established on more stable slopes. The complex landforms (gulleys, ridges, slopes) and processes (erosion, landslides, micro-climate) in the sub-alpine contribute considerably to the low patch size and high diversity measured in this zone. While the alpine shares many of these attributes, it lacks richness of land cover types. As the interface between the alpine and montane, the sub-alpine contains a high number of land cover types and experiences disturbances common to areas above and below it altitudinally.

CHAPTER 6: CONCLUSION

The study area landscape has developed according to the spatial variability of topographic, edaphic, and micro-climatic conditions in the region. It has also been impacted by the combined influences of disturbances on a number of scales. The size, frequency, distribution, intensity, and synergy of these disturbances have been reviewed along with the initial factors responsible for landscape development. The mechanisms of landscape development and change, including natural disturbance, have been reviewed to place in context the investigations of landscape pattern.

Land cover for the study area was classified from multispectral imagery for 1989 and 1996. Using a digital elevation model, the resulting land cover images were stratified to three elevation zones. Landscape pattern was measured using *Fragstats* for each elevation zone and the landscape as a whole. This quantitative analysis produced a myriad of landscape pattern indices. Metrics measuring attributes of landscape structure related to the impact of disturbance regimes were presented in three ways: temporally, by land cover class, and by altitudinal zone.

Landscape pattern analyses of these land cover mosaics revealed little variation over that time period. This is consistent with the long return interval of the major natural disturbances occurring in the region. A landscape experiencing more rapid disturbances may show some variation in landscape pattern over a decade. The Kluane landscape experiences longer cycles of landscape change, due to its cold, dry climate (low productivity) and infrequent disturbances. However, the landscape remains a diverse one. Topographic and micro- climatic gradients are largely responsible for the complex mosaic of land cover communities in the study area.

Spatial variation of landscape pattern within the study area is significant. Landscape diversity is highest in the montane and sub-alpine zones. The alpine zone exhibits lower diversity due to a lower patch richness and predominance of the gravel/rock land cover. The sub-alpine zone contains an even distribution of montane and alpine communities. The braided-channel along the Alsek river is not an insignificant contributor to the high diversity values of the montane zone. The montane and alpine zones consist of many large patches, whereas the mean patch size in the sub-alpine zone is significantly smaller. However, patch size was found to vary considerably. There were many small patches in the study area – 85% were less than 5 hectares.

Patch shape complexity is generally lowest in the sub-alpine, with the montane and alpine zones showing highly irregular patches. In this mountainous landscape, large patches become more complex as regulated by changes in elevation, slope, and aspect. In most cases, patch shape complexity of land cover classes is maximized in the altitudinal zone with the greatest area.

The Kluane region experiences infrequent, large and small scale fire and insect disturbances. More frequent, small and medium-scale geomorphological disturbances also affect landscape pattern. On a much longer interval are catastrophic disturbances such as earthquakes, volcanoes, and glacial lakes. These disturbance regimes play important roles in maintaining diversity and heterogeneity in forest ecosystems. Heterogeneity also functions as a moderator of impacts from subsequent disturbances, natural and anthropogenic. Fire and insect infestations impact mostly montane forests and adjacent communities. Geomorphological disturbances and topographic variation create the diverse land cover mosaic outside of the landscape matrix.

Disturbances in alpine regions are influenced by changing vegetation patterns and environmental conditions and enhanced by topographic variation. The boreal forests show resilience and stability as a result of the co-evolution of these disturbance regimes and the vegetation communities. Stability is most noticeable over the long term, as catastrophic changes are part of the natural disturbance cycle. The ability to maintain landscape functioning and re-establish structure with catastrophic disturbance regimes is characteristic of high resilience.

Due to the long return interval of disturbances in Kluane and the low productivity of the region, long-term studies are required to effectively assess the role of disturbances in landscape pattern. In the absence of empirical evidence over the entire disturbance-landscape cycle, modelling approaches to disturbance-landscape behaviour may allow more rapid investigation of the relationship. However, the challenges of simulating a complex environment of changing land cover and disturbances are significant. Yet, modelling landscape pattern under disturbance regimes of differing frequency and intensity may present the best option to overcome the limitations on effective research imposed by long term disturbance and landscape change cycles. Also, to fully explore the dynamics of landscape pattern and disturbance, a more focussed study area might be useful, especially when considering the focussed impact of many disturbances. Researching a smaller area at a greater scale (conducting a detailed land cover classification versus reconnaissance level) may be the next logical step to explore in depth the pattern-disturbance relationship.

Natural resource managers may benefit from this characterization of landscape pattern and associated links with natural disturbances. The long return intervals of disturbances and variable scale of landscape change are important considerations for their management activities and educational programs. Also, the techniques for land cover classification may prove useful in any future endeavours to update the vegetation layer of the biophysical inventory.

Landscape patterns in the Kluane region are influenced by fire, insect, and geomorphological disturbance regimes, normally producing higher diversity and more complex, irregular patch shapes. However at the landscape scale, the contributions of landforms and geomorphology to landscape pattern are equally significant. Disturbances and a complex landscape substrate give the Kluane landscape high diversity measures. The abundant number and area of non-forested land cover types, especially adjacent and within drainage features, influence landscape pattern by increasing diversity, patch shape complexity, and edge densities. The changing distribution and frequency of disturbances and variable landforms along the altitudinal gradient enhance the complexity of the pattern-disturbance system in Kluane.

APPENDICES

Appendix A: Landscape Indices

Code	Index
TA	Total Landscape Area (ha)
LPI	Largest Patch Index (%)
NP	Number of Patches (#)
PD	Patch Density (#/100 ha)
MPS	Mean Patch Size (ha)
PSSD	Patch Size Standard Deviation (ha)
PSCV	Patch Size Coefficient of Variation (%)
TE	Total Edge (m)
ED	Edge Density (m/ha)
LSI	Landscape Shape Index
MSI	Mean Shape Index
AWMSI	Area-Weighted Mean Shape Index
DLFD	Double Log Fractal Dimension
MPFD	Mean Patch Fractal Dimension
AWMPFD	Area-Weighted Mean Patch Fractal Dimension
TCA	Total Core Area (ha)
NCA	Number of Core Areas (#)
CAD	Core Area Density (#/100 ha)
MCA1	Mean Core Area per Patch (ha)
CASD1	Patch Core Area Standard Deviation (ha)
CACV1	Patch Core Area Coefficient of Variation (%)
MCA2	Mean Area per Disjunct Core (ha)
CASD2	Disjunct Core Area Standard Deviation (ha)
CACV2	Disjunct Core Area Coefficient of Variation (%)
TCAI	Total Core Area Index (%)
MCAI	Mean Core Area Index (%)
SHDI	Shannon's Diversity Index
SIDI	Simpson's Diversity Index
MSIDI	Modified Simpson's Diversity Index
PR	Patch Richness (#)
PRD	Patch Richness Density (#/100 ha)
SHEI	Shannon's Evenness Index
SIEI	Simpson's Evenness Index
MSIEI	Modified Simpson's Evenness Index
IJI	Interspersion and Juxtaposition Index (%)
CONTAG	Contagion Index (%)

Appendix B: Class Indices

Code	Index
CA	Class area (ha)
TA	Total landscape area (ha)
%LAND	Percent of landscape (%)
LPI	Largest patch index (%)
NP	Number of patches (#)
PD	Patch density (#/100 ha)
MPS	Mean patch size (ha)
PSSD	Patch size standard deviation (ha)
PSCV	Patch size coefficient of variation (%)
TE	Total edge (m)
ED	Edge density (m/ha)
LSI	Landscape shape index
MSI	Mean shape index
AWMSI	Area-weighted mean shape index
DLFD	Double log fractal dimension
MPFD	Mean patch fractal dimension
AWMPFD	Area-weighted mean patch fractal dimension
C%LAND	Core area percent of landscape (%)
TCA	Total core area (ha)
NCA	Number of core areas (#)
CAD	Core area density (#/100 ha)
MCA1	Mean core area index (%)
CASD1	Patch core area standard deviation (ha)
CACV1	Patch core area coefficient of variation (%)
MCA2	Meanb area per disjunct core (ha)
CASD2	Disjunct core area standard deviation (%)
CACV2	Disjunct core area coefficient of variation (%)
TCAI	Total core area index (%)
MCAI	Mean core area index (%)
IJI	Interspersion and Juxtaposition Index (%)

Appendix C: Quantitative Analysis Results - Landscape

Code	1989				1996			
	Montane	Sub-Alpine	Alpine	Total	Montane	Sub-Alpine	Alpine	Total
TA	109,178.91	56,470.70	67,997.00	233,646.57	108,257.22	54,057.20	60,413.90	222,728.20
LPI	9.40	4.30	33.60	11.14	9.40	4.50	31.50	9.89
NP	9,023	8,160	4,621	19,047	9,091	8,306	4,867	19,484
PD	8.26	14.50	6.80	8.15	8.40	15.40	8.10	8.75
MPS	12.10	6.90	14.70	12.27	11.90	6.50	12.40	11.43
PSSD	184.84	42.70	352.60	254.11	182.90	40.60	286.10	225.81
PSCV	1,527.58	616.90	2,396.40	2,071.56	1,535.80	624.40	2,304.70	1,975.34
TE	6,567,300	4,544,430	2,808,390	14,026,020	6,497,160	4,431,120	2,622,120	13,653,030
ED	60.15	80.50	41.30	60.03	60.00	82.00	43.40	61.30
LSI	56.20	65.60	48.00	85.96	57.70	68.90	56.80	92.89
MSI	1.41	1.43	1.40	1.41	1.41	1.43	1.41	1.41
AWMSI	7.16	3.66	9.74	8.90	7.23	3.69	10.95	9.25
DLFD	1.34	1.33	1.31	1.34	1.34	1.33	1.32	1.34
MPFD	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
AWMPFD	1.21	1.16	1.23	1.22	1.21	1.16	1.24	1.22
TCA	23,051.97	3,225.60	14,808.00	44,217.54	22,696.10	2,736.70	9,120.90	36,769.41
NCA	789	415	492	1,681	782	359	525	1,690
CAD	0.72	0.73	0.72	0.72	0.72	0.66	0.87	0.76
MCA1	2.55	0.40	3.20	2.32	2.50	0.33	1.87	1.89
CASD1	70.15	8.80	139.90	95.10	69.60	8.30	85.20	72.81
CACV1	2,745.70	2,213.40	4,366.90	4,096.63	2,788.20	2,511.70	4,546.90	3,858.02
MCA2	29.22	7.80	30.10	26.30	29.00	7.60	17.40	21.76
CASD2	235.57	38.10	427.90	319.14	235.70	39.10	258.90	246.34
CACV2	9,220.69	9,626.20	13,353.70	13,747.24	9,441.40	11,867.40	13,816.40	13,053.26
TCAI	21.11	5.70	21.80	18.92	21.00	5.10	15.10	16.51
MCAI	0.19	0.14	0.15	0.16	0.18	0.12	0.11	0.14
SHDI	1.79	1.80	1.00	2.00	1.80	1.80	1.00	2.01
SIDI	0.77	0.80	0.50	0.83	0.80	0.80	0.50	0.84
MSIDI	1.49	1.80	0.60	1.77	1.50	1.80	0.70	1.81
PR	11	10	8	11	11	10	8	11
PRD	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SHEI	0.75	0.80	0.50	0.83	0.70	0.80	0.50	0.84
SIEI	0.85	0.90	0.50	0.91	0.90	0.90	0.60	0.92
MSIEI	0.62	0.80	0.30	0.74	0.60	0.80	0.30	0.75
IJI	60.16	66.70	57.70	68.12	60.10	66.50	57.60	67.86
CONTAG	54.35	48.40	69.30	49.71	54.40	48.20	68.20	49.20

Appendix D: Quantitative Analysis Results - Class: 1989

Index	spruce forest	rock	alpine meadow	alpine barrens	alluvial deposits	alpine tundra	mixed forest	deciduous shrub	lake	river	snow/ice
CA	48,588.03	67,183.65	24,228.00	10,179.27	3,182.31	10,518.03	28,734.03	26,289.45	7,942.50	3,217.14	3,584.16
TA	233,646.56	233,646.56	233,646.56	233,646.56	233,646.56	233,646.56	233,646.56	233,646.56	233,646.56	233,646.56	233,646.56
%LAND	20.80	28.75	10.37	4.36	1.36	4.50	12.30	11.25	3.40	1.38	1.53
LPI	5.53	11.14	0.54	0.21	0.14	0.25	1.07	3.01	1.47	1.24	0.07
NP	1,864	2,306	4,639	1,972	431	1,636	3,121	2,203	162	51	662
PD	0.80	0.99	1.99	0.84	0.18	0.70	1.34	0.94	0.07	0.02	0.28
MPS	26.07	29.13	5.22	5.16	7.38	6.43	9.21	11.93	49.03	63.08	5.41
PSSD	404.46	583.32	30.62	23.50	27.79	27.92	76.39	198.00	337.48	403.85	15.80
PSCV	1,551.65	2,002.17	586.33	455.25	376.40	434.27	829.73	1,659.21	688.34	640.20	291.74
TE	4,061,850	4,509,930	5,681,700	1,872,630	532,680	1,860,300	4,960,650	3,426,900	231,870	343,170	570,360
ED	17.38	19.30	24.32	8.01	2.28	7.96	21.23	14.67	0.99	1.47	2.44
LSI	34.42	36.74	42.80	23.10	16.17	23.03	39.07	31.14	14.61	15.19	16.36
MSI	1.41	1.41	1.46	1.37	1.45	1.37	1.43	1.37	1.27	1.62	1.32
AWMSI	10.31	13.38	4.18	3.12	2.75	3.21	6.06	9.96	2.01	14.28	1.90
DLFD	1.32	1.35	1.38	1.31	1.32	1.31	1.36	1.32	1.16	1.48	1.24
MPFD	1.06	1.05	1.06	1.05	1.06	1.05	1.06	1.05	1.04	1.06	1.05
AWMPFD	1.24	1.27	1.17	1.15	1.14	1.15	1.21	1.23	1.08	1.30	1.09
C%LAND	6.24	7.71	0.16	0.08	0.11	0.14	0.57	1.41	2.35	0.09	0.07
TCA	14,590.17	18,022.95	364.86	179.01	257.40	320.13	1,325.97	3,285.72	5,489.64	207.81	173.88
NCA	337	478	106	72	16	91	266	242	10	32	31
CAD	0.14	0.20	0.05	0.03	0.01	0.04	0.11	0.10	0.00	0.01	0.01
MCA1	7.83	7.82	0.08	0.09	0.60	0.20	0.42	1.49	33.89	4.07	0.26
CASD1	146.07	225.74	2.00	1.05	6.35	2.00	10.27	38.18	260.83	25.62	2.67
CACV1	1,866.11	2,888.34	2,542.29	1,152.63	1,063.55	1,021.15	2,417.35	2,559.87	769.70	628.77	1,016.14
MCA2	43.29	37.70	3.44	2.49	16.09	3.52	4.98	13.58	548.96	6.49	5.61
CASD2	341.28	494.69	12.78	4.90	28.94	7.75	34.85	114.48	905.17	32.10	11.05
CACV2	788.29	1,312.01	371.37	197.16	179.90	220.36	699.21	843.17	164.89	494.31	197.03
TCAI	30.03	26.83	1.51	1.76	8.09	3.04	4.61	12.50	69.12	6.46	4.85
MCAI	0.33	0.26	0.04	0.07	0.29	0.14	0.10	0.13	2.05	0.31	0.24
IJI	49.89	73.71	78.31	39.07	56.36	49.22	49.56	56.49	54.55	41.78	14.43

Appendix E: Quantitative Analysis Results - Class: 1996

Index	spruce forest	rock	alpine meadow	alpine barrens	alluvial deposits	alpine tundra	mixed forest	deciduous shrub	lake	river	snow/ice
CA	47,642.94	59,159.07	24,131.88	10,044.63	3,179.25	10,290.69	28,500.12	25,914.15	7,939.44	3,216.69	2,709.36
TA	222,728.22	222,728.22	222,728.22	222,728.22	222,728.22	222,728.22	222,728.22	222,728.22	222,728.22	222,728.22	222,728.22
%LAND	21.39	26.56	10.83	4.51	1.43	4.62	12.80	11.63	3.56	1.44	1.22
LPI	5.72	9.89	0.57	0.22	0.15	0.26	1.06	3.14	1.54	1.31	0.06
NP	1,902	2,554	4,651	1,986	433	1,655	3,139	2,233	161	51	719
PD	0.85	1.15	2.09	0.89	0.19	0.74	1.41	1.00	0.07	0.02	0.32
MPS	25.05	23.16	5.19	5.06	7.34	6.22	9.08	11.61	49.31	63.07	3.77
PSSD	396.20	467.31	30.53	23.14	27.72	26.85	74.47	194.57	338.49	403.78	11.84
PSCV	1,581.69	2,017.45	588.50	457.60	377.58	431.86	820.21	1,676.59	686.41	640.19	314.30
TE	3,954,510	4,236,030	5,634,300	1,850,190	532,080	1,828,320	4,905,960	3,368,310	228,120	343,050	425,190
ED	17.75	19.02	25.30	8.31	2.39	8.21	22.03	15.12	1.02	1.54	1.91
LSI	41.51	43.01	50.41	30.37	23.38	30.25	46.55	38.41	21.77	22.38	22.82
MSI	1.42	1.43	1.46	1.37	1.45	1.38	1.43	1.37	1.27	1.62	1.35
AWMSI	10.37	14.96	4.18	3.14	2.76	3.28	6.13	10.23	2.01	14.29	2.10
DLFD	1.33	1.36	1.38	1.31	1.31	1.32	1.36	1.33	1.16	1.48	1.27
MPFD	1.06	1.06	1.06	1.05	1.06	1.05	1.06	1.05	1.04	1.06	1.05
AWMPFD	1.24	1.28	1.17	1.15	1.14	1.15	1.21	1.24	1.08	1.30	1.11
C%LAND	6.44	5.10	0.16	0.08	0.12	0.12	0.53	1.37	2.46	0.09	0.03
TCA	14,354.01	11,368.17	362.07	168.66	256.59	263.25	1,178.01	3,044.43	5,489.28	207.81	77.13
NCA	323	539	105	71	16	82	259	237	10	32	16
CAD	0.15	0.24	0.05	0.03	0.01	0.04	0.12	0.11	0.00	0.01	0.01
MCA1	7.55	4.45	0.08	0.08	0.59	0.16	0.38	1.36	34.09	4.07	0.11
CASD1	143.83	138.93	2.00	0.98	6.31	1.68	8.92	36.74	261.61	25.62	1.22
CACV1	1,905.78	3,121.24	2,563.98	1,148.25	1,064.39	1,055.55	2,375.70	2,694.62	767.31	628.77	1,137.76
MCA2	44.44	21.09	3.45	2.38	16.04	3.21	4.55	12.85	548.93	6.49	4.82
CASD2	346.65	301.84	12.84	4.60	28.79	6.86	30.73	112.11	905.16	32.10	6.65
CACV2	780.06	1,431.12	372.34	193.63	179.54	213.78	675.65	872.76	164.90	494.31	137.95
TCAI	30.13	19.22	1.50	1.68	8.07	2.56	4.13	11.75	69.14	6.46	2.85
MCAI	0.29	0.20	0.04	0.06	0.29	0.11	0.09	0.11	2.06	0.31	0.11
IJI	48.98	72.53	78.41	39.13	56.33	49.12	49.53	56.45	54.80	41.79	17.86

Appendix F: Quantitative Analysis Results - Class by Elevation Zone: 1989 (spruce forest, rock, alpine meadow)

Index	Spruce Forest			Rock			Alpine Meadow		
	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine
CA	42,285.78	5,817.20	485.10	5,977.40	12,259.30	48,947.00	7,227.60	11,720.80	5,279.60
TA	109,178.91	56,470.70	67,997.00	109,178.90	56,470.70	67,997.00	109,178.90	56,470.68	67,997.00
%LAND	38.73	10.30	0.70	5.50	21.70	72.00	6.60	20.80	7.80
LPI	9.37	0.60	0.10	0.60	1.10	33.60	0.20	1.90	0.50
NP	1,147	840	181	988	1,253	646	1,953	2,113	1,262
PD	1.05	1.50	0.30	0.90	2.20	1.00	1.80	3.70	1.90
MPS	36.90	6.90	2.70	6.10	9.80	75.80	3.70	5.60	4.20
PSSD	455.70	25.60	5.00	32.90	43.80	939.70	14.40	33.70	14.20
PSCV	1,236.10	370.10	184.80	543.40	447.40	1,240.20	389.80	608.10	338.80
TE	3,043,110	889,320	106,410	1,009,980	1,385,370	2,075,520	1,886,550	2,527,110	1,211,940
ED	27.90	15.80	1.60	9.30	24.50	30.50	17.30	44.80	17.80
LSI	29.60	27.20	22.10	14.20	32.40	40.90	20.80	44.40	32.70
MSI	1.42	1.43	1.32	1.40	1.46	1.54	1.41	1.48	1.42
AWMSI	9.85	2.67	1.56	2.94	3.47	12.51	3.02	4.22	2.72
DLFD	1.32	1.31	1.22	1.33	1.34	1.37	1.37	1.37	1.34
MPFD	1.06	1.06	1.05	1.06	1.06	1.06	1.06	1.06	1.06
AWMPFD	1.24	1.14	1.08	1.14	1.16	1.26	1.15	1.18	1.14
C%LAND	12.63	0.68	0.01	0.62	1.60	21.23	0.04	0.45	0.06
TCA	13,794.48	385.74	6.30	672.75	901.98	14,433.57	47.97	252.18	38.52
NCA	296	42	2	43	113	365	26	53	19
CAD	0.27	0.07	0.00	0.04	0.20	0.54	0.02	0.09	0.03
MCA1	12.03	0.46	0.03	0.68	0.72	22.34	0.02	0.12	0.03
CASD1	167.12	6.39	0.39	12.33	7.91	373.69	0.58	2.85	0.64
CACV1	1,389.59	1,392.34	1,133.94	1,811.44	1,098.65	1,672.50	2,365.27	2,386.88	2,083.00
MCA2	46.60	9.18	3.15	15.65	7.98	39.54	1.85	4.76	2.03
CASD2	326.52	27.16	2.07	57.11	25.21	496.46	4.69	17.36	4.78
CACV2	700.64	295.69	65.71	365.03	315.84	1,255.45	254.19	364.90	235.53
TCAI	32.62	6.63	1.30	11.25	7.36	29.49	0.66	2.15	0.73
MCAI	0.49	0.23	0.09	0.22	0.24	0.60	0.02	0.06	0.02
IJI	42.85	61.98	55.82	77.03	62.49	64.44	75.83	74.77	67.23

Appendix F: Quantitative Analysis Results - Class by Elevation Zone: 1989 (alpine barren, alluvial deposits, alpine tundra)

	Alpine Barrens			Alluvial Deposits			Alpine Tundra		
Index	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine
CA	496.26	1,848.06	7,834.95	3,182.13	0.18		1,408.68	7,466.04	1,643.31
TA	109,178.91	56,470.68	67,996.98	109,178.91	56,470.68		109,178.91	56,470.68	67,996.98
%LAND	0.45	3.27	11.52	2.91	0.00		1.29	13.22	2.42
LPI	0.03	0.12	0.69	0.31	0.00		0.11	0.78	0.09
NP	272	762	1,194	431	1		438	1,069	466
PD	0.25	1.35	1.76	0.39	0.00		0.40	1.89	0.69
MPS	1.82	2.43	6.56	7.38	0.18		3.22	6.98	3.53
PSSD	4.30	6.36	27.31	27.79	0.00		10.29	25.78	8.18
PSCV	235.74	262.23	416.15	376.42	0.00		320.08	369.11	231.99
TE	150,630	461,280	1,242,600	531,810	60		304,170	1,219,470	313,110
ED	1.38	8.17	18.27	4.87	0.00		2.79	21.59	4.60
LSI	7.67	22.65	32.94	10.56	17.80		8.83	30.63	24.03
MSI	1.27	1.32	1.40	1.45	1.06		1.32	1.41	1.32
AWMSI	1.69	2.09	3.12	2.75	1.06		2.29	2.95	1.93
DLFD	1.25	1.30	1.31	1.32			1.30	1.30	1.26
MPFD	1.05	1.05	1.06	1.06	1.02		1.05	1.06	1.05
AWMPFD	1.08	1.11	1.15	1.14	1.02		1.12	1.14	1.10
C%LAND	0.00	0.00	0.24	0.24	0.00		0.00	0.36	0.01
TCA	0.45	0.00	160.20	257.40	0.00		1.35	206.10	5.49
NCA	1	0	68	16	0		7	60	8
CAD	0.00	0.00	0.10	0.01	0.00		0.01	0.11	0.01
MCA1	0.00	0.00	0.13	0.60	0.00		0.00	0.19	0.01
CASD1	0.03	0.00	1.23	6.35	0.00		0.03	1.84	0.14
CACV1	1,646.21	0.00	916.00	1,063.55	0.00		1,102.91	952.72	1,150.55
MCA2	0.45	0.00	2.36	16.09	0.00		0.19	3.43	0.69
CASD2	0.00	0.00	4.61	28.94	0.00		0.19	7.00	0.78
CACV2	0.00	0.00	195.84	179.90	0.00		97.98	203.73	113.57
TCAI	0.09	0.00	2.04	8.09	0.00		0.10	2.76	0.33
MCAI	0.00	0.00	0.10	0.29	0.00		0.01	0.14	0.02
IJI	53.08	46.53	37.74	56.36	31.55		40.30	50.22	45.18

Appendix F: Quantitative Analysis Results - Class by Elevation Zone: 1989 (mixed forest, deciduous shrub, lake)

Index	Mixed Forest			Deciduous Shrub			Lake		
	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine
CA	28,734.03	5,435.37	162.90	14,229.18	11,810.61	249.66	7,853.85	88.65	
TA	233,646.56	56,470.68	67,996.98	109,178.91	56,470.68	67,996.98	109,178.91	56,470.68	
%LAND	12.30	9.63	0.24	13.03	20.91	0.37	7.19	0.16	
LPI	1.07	0.48	0.04	3.87	4.31	0.04	3.14	0.05	
NP	3,121	1,016	100	1,265	1,027	174	116	47	
PD	1.34	1.80	0.15	1.16	1.82	0.26	0.11	0.08	
MPS	9.21	5.35	1.63	11.25	11.50	1.43	67.71	1.89	
PSSD	76.39	18.33	3.30	144.83	90.29	2.77	397.27	4.44	
PSCV	829.73	342.70	202.81	1,287.52	785.16	192.80	586.75	235.34	
TE	4,960,650	1,017,750	48,540	1,767,240	1,554,750	81,360	207,720	24,000	
ED	21.23	18.02	0.71	16.19	27.53	1.20	1.90	0.42	
LSI	39.07	28.51	21.49	19.90	34.16	21.81	8.10	18.05	
MSI	1.43	1.40	1.27	1.36	1.43	1.26	1.29	1.20	
AWMSI	6.06	2.62	1.68	7.74	4.99	1.54	2.02	1.50	
DLFD	1.36	1.30	1.23	1.32	1.33	1.26	1.15	1.20	
MPFD	1.06	1.06	1.05	1.05	1.06	1.05	1.05	1.04	
AWMPFD	1.21	1.13	1.08	1.22	1.19	1.08	1.08	1.07	
C%LAND	0.57	0.21	0.00	1.39	2.41	0.00	5.03	0.00	
TCA	1,325.97	120.78	0.00	1,516.77	1,358.82	0.00	5,489.64	0.00	
NCA	266	49	0	150	98	0	10	0	
CAD	0.11	0.09	0.00	0.14	0.17	0.00	0.01	0.00	
MCA1	0.42	0.12	0.00	1.20	1.32	0.00	47.32	0.00	
CASD1	10.27	1.07	0.00	22.21	21.81	0.00	307.20	0.00	
CACV1	2,417.35	902.67	0.00	1,851.97	1,648.57	0.00	649.13	0.00	
MCA2	4.98	2.46	0.00	10.11	13.87	0.00	548.96	0.00	
CASD2	34.85	4.25	0.00	63.78	69.37	0.00	905.17	0.00	
CACV2	699.21	172.57	0.00	630.78	500.30	0.00	164.89	0.00	
TCAI	4.61	2.22	0.00	10.66	11.51	0.00	69.90	0.00	
MCAI	0.10	0.14	0.00	0.13	0.25	0.00	2.86	0.00	
IJI	49.56	56.13	68.96	48.00	61.13	60.66	54.58	50.08	

Appendix F: Quantitative Analysis Results - Class by Elevation Zone: 1989 (river, snow/ice)

Index	River			Snow/Ice		
	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine
CA	3,217.14			165.15	24.57	3,394.44
TA	109,178.91			109,178.91	56,470.68	67,996.98
%LAND	2.95			0.15	0.04	4.99
LPI	2.66			0.10	0.01	0.26
NP	51			41	32	598
PD	0.05			0.04	0.06	0.88
MPS	63.08			4.03	0.77	5.68
PSSD	403.85			16.63	0.98	16.01
PSCV	640.20			412.79	127.80	282.01
TE	343,170			22,560	9,750	537,300
ED	3.14			0.21	0.17	7.90
LSI	9.13			6.70	17.90	26.18
MSI	1.62			1.26	1.23	1.33
AWMSI	14.28			2.56	1.36	1.88
DLFD	1.48			1.25	1.28	1.24
MPFD	1.06			1.04	1.04	1.05
AWMPFD	1.30			1.13	1.06	1.09
C%LAND	0.19			0.01	0.00	0.24
TCA	207.81			9.99	0.00	163.89
NCA	32			1	0	30
CAD	0.03			0.00	0.00	0.04
MCA1	4.07			0.24	0.00	0.27
CASD1	25.62			1.54	0.00	2.78
CACV1	628.77			632.46	0.00	1,013.82
MCA2	6.49			9.99	0.00	5.46
CASD2	32.10			0.00	0.00	11.20
CACV2	494.31			0.00	0.00	205.10
TCAI	6.46			6.05	0.00	4.83
MCAI	0.31			0.23	0.00	0.25
IJI	41.78			39.95	29.75	6.71

Appendix G: Quantitative Analysis Results - Class by Elevation Zone: 1996 (spruce forest, rock, alpine meadow)

Index	Spruce Forest			Rock			Alpine Meadow		
	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine
CA	42,004.62	5,223.33	414.99	5,874.57	10,821.15	42,463.35	7,218.27	11,660.40	5,253.21
TA	108,257.22	54,057.15	60,413.85	108,257.22	54,057.15	60,413.85	108,257.22	54,057.15	60,413.85
%LAND	38.80	9.66	0.69	5.43	20.02	70.29	6.67	21.57	8.70
LPI	9.37	0.63	0.08	0.64	0.76	31.51	0.23	1.93	0.51
NP	1,159	878	166	983	1,339	834	1,955	2,122	1,259
PD	1.07	1.62	0.27	0.91	2.48	1.38	1.81	3.93	2.08
MPS	36.24	5.95	2.50	5.98	8.08	50.92	3.69	5.50	4.17
PSSD	450.58	23.25	4.82	32.85	32.91	688.71	14.42	33.64	14.17
PSCV	1,243.25	390.84	192.67	549.71	407.17	1,352.65	390.48	612.27	339.54
TE	3,018,090	823,680	91,980	993,810	1,311,390	1,893,930	1,881,330	2,497,680	1,199,730
ED	27.88	15.24	1.52	9.18	24.26	31.35	17.38	46.20	19.86
LSI	31.26	30.14	31.03	15.87	35.38	49.36	22.62	48.14	42.30
MSI	1.42	1.43	1.33	1.40	1.48	1.54	1.41	1.47	1.42
AWMSI	9.85	2.69	1.61	2.95	3.32	14.44	3.02	4.22	2.73
DLFD	1.32	1.31	1.24	1.33	1.35	1.37	1.37	1.37	1.34
MPFD	1.06	1.06	1.05	1.06	1.06	1.06	1.06	1.06	1.06
AWMPFD	1.24	1.14	1.08	1.15	1.16	1.28	1.15	1.18	1.14
C%LAND	12.65	0.60	0.01	0.62	1.04	14.66	0.04	0.46	0.06
TCA	13,691.07	322.56	3.42	672.03	562.59	8,856.81	47.97	249.75	38.16
NCA	300	27	1	40	86	416	26	53	18
CAD	0.28	0.05	0.00	0.04	0.16	0.69	0.02	0.10	0.03
MCA1	11.81	0.37	0.02	0.68	0.42	10.62	0.02	0.12	0.03
CASD1	165.69	6.11	0.26	12.37	4.80	205.61	0.58	2.84	0.63
CACV1	1,402.62	1,662.78	1,284.52	1,808.74	1,143.59	1,936.12	2,366.49	2,414.38	2,089.30
MCA2	45.64	11.95	3.42	16.80	6.54	21.29	1.85	4.71	2.12
CASD2	323.29	32.79	0.00	59.05	17.87	290.73	4.69	17.37	4.86
CACV2	708.40	274.47	0.00	351.47	273.20	1,365.57	254.19	368.57	229.24
TCAI	32.59	6.18	0.82	11.44	5.20	20.86	0.66	2.14	0.73
MCAI	0.47	0.16	0.04	0.22	0.18	0.36	0.02	0.05	0.02
IJI	42.53	61.87	58.68	76.90	61.52	62.84	75.83	74.77	67.28

Appendix G: Quantitative Analysis Results - Class by Elevation Zone: 1996 (alpine barrens, alluvial deposits, alpine tundra)

Index	Alpine Barrens			Alluvial Deposits			Alpine Tundra		
	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine
CA	495.63	1,836.90	7,712.10	3,179.16	0.09		1,310.22	7,344.18	1,636.29
TA	108,257.22	54,057.15	60,413.85	108,257.22	54,057.15		108,257.22	54,057.15	60,413.85
%LAND	0.46	3.40	12.77	2.94	0.00		1.21	13.59	2.71
LPI	0.03	0.13	0.77	0.31	0.00		0.10	0.82	0.10
NP	273	762	1,209	432	1		456	1,070	468
PD	0.25	1.41	2.00	0.40	0.00		0.42	1.98	0.77
MPS	1.82	2.41	6.38	7.36	0.09		2.87	6.86	3.50
PSSD	4.29	6.34	26.90	27.75	0.00		8.90	25.36	8.16
PSCV	236.56	263.20	421.75	377.13	0.00		309.65	369.47	233.26
TE	150,270	458,220	1,223,640	531,210	60		287,250	1,205,370	312,330
ED	1.39	8.48	20.25	4.91	0.00		2.65	22.30	5.17
LSI	9.47	26.21	42.54	12.36	21.28		10.51	34.24	33.27
MSI	1.26	1.32	1.41	1.45	1.00		1.33	1.42	1.33
AWMSI	1.69	2.09	3.16	2.76	1.00		2.27	3.02	1.93
DLFD	1.25	1.30	1.31	1.31			1.32	1.31	1.26
MPFD	1.05	1.05	1.06	1.06	1.00		1.05	1.06	1.05
AWMPFD	1.08	1.11	1.15	1.14	1.00		1.12	1.15	1.10
C%LAND	0.00	0.00	0.25	0.24	0.00		0.00	0.34	0.01
TCA	0.45	0.00	149.85	256.59	0.00		1.08	182.97	5.49
NCA	1	0	67	16	0		7	55	8
CAD	0.00	0.00	0.11	0.01	0.00		0.01	0.10	0.01
MCA1	0.00	0.00	0.12	0.59	0.00		0.00	0.17	0.01
CASD1	0.03	0.00	1.15	6.31	0.00		0.03	1.73	0.14
CACV1	1,649.24	0.00	925.41	1,063.15	0.00		1,228.82	1,008.96	1,153.03
MCA2	0.45	0.00	2.24	16.04	0.00		0.15	3.33	0.69
CASD2	0.00	0.00	4.36	28.79	0.00		0.18	6.89	0.78
CACV2	0.00	0.00	194.97	179.54	0.00		115.47	206.98	113.57
TCAI	0.09	0.00	1.94	8.07	0.00		0.08	2.49	0.34
MCAI	0.00	0.00	0.10	0.29	0.00		0.01	0.13	0.02
IJI	52.94	46.50	37.86	56.33	31.55		41.18	50.05	45.15

Appendix G: Quantitative Analysis Results - Class by Elevation Zone: 1996 (mixed forest, deciduous shrub, lake)

Index	Mixed Forest			Deciduous Shrub			Lake		
	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine
CA	22,956.75	5,382.99	160.38	13,984.56	11,681.73	247.86	7,851.60	87.84	
TA	108,257.22	54,057.15	60,413.85	108,257.22	54,057.15	60,413.85	108,257.22	54,057.15	
%LAND	21.21	9.96	0.27	12.92	21.61	0.41	7.25	0.16	
LPI	1.68	0.50	0.05	3.82	4.49	0.04	3.17	0.06	
NP	2,338	1,020	100	1,288	1,038	174	115	47	
PD	2.16	1.89	0.17	1.19	1.92	0.29	0.11	0.09	
MPS	9.82	5.28	1.60	10.86	11.25	1.42	68.27	1.87	
PSSD	75.34	18.16	3.31	140.92	89.35	2.69	398.93	4.44	
PSCV	767.29	344.19	206.20	1,297.91	793.96	188.76	584.30	237.60	
TE	3,833,400	999,450	47,220	1,728,300	1,535,790	81,150	205,050	22,920	
ED	35.41	18.49	0.78	15.96	28.41	1.34	1.89	0.42	
LSI	37.45	32.03	30.58	21.46	37.80	30.92	9.88	21.53	
MSI	1.45	1.40	1.27	1.37	1.44	1.26	1.30	1.20	
AWMSI	6.21	2.64	1.69	8.03	5.10	1.58	2.02	1.50	
DLFD	1.37	1.30	1.24	1.32	1.33	1.26	1.15	1.21	
MPFD	1.06	1.06	1.05	1.05	1.06	1.05	1.05	1.04	
AWMPFD	1.21	1.13	1.09	1.22	1.19	1.08	1.08	1.07	
C%LAND	0.87	0.21	0.00	1.28	2.41	0.00	5.07	0.00	
TCA	939.15	115.38	0.00	1,380.69	1,303.47	0.00	5,489.28	0.00	
NCA	200	47	0	149	91	0	10	0	
CAD	0.18	0.09	0.00	0.14	0.17	0.00	0.01	0.00	
MCA1	0.40	0.11	0.00	1.07	1.26	0.00	47.73	0.00	
CASD1	8.57	1.05	0.00	20.53	21.56	0.00	308.49	0.00	
CACV1	2,133.03	930.59	0.00	1,915.64	1,717.01	0.00	646.29	0.00	
MCA2	4.70	2.45	0.00	9.27	14.32	0.00	548.93	0.00	
CASD2	28.95	4.28	0.00	59.74	71.52	0.00	905.16	0.00	
CACV2	616.49	174.25	0.00	644.73	499.33	0.00	164.90	0.00	
TCAI	4.09	2.14	0.00	9.87	11.16	0.00	69.91	0.00	
MCAI	0.08	0.13	0.00	0.11	0.24	0.00	2.88	0.00	
IJI	47.19	56.11	68.76	47.85	60.99	60.61	54.82	50.57	

Appendix G: Quantitative Analysis Results - Class by Elevation Zone: 1996 (river, snow/ice)

Index	River			Snow/Ice		
	Montane	Sub-Alpine	Alpine	Montane	Sub-Alpine	Alpine
CA	3,216.69			165.15	18.54	2,525.67
TA	108,257.22			108,257.22	54,057.15	60,413.85
%LAND	2.97			0.15	0.03	4.18
LPI	2.69			0.10	0.00	0.23
NP	51			41	29	657
PD	0.05			0.04	0.05	1.09
MPS	63.07			4.03	0.64	3.84
PSSD	403.78			16.63	0.66	11.66
PSCV	640.19			412.79	102.54	303.30
TE	343,050			22,560	7,680	394,260
ED	3.17			0.21	0.14	6.53
LSI	10.93			8.49	21.37	34.11
MSI	1.62			1.26	1.23	1.35
AWMSI	14.29			2.56	1.35	2.07
DLFD	1.48			1.25	1.30	1.28
MPFD	1.06			1.04	1.04	1.05
AWMPFD	1.30			1.13	1.06	1.11
C%LAND	0.19			0.01	0.00	0.11
TCA	207.81			9.99	0.00	67.14
NCA	32			1	0	15
CAD	0.03			0.00	0.00	0.02
MCA1	4.07			0.24	0.00	0.10
CASD1	25.62			1.54	0.00	1.22
CACV1	628.77			632.46	0.00	1,190.66
MCA2	6.49			9.99	0.00	4.48
CASD2	32.10			0.00	0.00	6.73
CACV2	494.31			0.00	0.00	150.32
TCAI	6.46			6.05	0.00	2.66
MCAI	0.31			0.23	0.00	0.10
IJI	41.79			39.95	32.73	8.29

Appendix H: Sensitivity Analysis Results - Subregion 1

Code	Index	Landscape 1	2	3	4	5
TA	Total Landscape Area (ha)	14,739.03	14,576.13	15,275.16	15,275.16	15,275.16
LPI	Largest Patch Index (%)	12.05	9.87	3.00	8.26	8.20
NP	Number of Patches (#)	1,258	1,339	4,545	2,279	1,108
PD	Patch Density (#/100 ha)	8.54	9.19	29.75	14.92	7.25
MPS	Mean Patch Size (ha)	11.72	10.89	3.36	6.70	13.79
PSSD	Patch Size Standard Deviation (ha)	82.41	73.03	14.50	37.50	79.50
PSCV	Patch Size Coefficient of Variation (%)	703.36	670.84	431.44	559.43	576.65
TE	Total Edge (m)	957,330	925,470	2,004,330	1,452,720	1,037,430
ED	Edge Density (m/ha)	64.95	63.49	131.21	95.10	67.92
LSI	Landscape Shape Index	23.13	23.21	41.59	30.43	22.03
MSI	Mean Shape Index	1.45	1.42	1.36	1.42	1.45
AWMSI	Area-Weighted Mean Shape Index	4.45	4.19	2.79	3.64	4.87
DFLD	Double Log Fractal Dimension	1.35	1.33	1.34	1.34	1.33
MPFD	Mean Patch Fractal Dimension	1.06	1.06	1.05	1.06	1.06
AWMPFD	Area-Weighted Mean Patch Fractal Dimension	1.18	1.17	1.14	1.16	1.19
TCA	Total Core Area (ha)	2,138.58	2,088.27	202.05	917.46	1,835.10
NCA	Number of Core Areas (#)	116	121	55	102	144
CAD	Core Area Density (#/100 ha)	0.79	0.83	0.36	0.67	0.94
MCA1	Mean Core Area per Patch (ha)	1.70	1.56	0.04	0.40	1.66
CASD1	Patch Core Area Standard Deviation (ha)	23.52	18.21	0.91	7.36	16.21
CACV1	Patch Core Area Coefficient of Variation (%)	1,383.50	1,167.80	2,053.67	1,828.75	979.00
MCA2	Mean Area per Disjunct Core (ha)	18.44	17.26	3.67	8.99	12.74
CASD2	Disjunct Core Area Standard Deviation (ha)	75.43	58.31	7.45	33.67	43.38
CACV2	Disjunct Core Area Coefficient of Variation (%)	4,437.37	3,738.65	16,764.92	8,363.83	2,619.09
TCAI	Total Core Area Index (%)	14.51	14.33	1.32	6.01	12.01
MCAI	Mean Core Area Index (%)	0.31	0.37	0.04	0.17	0.44
MNN	Mean Nearest Neighbour Distance (m)	154.10	162.50	145.10	136.10	118.60
NNSD	Nearest Neighbour Standard Deviation (m)	300.28	273.09	298.99	262.65	127.01
NNCV	Nearest Neighbour Coefficient of Variation (%)	194.88	168.10	205.99	192.97	107.11
SHDI	Shannon's Diversity Index	1.82	1.85	2.92	2.21	1.47
SIDI	Simpson's Diversity Index	0.79	0.80	0.94	0.88	0.75
MSIDI	Modified Simpson's Diversity Index	1.56	1.60	2.76	2.10	1.37
PR	Patch Richness (#)	11	10	24	11	5
PRD	Patch Richness Density (#/100 ha)	0.07	0.07	0.16	0.07	0.03
SHEI	Shannon's Evenness Index	0.76	0.81	0.92	0.92	0.91
SIEI	Simpson's Evenness Index	0.87	0.89	0.98	0.97	0.93
MSIEI	Modified Simpson's Evenness Index	0.65	0.69	0.87	0.88	0.85
IJI	Interspersion and Juxtaposition Index (%)	63.70	67.89	73.78	72.68	76.31
CONTAG	Contagion Index (%)	52.96	50.38	40.19	41.06	41.07

Appendix I: Landsat Thematic Mapper Acquisition Parameters and Specifications

a. Details of Landsat TM Imagery.

	[illegible]	[illegible]
TM Bands	3,4,5	1,2,3,4,5,6,7
Scene Centre	60°44'56"N 137°58'17"W	60°32'48"N 137°25'59"W
Scene (WRS - Track/Frame)	61 / 17	60 / 18
Database Size (Cols x Rows)	4718 x 6919	3820 X 3531
Date Acquired	August 27	September 8

b. Landsat 5 Thematic Mapper Bands.

TM Band	Spectral Range (µm)	Description
1	0.45 - 0.52	blue
2	0.52 - 0.60	green
3	0.63 - 0.69	red
4	0.76 - 0.90	near IR
5	1.55 - 1.75	mid IR
7	2.08 - 2.35	mid IR
6	10.4 - 12.5	thermal

Appendix J: Fragstats Command-Line Parameters

Parameter	Description	Value
in_image	Input landscape file.	1989.raw
out_file	Basename for output ASCII files.	1989
cellsize	Size of cell (metres) in the input image.	30
edge_dist	Distance from patch edge (metres) for core area calculations.	200
data_type	Type of input file.	4 (16-bit binary, no header)
rows	Number of rows in image.	1800
cols	Number of columns in image.	1520
background	Value of background (interior) cells.	99
max_classes	Maximum number of patch types that could be present in landscape. Used to calculate relative patch richness. (Default: none. Metric not calculated)	$
weight_file	Name of ASCII file containing weights for each combination of patch type. Used to calculate contrast weighted edge indices. (Default: none. Metric not calculated)	$
id_image	Method for assigning patch IDs to each patch in the landscape and creating a patch ID map to relate patch statistics. (Default: do not produce ID image)	$
desc_file	Name of ASCII file containing character descriptors for each patch type.	class.txt
bound_wght	Proportion of the landscape boundary and background class edges to be considered edge. (Default: 0)	$
diags	Should diagonal neighbours be evaluated when finding cells that make up a patch. (Default: yes)	$
prox_dist	Search radius (metres) to use for calculating the proximity index.	200
nndist	Should nearest neighbour distance be calculated.	yes
patch_stats	Write patch statistics to output file.	yes
class_stats	Write class statistics to output file.	yes

Note: $ indicates the default value was used.

Appendix K: Land cover classes from Douglas (1974)

Community	Scientific Names
Deciduous Forest	
Balsam Poplar	*Populus balsamifera*
Balsam Poplar / buffaloberry deciduous forest	*Populus balsamifera / Sheperdiua canadensis*
Balsam Poplar / bearberry deciduous forest	*Populus balsamifera / Arctostaphylos uva-uris*
Balsam Poplar / buffalo bunchgrass-bearberry deciduous forest	*Populus balsamifera / Festuca altaica-Arctostaphylos uva-uris*
Poplar	*Populus*
Scouler's willow / buffaloberry deciduous forest	*Salix scouleriana / Sheperdia canadensis*
Trembling aspen / bearberry deciduous forest	*Populus tremuloides / Arctostaphylos uva-ursi*
Coniferous Forest	
White spruce	*Picea glauca*
White spruce-tembling aspen / buffaloberry twin flower mixed forest	*Picea glauca-Populus tremuloides / Sheperdia canadensis-Linnaea boreale*
White spruce / bearberry	*Picea glauca / Arctostaphylos uva-ursi*
White spruce / aulacomium moss coniferous forest	*Picea glauca / Aulacomnium palustre*
White spruce / shrub birch / crowberry coniferous forest	*Picea glauca / Betula glandulosa / Epetrum nigrum*
White spruce / reindeer lichen coniferous forest	*Picea glauca / Cladina arbuscula*
White spruce / shrub birch / sedge fen	*Picea glauca / Betula glandulosa / Carex aquatilis*
White spruce / hypnum moss coniferous forest	*Picea glauca / Hypnum revolutum*
White spruce / grayleaf willow	*Picea glauca / Salix glauca*
White spruce / thuidium moss coniferous forest	*Picea glauca / Thuidium abietinum*
Grassland / meadow	
Prairie Sagewort - Yukon wheatgrass shrub grassland	*Artemisia frigida-Agropyron yukonense*
Prairie Sagewort - Glaucous bluegrass shrub grassland	*Artemisia frigida-Poa glauca*
Prairie Sagewort dry meadow	*Artemisia frigida-Artemisia repestris*
Yukon wheatgrass dry meadow	*Agropyron yukonense*
Canadian reedgrass meadow	*Calamagrostis canadensis*
Purple reedgrass dry meadow	*Calamagrostis purpurascens*
Sabulosa sedge dunes	*Carex sabulosa*
Sedge	*Carex aquatilis*
Yellow dryas (mountain avens)	*Dryas drummondii*
Field oxytrope-Prairie sagewort dry meadow	*Oxytropis campestris-Artemisia frigidia*
Entire leaved white mountain avens mesic meadow	*Dryas integrifolia*
Yellow dryas dry meadow	*Dryas drummondii (south central phase)*
Rough fescue meadow	*Festuca altaica*
Northern sweet vetch dry meadow	*Hedysarum boreale*

Appendix K: Land cover classes from Douglas (1974) (continued)

Community	Scientific Name
Shrub	
Glandular birch / Aulacomnium shrub	*Betula glandulosa / Aulacomnium palustre*
Shrub birch-low blueberry - willow / rough fescue	*Betula glandulosa-salix myrtillifolia / Festuca altaica*
Soapberry shrub	*Sheperdia canadensis*
Soapberry / rough fescue shrub	*Sheperdia canadensis / Festuca altaica*
Soapberry / red fescue shrub	*Sheperdia canadensis / Festuca rubra*
Common juniper-bearberry	*Juniperus communis / Arctostaphylos uva-ursi*
Creeping juniper shrub	*Juniperus horizontalis*
Alaska willow shrub	*Salix Alaxensis*
Willow / sedge / sphagnum fen	*Salix / Carex aquatilis / Sphagnum*
Setchell willow shrub	*Salix Setchilliana*
Alpine*	
Willow / Birch / heath / krummholz shrub mosaic	*Salix / Betula*
dwarfed vascular plants	
Subalpine*	
Willow Shrub	*Salix*

*the alpine and subalpine vegetation zones of KNPR have not been investigated as thoroughly as the montane zone, and thus the species composition is less well known.

Appendix L: Land cover classes from Franklin and Wilson (1991)

# Class	Species
1. spruce forest	white spruce
2. deciduous shrub	willow, balsam, poplar, some grasses/sedges
3. mixed forest	classes 1 and 2
4. organic terrain	peat bogs
5. alpine tundra	mosses and lichens
6. alpine meadows	grasses and sedges
7. alpine barrens	exposed soil, some mosses, lichens, grasses/sedges
8. gravel and alluvial deposits	
9. water	lake and Slims river
10. eolian deposits	delta area Slims river
11. montane grassland	dry grassland, exposed soil/rock

REFERENCES

Agee, J.K. 1993. *Fire Ecology of the Pacific Northwest Forests.* Washington: Island Press.

Alexander, M.E. and D.E. Dubé. 1983. Fire management in wilderness areas, parks, and other nature reserves. In: Wein, R.W. and D.A. MacLean. Eds. *The Role of Fire in Northern Circumpolar Ecosystems.* Toronto: John Wiley.

Auerbach, S.I. 1981. Ecosystem Response to Stress: A Review of Concepts and Approaches. In: Barrett, G.W. and R. Rosenberg. Eds. *Stress Effects on Natural Ecosystems.* New York: John Wiley.

Bailey, R.G. 1996. *Ecosystem Geography.* New York: Springer.

Baker, W.L. 1994. Restoration of Landscape Structure Altered by Fire Suppression. *Conservation Biology.* 8:763-769.

Baker, W.L. and Y. Cai. 1992. The r.le programs for multiscale analysis of landscape structure using the GRASS geographical information system. *Landscape Ecology.* 7:291-302.

Baker, W.L., S.L. Egbert, and G.F. Frazier. 1991. A spatial model for studying the effects of climatic change on the structure of landscapes subject to large disturbances. *Ecological Modelling.* 56:109-125.

Bastedo, J.D. 1986. *An ABC resource survey method for environmentally significant areas with special reference to biotic surveys in Canada's north.* Waterloo: Department of Geography, University of Waterloo.

Beaver, A. 1997. *Fire Behaviour Case Study: Haines Junction Fire HJ-03-97.* Yukon Forest Protection Program.

Bergeron, Y., P.J.H. Richard, C. Carcaillet, S. Gauthier, M. Flannigan, and Y.T. Prairie. 1998. Variability in fire frequency and forest composition in Canada's southeastern boreal forest: a challenge for sustainable forest management. *Conservation Ecology* [online] 2(2): Internet (URL): http://www.consecol.org/vol2/iss2/art6.

Berryman, A.A. 1986. *Forest Insects: Principles and Practice of Population Management.* New York: Plenum Press.

Billings, W.D. and L.C. Bliss. 1959. An alpine snowbank environment and its effects on vegetation, plant development, and productivity. *Ecology.* 40:388-397.

Brockhaus, J.A., S. Khorram, R. Bruck, and M.V. Campbell. 1993. Characterization of Defoliation Conditions Within a Boreal Montane Forest Ecosystem. Geocarto International. 8(1):35-42.

Christensen, N.L., J.K Agee, P.F. Brussard, J. Hughes, D.H Knight, G.W. Minshall, J.M. Peek, S.J. Pyne, F.J Swanson, J.W. Thomas, S. Wells, S.E. Williams, and H.A Wright. 1989. Interpreting the Yellowstone fires of 1988. *Bioscience.* 39:678-685.

Clague, J.J. 1979a. *An assessment of some possible flood hazards in Shakwak Valley, Yukon Territory.* Geological Survey of Canada, Paper 79-1B: 63-70.

Clague, J.J. 1979b. *The Denali Fault System in Southwest Yukon Territory - A Geologic Hazard.* Geological Survey of Canada, Paper 79-1A: 169-178.

Crown Forests Sustainability Act. 1994. Ontario Statute.

Cullinan, V.I. and J.M. Thomas. 1992. A comparison of quantitative methods for examining landscape pattern and scale. *Landscape Ecology*. 7:211-227.

Davidson, D.A. 1992. *The Evaluation of Land Resources*. Essex: Longman.

Delcourt, P.A. and H.R. Delcourt. 1983. Dynamic plant ecology: the spectrum of vegetational change in space and time. *Quaternary Science Reviews*. 1:153-175.

Delcourt, P.A. and H.R. Delcourt. 1987. *Long-term forest dynamics of the temperate zone: a case study of late-quaternary forests in eastern North America.* New York: Springer-Verlag.

Denslow, J.S. 1985. Disturbance-mediated coexistence of species. In: Pickett, S.T.A. and P.S. White. Eds. *The Ecology of Natural Disturbance and Patch Dynamics*. Toronto: Academic Press.

Dillworth, M.E., J.L. Whistler, and J.W. Merchant. 1994. Measuring landscape structure using geographic and geometric windows. *Photogrammetric Engineering and Remote Sensing*. 60:1215-1224.

Division of Forestry. 1998. *Kenai Peninsula spruce beetle epidemic fire danger/behaviour status report.* State of Alaska, Department of Natural Resources.

Dobson, Jerome E. 1993. The Geographic Revolution: A Retrospective on the Age of Automated Geography. *Professional Geographer*. 45:431-439.

Douglas, George W. 1974. Montane zone vegetation of the Alsek River region, southwestern Yukon. *Canadian Journal of Botany*. 52:2505-2532.

Ekstrand, S. 1994. Assessment of Forest Damage with Landsat TM: Correction for Varying Forest Stand Characteristics. *Remote Sensing of Environment*. 47:291-302.

Environment Canada, Parks. *Kluane National Park Reserve Biophysical Map Series 1:50,000. Digital vegetation layer*. MapInfo format.

Environment Canada, Parks. 1987. *Kluane National Park Resource Description and Analysis.* Winnipeg: Environment Canada, Parks, Prairie and Northern Region.

Environment Canada, Parks Service. 1990. *Kluane National Park Reserve Management Plan.* Minister of Supply and Services Canada.

Ferris, R. 1991. *History of Important Forest Pests in the Yukon Territory, 1952-1990.* FIDS Report 91-13. Victoria: Canadian Forest Service, Pacific and Yukon Region.

Forman, R.T.T. and M. Godron. 1986. *Landscape Ecology*. New York: John Wiley & Sons.

Forman, R.T.T. and P.N. Moore. 1992. Theoretical foundations for understanding boundaries in landscape mosaics. In: Hansen, Andrew J. and F. Di Castri. Eds. *Landscape Boundaries: Consequences for Biotic Diversity and Ecological Flows.* New York: Springer-Verlag.

Franklin, S.E. 1991. Satellite Remote Sensing of Mountain Geomorphic Surfaces. *Canadian Journal of Remote Sensing*. 17:218-229.

Franklin, S.E. and J.E. Moulton. 1990. Variability and Classification of Landsat Thematic Mapper Spectral Response in Southwest Yukon. *Canadian Journal of Remote Sensing*. 16:2-13.

Franklin, S.E. and B.A. Wilson. 1991. Vegetation mapping and change detection using SPOT MLA and LANDSAT imagery in Kluane National Park. *Canadian Journal of Remote Sensing*. 17:2-17.

Franklin, S.E. and B.A. Wilson. 1992. A three-stage classifier for remote sensing of mountain environments. *Photogrammetric Engineering and Remote Sensing*. 58:449-454.

Franklin, S.E., R.H. Waring, R.W. McCreight, W.B. Cohen, and M. Fiorella. 1995. Aerial and Satellite Sensor Detection and Classification of Western Spruce Budworm Defoliation in a Subalpine Forest. *Canadian Journal of Remote Sensing*. 21:299-308.

Frelich, L.E. and P.B. Reich. 1995. Spatial Patterns and Succession in a Minnesota Southern Boreal Forest. *Ecological Monographs*. 65:325-346.

Frelich, L.E. and P.B. Reich. 1998. Disturbance severity and threshold responses in the boreal forest. *Conservation Ecology* [online] 2(2):7. Internet (URL): http://www.consecol.org/vol2/iss2/art7.

Funk and Wagnalls Standard Dictionary. 1980. New York: Lippincott and Crowell.

Garbutt, R. 1994. *Forest Insect and Disease Conditions, Yukon Forest Region - 1994*. Victoria: Canadian Forest Service, Pacific and Yukon Region.

Golley, F.B. 1987. Introducing landscape ecology. *Landscape Ecology*. 1:1-3.

Greater Kluane Land Use Planning Commission. 1991. *Greater Kluane Regional Land Use Plan*. Whitehorse: Yukon Territory. Fish and Wildlife Branch. Habitat and Research Section.

Grey, J.L. and M.V. Wilson. 1990. Initial establishment of riparian vegetation after disturbance by debris flows in Oregon. *American Midland Naturalist*. 123:282-291.

Hall, F.G., D.E. Strebel, J.E. Nickeson, and S.J. Goetz. 1991. *Remote Sensing of the Environment*. 35:11-27.

Hargis, C.D., J.A. Bissonette, and J.L. David. 1998. The behaviour of landscape metrics commonly used in the study of habitat fragmentation. *Landscape Ecology*. 13:167-186.

Hawkes, B.C. 1983a. Fire history and ecology of forest ecosystems in Kluane National Park: fire management implications. In: Wein, R.W., R.R. Riewe, and I.R. Methven. Eds. *Resources and Dynamics of the Boreal Zone*. Association of Canadian Universities for Northern Studies.

Hawkes, B.C. 1983b. *Fire History and Management Study of Kluane National Park*. Winnipeg: Parks Canada, Prairie Region.

Hendee, J.C., G.H. Stankey, and R.C. Lucas. 1990. *Wilderness Management.* Golden, Colorado: North American Press.

Hess, George. 1994. Pattern and error in landscape ecology: a commentary. *Landscape Ecology.* 9:3-5.

Hills, G.A. 1959. *A ready reference to the description of the land of Ontario and its productivity.* Maple: Division of Research, Ontario Department of Lands and Forests.

Holling, C.S. 1974. Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics.* 4:1-23.

Hulsshoff, R.M. 1995. Landscape indices describing a Dutch landscape. *Landscape Ecology.* 10:101-111.

Hunter, M.L. 1990. *Wildlife, Forests, and Forestry: Principles of Managing Forests for Biological Diversity.* Englewood Cliffs, NJ: Prentice-Hall.

Ivanovici, A.M. and W.J. Wiebe. 1981. Towards a Working Definition of Stress: A Review and Critique. In: Barrett, G.W. and R. Rosenberg. Eds. *Stress Effects on Natural Ecosystems.* New York: John Wiley.

Johnson, E.A. 1992. *Fire and Vegetation Dynamics: Studies from the North American Boreal Forest.* Cambridge: Cambridge University Press.

Johnson, E.A. and S.L. Gutsell. 1994. Fire frequency models, methods and interpretations. In: Begon, M. and A.H. Fitter. *Advances in Ecological Research, 25.* Toronto: Academic Press.

Kamada, M. and N. Nakagoshi. 1996. Landscape structure and the disturbance regime at three rural regions in Hiroshima Prefecture, Japan. *Landscape Ecology.* 11:15-25.

Kartikeyan, B., K.L Majumder, and A.R. Dasgupta. 1995. An expert system for land cover classification. *IEEE Transactions on Geoscience and Remote Sensing.* 33: 58-66.

Knight, D.H. 1987. Parasites, Lightning, and the Vegetation Mosaic in Wilderness Landscapes. In: Turner, M.G. Ed. *Landscape Heterogeneity and Disturbance.* New York: Springer-Verlag.

Kupfer, J.A. 1995. Landscape ecology and biogeography. *Progress in Physical Geography.* 19:18-34.

Lafleur, P., B. Wurtele, and C. Duguay. 1997. Spatial and Temporal Variations in Surface Albedo of a Subarctic Landscape Using Surface-Based Measurements and Remote Sensing. *Arctic and Alpine Research.* 29: 261-269.

McGarigal, K. and B.J. Marks. 1994. FRAGSTATS - Spatial Analysis Program for Quantifying Landscape Structure. Version 2.0.

McGarigal, K. and W.C. McComb. 1995. Relationships between landscape structure and breeding birds in the Oregon Coast Range. *Ecological Monographs.* 65:235-260.

Methven, I. and U. Feunekes. 1988. Fire games for park managers: exploring the effect of fire on landscape vegetation patterns. In: Moss, M.R. Ed. *Landscape Ecology and*

Management, Proceedings of the First Symposium of the Canadian Society for Landscape Ecology and Management. Montreal: Polyscience Publications.

Miller, G.T. 1990. *Living in the Environment: an introduction to environmental science. 6th Edition.* Belmont, CA: Wadsworth.

Mladenoff, D.J., M.A White, J. Pastor, and T.R. Crow. 1993. Comparing spatial pattern in unaltered old-growth and disturbed forest landscapes. *Ecological Applications.* 3:294-306.

Morrison, P.H. and F.J. Swanson. 1990. *Fire history and pattern in a Cascade Range landscape.* Gen. Tech. Rep. PNW-GTR-254. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Mushinsky, H.R. and D.J. Gibson. 1991. The Influence of Fire Periodicity on Habitat Structure. In: Bell, S.S., E.D. McCoy, and H.R. Mushinsky. *Habitat Structure: The Physical Arrangement of Objects in Space.* London: Chapman & Hall.

Musick, H.B. and H.D. Grover. 1990. Image Textural Measures as Indices of Landscape Pattern. In: Turner, M.G. and R.H. Gardner. Eds. *Quantitative Methods in Landscape Ecology.* New York: Springer-Verlag.

Naveh, Z. and A.S. Lieberman. 1994. *Landscape Ecology: theory and application.* Second Edition. New York: Springer-Verlag.

O'Neill, R.V., J.R. Krummel, R.H. Gardner, G. Sugihara, B. Jackson, D.L. DeAngelis, B.T. Milne, M.G. Turner, B. Zygmunt, S.W. Christensen, V.H. Dale, and R.L. Graham. 1988. Indices of Landscape pattern. *Landscape Ecology.* 1:153-162.

Oswald, E.T. and B.N. Brown. 1990. *Vegetation Establishment During 5 Years Following Wildfire in Northern British Columbia and Southern Yukon Territory.* Victoria: Pacific Forestry Centre, Forestry Canada. Information Report BC-X-320.

PCI EASI/PACE Users Manual. Version 6.0

Pearson, S.M. 1994. Ecological Perspective: Understanding the impacts of forest fragmentation. In: Sample, V.A. Ed. *Remote Sensing and GIS in Ecosystem Management.* Washington, D.C.: Island Press.

Raven, P.H., R.F. Evert, and S.E Eichhorn. 1992. *Biology of Plants.* 5th Edition. New York: Worth Publishers.

Richards, John A. 1993. *Remote Sensing Digital Image Analysis.* Second Edition. New York: Springer-Verlag.

Riitters, K.H., R.V. O'Neill, C.T. Hunsaker, J.D. Wickham, D.H. Yankee, S.P. Timmins, K.B. Jones and B.L. Jackson. 1995. A factor analysis of landscape pattern and structure metrics. *Landscape Ecology.* 10:23-29.

Ripple, W.J., G.A. Bradshaw, and T.A. Spies. 1991. Measuring forest landscape patterns in the Cascade Range of Oregon, USA. *Biological Conservation.* 57:73-88.

Romme, W.H. and D.H. Knight. 1981. Fire frequency and subalpine forest succession along a topographic gradient in Wyoming. *Ecology.* 62:319-326.

Romme, W.H. 1982. Fire and landscape diversity in subalpine forests of Yellowstone National Park. *Ecological Monographs*. 52:199-221.

Rowe, J.S. 1961. The level-of-integration concept and ecology. *Ecology*. 42:420-427.

Sample, V.A. Ed. 1994. *Remote Sensing and GIS in Ecosystem Management*. Washington: Island Press.

Savaria, A. 1994. *Spruce Beetle Infestation Discussion Paper*. Whitehorse: Northern Affairs Program, Forest Management Section.

Schimel, D.S., T.G.F. Kittel, and W.J. Parton. 1991. Terrestrial biogeochemical cycles: global interactions with the atmosphere and hydrology. *Tellus*. 43AB: 188-203.

Suffling, Roger. 1988. Catastrophic disturbance and landsape diversity: the implications of fire control and climate change in subarctic forests. In: Moss, M.R. Ed. *Landscape Ecology and Management, Proceedings of the First Symposium of the Canadian Society for Landscape Ecology and Management*. Montreal: Polyscience Publications.

Theberge, J.B. 1972. *Considerations for Fire Management in Kluane National Park*. National and Historic Parks Branch. DIAND.

Theberge, J.B. 1978. Kluane National Park. In: E.B. Peterson and J.B Wright. Eds. *Northern Transitions, Volume 1*. Ottawa: Canadian Arctic Resources Committee.

Theberge, J.B. Ed. 1980. *Kluane: Pinnacle of the Yukon*. Toronto: Doubleday.

Trabaud, L. and J.F. Galtié. 1996. Effects of fire frequency on plant communities and landscape pattern in the Massif des Aspres (southern France). *Landscape Ecology*. 11: 215-224.

Troll, C. 1971. Landscape ecology (geo-ecology) and bio-ceonology - a terminology study. *Geoforum*. 8:43-46.

Turner, M.G. and R.H. Gardner. 1991. Quantitative methods in landscape ecology: an introduction. In: Turner, M.G. and R.H. Gardner. *Quantitative Methods in Landscape Ecology*. New York: Springer-Verlag.

Turner, M.G. and S.P. Bratton. 1987. Fire, grazing, and the landscape heterogeneity of a Geogia barrier island. In: Turner, M.G. Ed. *Landscape Heterogeneity and Disturbance*. New York: Springer-Verlag.

Turner, M.G. and V.H. Dale. 1991. Modelling Landscape Disturbance. In: Turner, M.G. and R.H. Gardner. Eds. *Quantitative Methods in Landscape Ecology*. New York: Springer-Verlag.

Turner, M.G., R.V. O'Neill, R.H. Gardner, and B.T. Milne. 1989. Effects of changing spatial scale on the analysis of landscape pattern. *Landscape Ecology*. 3:153-162.

Wharton, S.W. 1987. A spectral-knowledge-based approach for urban land-cover discrimination. *IEEE Transactions on Geoscience and Remote Sensing*. GE-25:272-282.

White, P.S. and S.T.A. Pickett. 1985. Natural Disturbance and Patch Dynamics: An Introduction. In: Pickett, S.T.A. and P.S. White. Eds. *The Ecology of Natural Disturbance and Patch Dynamics*. Toronto: Academic Press.

Wickham, J.D. and D.J. Norton. 1994. Mapping and analyzing landscape patterns. *Landscape Ecology.* 9:7-23.

Wurtele, B. and S. Slocombe. 1997a. *Assessment of Landsat TM Imagery for Detection of Spruce Beetle Infestation.* Report to Parks Canada. Waterloo: Cold Regions Research Centre.

Wurtele, B. and S. Slocombe. 1997b. Landscape Pattern, Disturbance, and Protected Areas: the Kluane Region, Yukon. In: In: Jonker, P., J. Vandall, L. Baschak, and D. Gauthier. Eds. *Caring for Home Place: Protected Areas and Landscape Ecology.* Saskatoon: University Press Extension & Canadian Plains Research Centre.