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**DEVELOPMENT OF A FOREST HEALTH INDEX USING HIGH-RESOLUTION
REMOTELY-SENSED MULTISPECTRAL DIGITAL IMAGERY**

by

Ian Olthof, B.Sc.

A thesis submitted to

The Faculty of Graduate Studies and Research

in partial fulfillment of

the requirements for the degree of

Master of Arts

Department of Geography

Carleton University

Ottawa, Ontario

August, 1999

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acceptance of this thesis**

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REMOTELY-SENSED MULTI-SPECTRAL DIGITAL IMAGERY”**

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**in partial fulfillment of the requirements for
the degree of Master of Arts**

Chair, Department of Geography

Thesis Supervisor

Carleton University

August 1999

Abstract – This research was conducted at an abandoned acid mine site near Timmins, Ontario, to determine if forest health is affected by adjacent tailings and to determine if the variation in forest health can be modeled with high-resolution multi-spectral digital imagery. Eighty-four plots were sampled to obtain sets of soil, forest structure and image variables. The objectives of this thesis were 1. to examine the spatial distribution of soil, forest structure and image variables to determine the integrated effect of mine site stress conditions on forest health as a function of distance from the contaminant source, 2. to conduct a multivariate analysis between the sets of variables to determine a) if changes in forest structure are dependent upon soil properties, and b) if image variables are related to the observed variation in forest structure and 3. to develop an image-based forest health index from the relations between forest structure and image variables. Significant trends with increasing distance from the tailings boundary existed for soil calcium, magnesium and iron content, all forest structure variables, and some spectral and textural image variables, thus demonstrating the effects of the mine site on the adjacent study area. Relations between the sets revealed changes in forest structure associated with certain soil properties, most notably increased blowdown was associated with coarse-textured soils. From relations between forest structure and image variables, an image-based forest health index was developed that explained 34% of the variance in three health-related forest structure components.

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1 INTRODUCTION

Forest health is becoming an increasingly important concept in forest management for both ecological monitoring and wood production. From an ecological perspective, forests play a vital role in global ecosystem health and maintenance. They capture energy and fix carbon from the atmosphere, producing carbohydrates in plant tissue, which are the source of energy for all trophic levels of the food chain. Forest plants help stabilize soil and play an important role in the filtration of soil and ground water. They also produce oxygen, which is essential for respiration of all living things.

From a utilitarian perspective, forests provide products for human consumption, from lumber and fiber to medicine and food. Forests also provide jobs; the economic sector is one of the largest in Canada. Forests cover 45% of Canada's landmass, 56% of which are capable of growing commercial tree species. There are roughly 340 communities in Canada that are dependent upon the forestry industry, employing 1 in 16 people directly or indirectly (an estimated 842 000 jobs) (Natural Resources Canada, 1997).

Monitoring of forest health is a necessary part of forest management to ensure the continuity of forest ecosystems, their environments and the economic benefits that they bring to communities across Canada. Forest continuity implies that forest productivity and diversity be maintained through a variety of natural and human disturbances at pre-disturbance levels (MNR, 1997). Continuity can only occur in a healthy forest where productivity and regeneration occur at natural levels.

A healthy forest occupies land that will provide the necessary resources to guarantee its continuity. Any change beyond the range of resources that the land naturally provides over time may diminish the health status of the forest and possibly lead to changes in composition and structure. Soil, water and air can all be altered through natural and human-induced disturbance. These disturbances alter the environment, resulting in stressful conditions to plants growing there. A healthy forest has a resilience to cope with a certain amount of stress from natural and unnatural disturbances- including fire, insect attacks, disease, pollution and other human activity (MNR, 1997).

Natural disturbances are a part of the cycle of death and renewal that present the opportunity for regeneration. These disturbances ensure the continuity and diversity of forest systems. A healthy and diverse ecosystem is more resilient and better able to respond to and recover from changes in the environment (Natural Resources Canada, 1994). Therefore, natural disturbances by themselves are an essential part of the maintenance of healthy forest ecosystems. However, if forest resilience is diminished by human-induced changes in the forest environment, then natural disturbance can accelerate the decline of the forest system by stressing it further. Though forest systems are in a constant state of flux through cycles of disturbance, forest decline is considered permanent, and is the result of the inability of forest systems to cope with the level of stress that they are subject to (MNR, 1997).

1.1 Scale of forest health assessment

Forest health may be assessed at the level of the tree, the forest stand or the entire forest ecosystem (MNR, 1997). The death of a single tree does not imply that the forest system is declining; rather it is more likely a symptom of the cycle of renewal. The distinction between declining forest health and natural disturbance is an important one, and the difference is sometimes difficult to reconcile, since symptoms of both often appear quite similar. For this reason, forest health has been defined by forest managers at the USDA Forest Service in a broader sense as *'A condition wherein a forest has the capacity across the landscape for renewal, for recovery from a wide range of disturbances, and for retention of its ecological resiliency while meeting current and future needs of people for desired levels of values, uses, products and services'* (Twery and Gottschalk, 1996).

To date, the most common indicator of forest health has been the health of individual trees (e.g. Innes, 1993, Mohammed *et al.*, 1997), particularly crown health including foliage and branches. This is because of the relative importance of trees in forest ecosystems in terms of biomass, their significant role in energy capture and water exchange in forest ecosystems, and their commercial importance. Remote sensing, including aerial photography, can provide critical forest health information for monitoring and mapping at a variety of scales from local to global. It allows forest managers to collect this information from above, with images dominated by tree crowns. Therefore, when assessing forest health with remote sensing technologies, canopy condition is measured as a surrogate for forest health (Stone, 1998).

1.2 Spatial resolution of remotely-sensed forest imagery

Imagery with coarse spatial resolution that is less than the individual crown (2-30m) is generally limited in its usefulness to model stand structure since each pixel may image multiple tree crowns and pixels may straddle major boundaries between stands or sites (Chen and Cihlar, 1996; Wulder *et al.*, 1996). Finer resolution data are necessary to capture both within-crown and within-canopy spatial information. Satellite data with 1m spatial resolution may soon become available to forest managers for mapping and monitoring forest structure, and the advantages of using this fine resolution data to assess and monitor forest structure are numerous.

First, the use of fine resolution data allows the incorporation of spatial information into the estimation of forest structure. In this thesis, the spatial association of pixels at the canopy and crown level is shown to be complementary to spectral information for the estimation of forest structure. Second, estimations of forest structure from these data will be less sensitive to the corrections that are necessary to obtain actual reflectance. Measures of spatial association (texture) consider the digital value of pixels relative to each other in a specified distance and direction, usually on the order of a few meters in fine resolution imagery. Because spatial association considers relative, not absolute reflectance, estimates of forest structure that are based upon spatial information will be less sensitive to spectral variation across an image frame. But for temporal monitoring, some form of reference must be established, either relative (a given state at a given time), or absolute (reflectance or radiance). This research program and others have shown the potential for the

incorporation of spatial information at fine, sub 2m resolution for the estimation of forest structure (King, 1997; Wulder *et al.*, 1996). In this thesis, spatial information will be used to estimate forest structural variation related to forest health adjacent to an abandoned mine site.

1.3 Recent applications of remote sensing for monitoring forest health

Several studies have been conducted for mapping and monitoring of forest damage using medium resolution (10-30m) satellite sensors. The causes of damage are varied, and include air pollution and soil acidification in the Czech Republic (Ardo *et al.*, 1997), stands damaged by balsam wooly adelgid in western Newfoundland (Bowers *et al.*, 1994) and spruce budworm defoliation in western Newfoundland (Franklin and Raske, 1994).

Ardo *et al.* (1997) used bi-temporal Landsat TM data and a neural net per-pixel classifier to obtain 78% overall accuracy for three damage classes and 114 cases. Bowers *et al.* (1994) used spectral information from panchromatic SPOT data, as well as the sill, nugget and range of semi-variograms in a regression equation to obtain 96% of variance explained for 4 damage classes and 14 stands. Franklin and Raske (1994) used a normalized difference vegetation index (NDVI) and chromaticity index in a discriminant function with SPOT imagery to obtain 66% overall accuracy for predicting four damage classes and 56 cases. The authors added that stratification of the 56 samples using forest inventory data improved accuracies to 90-100% in certain strata. Other statistically significant relationships between forest damage and the visible (Ekstrand 1993; Lambert *et*

al. 1995) and near infrared (NIR) (Ekstrand, 1993; Brockhaus *et al.* 1992) have also been reported.

A number of studies have been conducted on the potential of high spectral and spatial resolution airborne sensors for monitoring forest damage. Studies by Gates *et al.* (1965), Collins (1978, 1983), Horler *et al.* (1980), Singhroy *et al.* (1986, 1995) and Curran *et al.* (1998) have shown that vegetation stress from geochemical anomalies produces changes in the spectral response of vegetation. These changes have been observed primarily in the spectral region between 690 and 740nm in the visible to NIR, referred to as the red edge, (Curran *et al.*, 1998) and at the green reflectance peak near 570nm (Singhroy, 1995). A decrease in chlorophyll concentration resulting from stress will produce a change in the spectral response of plants by decreasing the slope of the red edge and shifting the inflection point, resulting in a shift of the red edge towards longer wavelengths (Curran *et al.*, 1998). Others have reported a shift in the red edge toward shorter wavelengths (Rock, 1988).

Few studies have incorporated spatial information from high-resolution imagery into the estimation of forest health. Yuan *et al.* (1991) used a principal component transform of spectral information and first and second-order texture measures from individual crowns to predict interpreted photo decline of sugar maple trees. A combination of spectral (PC2) and spatial information (second-order contrast texture) explained 73% of the variance in the photo decline index for 78 sampled trees. Lévesque and King (1999) evaluated image semivariance for the estimation of forest structure and health symptoms related to acid

drainage conditions at the study site of this research. Semivariogram range, sill and nugget from three spatial resolution images (0.25, 0.5 and 1m) were correlated against measures of crown and canopy structure as well as damage symptoms. Both 0.5 and 1m pixel semivariograms were sensitive to average tree height and symptoms of damage across the canopy. Individual tree crown openness was modeled well with the 0.25m pixel semivariogram parameters. Franklin *et al.* (1995) calculated second-order texture from videographic imagery and obtained 78% accuracy for four defoliation classes and 21 plots. They compared this result with results obtained by classifying Landsat TM data over the same area, obtaining 67% accuracy with an unsupervised k-means classifier, 75% accuracy for four damage classes and 86% accuracy for three damage classes using multi-temporal TM image data between 1993 and 1994.

Other forest health-related work using high-resolution digital imagery includes that conducted by Hosking (1994) who evaluated the use of colour airborne video for forest damage assessment in New Zealand. A number of different forest types, flying conditions and image resolutions were evaluated in a visual estimation of damage classes. It was concluded that visual interpretation of airborne video is well suited to a coarse classification of forest damage into a few classes. Stone *et al.* (1998) are currently investigating the potential of airborne videography for forest health mapping in State Forests of New South Wales, Australia. Preliminary results show promise for the use of spectral and spatial information in predicting damage resulting from bell miner activity, a bird whose nesting creates psyllid overload and subsequent dieback of native Australian forests (Stone, 1996).

1.4 The approach of this thesis

Airphoto interpretation for applications in forestry is routinely conducted for timber management, maintenance and improvement of existing forest stands, and fire. Interpreters make use of shape, size, pattern, tone, texture, shadow, site and association in conjunction with ground-based measurements to process raw photographic data into usable information. In order to obtain estimates of timber yield, interpreters extract photo measurements that are statistically related to ground measurements. The airphoto interpreter relies on multiple photo elements and prior knowledge to interpret a multitude of structural parameters that relate to timber volume. This approach is common in airphoto interpretation, but has not been applied frequently in modeling of forest condition.

Remotely sensed forest imagery is a representation of multiple conditions of the forest, each one measurable to a degree by some combination of forest structure parameters. The imagery explains some variation in forest conditions such as health (Yuan *et al.*, 1991), successional stage (Jakubauskas, 1997), productivity (Franklin *et al.*, 1997), volume (Seed and King, 1997) and species association (Gerylo *et al.*, 1998). Because forest imagery is the representation of the sum of forest structure parameters and their associated conditions, the isolation of a particular condition from the imagery is difficult. A proportion of the overall variation in image information explains forest health, while the remaining variation explains a combination of successional stage, forest productivity, volume and species association among other conditions. The isolation of a health

condition from the imagery requires ancillary data to partition out the conditions that are not of interest.

The approach of extracting multiple structural parameters related to a particular condition is making its way into machine interpretation. Research has found that individual structural parameters are very difficult to extract from digital imagery using multivariate statistical techniques. The variation that is present in the texture and tone of remotely sensed data does not necessarily explain the variation in an individual structural parameter or condition. A recent approach has been to extract information related to a particular structural parameter or condition, and then to refine the estimate with ancillary data. *Wulder et al. (1997)* have demonstrated the effectiveness of this approach in using ancillary data from forest polygon data to refine leaf area index (LAI) estimates.

The approach in this research is similar. An image-based forest health index that explains the variation in a multitude of ground-based forest structure parameters related to the condition of forest health is developed. This variation cannot be explained by a single image variable (just as the variation in forest yield cannot be explained by a single photo element), and therefore multiple image variables are used. Since forest structure is a function of forest type, age and health, relations between multiple stress factors and forest health are also investigated to determine if the observed structural changes are health-related.

1.5 Objectives

The overall goal of this thesis is to develop an image-based health index using various spectral, textural and structural image characteristics that are sensitive to variations in health-related changes in forest structure. The study site, described in detail in the next section, is a forest adjacent to a large mine tailings deposit.

Specifically, the objectives of this study are to:

1. conduct a literature analysis to determine potential symptoms of forest stress that result from soil contamination by metals and acidic drainage,
2. identify and evaluate relationships of soil composition and soil structure variables with forest structure variables that are indicative of health status,
3. analyze the spatial pattern of the forest, soil and remote sensing variables to determine if gradients with distance from the tailings' edge or other patterns are present that may indicate the mine tailings as the causal agent of forest deterioration,
4. evaluate relations between forest structure and high-resolution airborne multispectral image brightness, texture and radiometric fractions, and

5. from significant relations discovered in Objective 4, determine appropriate image variables and weightings to form an image-based forest health index.

1.6 Site Description

The Kam Kotia mine site is located near Timmins, Ontario (Figure 1.1). It was a base metal mine before it closed in the early 1970s. During the period when the mine was active, tailings were pumped into an area that was contained by dikes on all sides. They consist of fine grained, non-cohesive tailings' dust. At some point during the mining operation, tailings were pumped into the swamp east of the impounded area and the dike on the northeast side of the contained area ruptured. As a result, tailings spilled into the forest and killed all the vegetation where spillage occurred. Today, an area in excess of 350ha is completely barren of vegetation, and it is suspected that the mine site affects the health of a much larger forested area.

The study area is located at the northeastern edge of the tailings. It is a forested area bounded by creeks on all sides. The creeks drain runoff from the tailings into the Kamiskotia River, and are themselves visibly affected by the tailings. The study area is almost rectangular and is approximately 1.4 kilometers along the tailings' edge by up to 800m from the tailings' edge to the north creek. Vegetation comprises boreal tree species with alder and other boreal shrubs as ground cover. The forest is typical of the mixed boreal region of Ontario and is quite varied across the southern portion of the study area (Figure 1.2). Deciduous species such as trembling aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*) dominate the upper canopy in the north-western

Figure 1. 1 Location of study area (Walsworth, 1998)

portion of the site (at 'A' in **Figure 1.2**) with occasional jack pine (*Pinus banksiana*). The upper canopy is between 20 and 25m in height in this area. Balsam fir (*Abies balsamea*) and spruce (*Picea mariana*, *Picea glauca*) are present here in the understory, becoming progressively more dominant with jack pine in stands in the south-western portion of the site (at 'B'). The site becomes progressively wetter towards the middle portion (at 'C'), where canopy cover becomes quite sparse and is composed of mainly black spruce, balsam fir and balsam poplar with occasional white birch (*Betula papyrifera*). The canopy trees in this portion of the study site are almost all under 10m in height. The ground is covered with sphagnum moss in many areas of this middle portion of the site. The study area becomes progressively drier again towards the west. The forest here (at 'D') is primarily deciduous, and is dominated by trembling aspen and the occasional balsam poplar with white spruce and balsam fir in the understory. The canopy is consistently between 25 and 30m in height. A narrow strip of forest at the north end of the study site along the creek varies much less from east to west than the southern portion does. This strip most closely resembles the northwestern portion in terms of species composition and canopy height.

The study area is the site of ongoing research into the effects of tailings on adjacent forest structure and the measurement of forest structure related to health using high-resolution airborne digital camera imagery (King, 1995; Seed and King, 1997; Lévesque and King, 1999; Walsworth and King, 1999). The site was originally chosen because of its known severe acid mine drainage problem, its relatively simple physiographic characteristics and the distinct gradient of contamination into and around the study area. There is very little relief in the area, with a maximum difference of approximately 10m in

Kamiskotia Study Area

Figure 1.2 Broad forest types according to field data. Balsam Fir (*Abies balsamea*) – Bf, Trembling Aspen (*Populus tremuloides*) – Ta, Balsam Poplar (*Populus balsamifera*) – Bpo, Black Spruce (*Picea mariana*) – Bs, White Spruce (*Picea glauca*) - Ws

elevation across the entire study area with a gradient in the north-eastern direction (Walsworth and King, 1999). Surface water drains from the tailings into one of two creeks that bound the study area. Overland flow appeared to play a significant role in the drainage of the unimpounded tailings, as there are numerous rills. Also, a few soil cores were taken in the tailings, revealing the same clay layer that was found almost throughout the study area in the B horizon. Soil water and ground water have not been tested to determine the exact direction of flow, though it is assumed that they follow the elevation gradient from the tailings towards the north-east. Because of the low relief, the clay B horizon and the massive granitic basement that underlies the study area, vertical and horizontal soil drainage was expected to be slow, providing conditions favourable for gradual accumulation of soil metals and increased acidity.

On the unimpounded tailings, there was a great deal of undecomposed organic matter in the form of tree stems and branches that have lost their bark and dried out (Figure 1.3). Many of these stems were still standing, the stem density increasing towards the current tailings' boundary. This was likely due to two factors. First the tailings were pumped into the adjacent forest, or leaked from the impounded area, over a period of at least ten years. They also continued to spread after deposition through natural drainage processes. Thus the dead trees near the current forest-tailings boundary have died more recently and have not yet disappeared through decay. Second, decreased windspeeds near the current forest edge result in reduced blowdown of dead stems than in the more open central portion of the tailings. A similar gradient appeared to exist for ground litter as well, being likely explained by overland flow following intense rain events and snowmelt that washes

branches and other organic debris in the drainage direction. There was also an iron crust on the unimpounded tailings and other sludge and surface deposits.

In the forest downstream from the unimpounded tailings (the study area), visible signs of tree damage near the tailings' edge include discolored and undersized leaves, open and contracted crowns resulting from die-back of branches and thinned foliage towards crown edges, thin and uneven canopy and significant blowdown (Figure 1.3). The likely causes of these symptoms of stress were direct toxicity from acid mine drainage and airborne deposition of pollutants, especially from the impounded area due to the fine texture of the tailings. It appears that the micro-climate has been altered as well. Research to determine the temperature and evapo-transpiration effects has not yet been conducted. However, the large clearing that is occupied by the tailings allows winds to blow directly into the study area with little obstruction. As well, the tailings themselves, particularly in the unimpounded area, were quite dark due to the iron oxides deposited at the surface. These surfaces must create a great deal of convection on warm days, increasing windspeeds and the air temperature flowing into the study area further.

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Figure 1.3 Field pictures from the Kam Kotia study area:
 1. Unimpounded tailings with undecomposed organic debris, 2. Blowdown in coniferous stand
 3. Sparse mixed canopy, 4. Impounded tailings
 5. North Creek, 6. Contracted Aspen crown

2 THE EFFECTS OF MINE SITE CONDITIONS ON FOREST HEALTH

2.1 Introduction

The effect of past mining activity has had a huge impact on our environment. The waste rock and mine tailings that have accumulated from the extraction process have resulted in what Environment Canada (1992) has called the most serious problem associated with metal and uranium mining in this country.

At present, there are over 100,000 abandoned mine sites in Canada and the United States (Singhroy, 1994). In Canada alone, the mining industry produces more than 500 million tonnes of waste rock and tailings each year, the vast majority of which are from sulphide ore operations. The accumulation of sulphide tailings and waste rock at these sites has resulted in the generation of continuous acid mine drainage (AMD) due to the oxidation of pyrite and other sulphides in tailings piles. It was estimated that some 14 000 hectares of acid generating waste rock and tailings existed in Canada in 1987, the majority of which were previously forested land. These affected areas have since become completely denuded of vegetation. It has been demonstrated that if left unchecked, tailings have the potential to migrate by wind and water and affect a progressively larger forested area (Walsworth and King, 1999).

The objective of this chapter is to describe the processes that govern the distribution of soil metals in forest ecosystems and their effects on tree health. An initial hypothesis of the research was that soil contamination from acid mine drainage is a major causal factor

of forest degradation in the study area. This literature analysis was therefore conducted to provide critical information and justification for the selection of soil and forest structure variables used in the research. Factors that contribute to the availability of metals to plants are considered, because of the well documented toxic effects of metals on plants and their environments (Milton *et al.*, 1989; Jokela *et al.*, 1990). Although our understanding of the mechanisms involved in the generation, transportation and effects of heavy metals on our ecosystem has improved immensely since this problem first became widely recognised, much is still unknown.

The problems that researchers have encountered while trying to study such a complex process as acid mine drainage and its effects on ecosystems are numerous. First, the process of pyrite oxidation is complex in itself. The rate and amount of sulphide oxidation that takes place is a function of a number of soil properties, each one contributing to feedback mechanisms that will increase or decrease the subsequent rate of oxidation (Paine, 1987). Second, the drainage basin must be considered, since it incorporates the mechanisms governing the flow of water that will dictate where, how much and in what form metals will be deposited or taken up by plants (Anderson, undated). The mechanisms of water movement in drainage basins have only recently become better understood since hydrologists have employed the use of isotopes to trace the path of water. Third, the effects of metals on the plants themselves are complex and highly variable, depending on a number of site characteristics as well as species and genotype (Page *et al.*, 1981).

The measurement of the effects on forest health is likewise ambiguous. Some researchers

have attempted to determine the effects of metal toxicity on plants as a function of growth rate or survivorship. Others have related metal concentrations in soils to concentrations in various plant tissues, and others still have measured plant stress by changes in spectral reflectance of leaves or changes in forest structure. The field measurements of many of these parameters related to forest health are difficult or expensive to obtain, and some have provided researchers with inconclusive results about the effects of metals on plants. All of the processes that affect metal distribution and availability to plants operate in conjunction with one another to create the extremely complex process of acid mine drainage and its effects on forest health.

Not all metals are toxic to plants. Many are required by plants for their maintenance and functioning. Because they are required in such small amounts, they are referred to as micronutrients by plant biologists. Background levels of metals in soils exist because of the weathering of parent materials that contain trace amounts of these metals (Page *et al.*, 1981). In most natural environments levels of metals are typically non-toxic; they are necessary for proper plant growth and maintenance. Only when other sources of metals are introduced into the environment (most often from processes associated with mining activities) do metals become toxic to plants. In order to understand the effects of metals on forest ecosystems, an attempt must first be made to understand some of the processes that govern the distribution and availability of metals in soils. This is because soil is a known sink of metals, generally containing more than 90% of metals in forest ecosystems (Keller and Vedy, 1992).

2.2 Soil Processes

2.2.1 *Metals in soils*

The form in which metals occur in soils dictates their availability to plants and their ability to cause plant stress. Metals occur in soils in four different forms. The first is in exchangeable form, whereby metals bind to exchange sites on soil solids (micelles) and which become available to plants only when these metal cations leave the exchange sites and enter into solution. The second form of metals occurs as elements bound by the soil's organic matter. These organic compounds generally occur in soil solution as uncharged molecules. Consequently, metals in this second form are not immediately available to plants and will only become available if the organic compound dissociates. The third form that metals may assume in soils is in association with carbonates and with oxides of iron and manganese. These forms are less available to plants than either the exchangeable forms or the organically bound forms, especially if the soils do not become too acidic. The fourth association of metals is referred to as the residual form, where metals are commonly found in sulphide compounds that are insoluble and therefore less available to plants than any of the other forms (Brady and Weil, 1996). This form will become available if the sulphide oxidizes, and will generate acid drainage when oxidation occurs.

The exchangeable or adsorbed forms of metals may only amount to two percent of the total amount of metals that occur in a neutral soil containing high levels of metals. As exchangeable cations are leached from the soil or are taken up by plants, others, which are bound by organic matter, are released into soil solution to maintain equilibrium. The

rate at which this occurs and the amount of metals that are released by the soil's organic matter depend upon several soil properties, the most important of which is soil acidity.

The amounts of metals and acidity that occur in soil solution at any given time are a function of the state of equilibrium of the dissociation reaction. Many of the reactions occurring in soils are reversible i.e. reactants can be reformed from the products of the reaction. For example, the dissociation of calcite into a carbonate and calcium is a reversible reaction, and the direction that the reaction takes is largely governed by the number of hydrogen ions present in the soil solution (Ward and Robinson, 1990).

When hydrogen atoms are present in large concentrations, as they are in acid drainage, then the reaction proceeds to dissociate calcite, which uses hydrogen atoms in the reaction. Thus the net effect of the presence of calcite is the buffering of soil acidity.

2.2.2 Soil acidity

Soil acidity is the most important factor governing the availability of soil metals to plants (Brady and Weil, 1996). Therefore, soil properties that affect the bio-availability of metals require knowledge of the factors affecting the rate and the amount of acid generation. Increasing soil acidity increases metal solubility and consequently more metals occur in soil solution in an acidic soil than they do in a neutral or alkaline soil of similar metal content. Metals in soluble form can be taken up by plants to produce toxic effects in the vegetation.

Acid generation occurs as a result of the oxidation of sulphide ores that are commonly found in tailings, the main waste product of base metal mining. Pyrite, which is an iron sulphide, will be considered to illustrate how acid generation occurs. A series of chemical reactions take place, producing two moles of sulphuric acid for every mole of pyrite. These reactions occur either chemically or biologically and their rates of reaction are governed by several factors including temperature, oxygen and carbon dioxide concentrations in the soil, the nutrient status and the moisture of the soil, the concentration of inhibitors and the mass and surface area of the sulphides in the soil (Paine, 1987).

In 1947, a chemotrophic bacterium was discovered in association with acid mine drainage. This bacterium, named *Thiobacillus*, derives all of its energy from the oxidation of sulphur compounds and all carbon from carbon dioxide. The genus *Thiobacillus* was described by Beijerinck in 1904 (Page *et al.*, 1981) as small (0.5 by 1.3 μm), gram-negative, generally motile, rod-shaped bacteria which inhabit a wide variety of marine, freshwater and terrestrial environments. All thiobacilli are capable of autotrophic growth in simple salt media containing an oxidizable inorganic sulphur compound and carbon dioxide (Paine, 1987). Nine species of *Thiobacilli* have been discovered, one of which is most commonly found in association with acid mine drainage: *T. Ferrooxidans*. This species also exhibits a remarkable tolerance to toxic levels of those metals commonly found in mine tailings.

A series of chemical reactions involving the iron sulphide mineral, pyrite, water, and

oxygen is summarized by the following two reactions where ferrous iron is oxidized both biologically and chemically producing acid mine drainage. In its simplest form, the reactions reduce to:

Then the oxidation of sulphide minerals by the ferric iron produced through bacterial oxidation produces ferrous iron, which is reused in the above equation, and acid mine drainage.

These two equations operate cyclically and are interdependent. Equation (1) is limiting to the production of acid mine drainage. Oxidation occurs more in the unsaturated zone than beneath the water table since the atmosphere is the source of oxygen required by the reaction, and oxygen diffusion is retarded in the saturated zone (Walsworth, 1998).

An understanding of the spatial distribution of metals in a drainage basin from a point source such as a tailings pond must focus upon the factors which affect the production rate and the total amount of acid drainage. These factors mainly involve soil properties that may vary at the level of the drainage basin, as well as other factors governing the rate of reactions that generally do not vary at this scale. Because the latter factors can be considered constant at this scale, they should not account for a heterogeneous distribution

of soil metals in the drainage basin. These factors include soil temperature, soil oxygen and carbon dioxide concentrations as well as soil nutrients. Many of these factors can be inferred indirectly by measuring soil moisture, for example, to estimate the amount of oxygen available for oxidation.

The most important factor that affects the rate of pyrite oxidation is soil acidity. The rate of biological oxidation by *T. ferrooxidans* is optimized at pH levels of 3-3.5. Above this pH range, the rate of biological pyrite oxidation declines steadily to a pH of about 6.0, where no measurable oxidation by *T. ferrooxidans* occurs. Chemical oxidation rates increase exponentially with increasing pH, to the point where the rate doubles for every two pH units above pH of 6.0. Under optimal field conditions, the rate of biological pyrite oxidation has been observed to be 20 times greater than the rate of chemical oxidation (Paine, 1987). Pyrite oxidation is generally about six times higher when biological processes control its rate than when chemical oxidation controls (Paine, 1987).

The rate of pyrite oxidation is also affected by the concentration of inhibitors such as organic and amino acids. These acids result from the decomposition of organic matter. The rate of organic matter decomposition is affected by acid mine drainage, since metals that are solubilized by acid drainage are toxic to most of the microfaunal and bacterial populations that are responsible for organic matter decomposition. Therefore, as soil acidity increases, decomposition slows due to the toxic effects of mobilized metals on soil microfauna. As the rate of organic matter decomposition decreases, organic and amino acids which inhibit the oxidation of pyrite and the subsequent further lowering of pH are

reduced. Thus, the net effect of pyrite oxidation increases the production of inorganic acids while inhibiting the production of organic acids due to a decreased rate of organic matter decomposition. Unusually high accumulation of undecomposed organic matter has been observed at sites affected by acid mine drainage, resulting in reduced nutrient cycling, poor aeration and low water infiltration (Keller and Vedy, 1992).

2.2.3 Buffering

When placed into a disposal area, almost all tailings have some buffering capacity. At a pH that is neutral or slightly alkaline, chemical oxidation controls the overall rate of pyrite oxidation. As pyrite oxidation proceeds, acidity within the tailings pile increases, immobilizing metals that are leached into the surrounding soils, or into the ground water. The rate of chemical oxidation is limited by the loss of ferrous ions, which precipitate rapidly from solution as an hydroxide. As the buffering capacity of the tailings is depleted and pH continues to drop, biological oxidation begins to control the rate of oxidation of sulphide minerals. The overall rate of oxidation increases rapidly, thereby reducing the pH of the tailings pond and surrounding soils further. The soils themselves become highly contaminated as metals become mobilized in solution.

Buffering of contaminated soil water occurs as it percolates through the soil profile. Iron that is present in the soil solution may precipitate as iron hydroxide. As acidity continues to increase through the profile, iron hydroxide may re-dissolve and leach into the saturated zone where oxygen is depleted. Further buffering will occur in the saturated zone,

increasing the pH of contaminated water containing sulphate and ferrous ions. Heavy metals are generally not present in large amounts as a solute in the saturated zone due to the near neutral pH of ground water. When contaminated soil water surfaces into an oxidizing environment, sulphates will quickly oxidize producing acidic conditions. As contaminated waters are finally buffered to near neutral levels, ferric hydroxides will precipitate forming gypsum and iron sludges which are commonly associated with acid drainage (Englund, 1983).

The weathering of bedrock largely determines the buffering of soil water as it moves through a catchment. Most of the boreal forest is situated in the Canadian Shield. The underlying geology of the Canadian Shield originated from massive igneous intrusions that underwent intense deformational episodes in Precambrian time (Press and Siever, 1986). This has resulted in basements dominated by granites and high-grade metamorphic rocks such as gneiss. The weathering of such rocks must be considered to fully understand the biogeochemical cycling of elements through the basin. Silicic igneous rocks are composed primarily of orthoclase and plagioclase feldspars, which together usually make up between 40 - 60% of these rocks by volume, while the remaining 40 - 60% consists of quartz, biotite and amphibole. Weathering of these minerals occurs at different rates, and has different effects on the chemical composition of the water flowing through them (Press and Siever, 1986).

In temperate regions, granite is considered to be one of the most permanent rocks, seemingly unaffected by natural weathering. However, in more tropical regions, the weathering of granites can be quite intense, as the interlocking matrix of feldspars holding

the rock together dissolves. The weathering of granites leaves behind quartz crystals since the rate of weathering of quartz is much slower than that of feldspar. Water is essential for weathering to take place. The bipolar nature of the water molecule tends to pull ions from the surface of solid materials which dissolves the mineral. The weathering process becomes much more intense when hydrogen atoms are in solution. The single positive charge on the hydrogen atom pulls ions from mineral surfaces in much the same way as water molecules, only at a much faster rate since the positive charge on a single hydrogen atom is much greater than the charge on a bipolar water molecule. Therefore, as the acidity of the water solution increases, the rate of weathering of the feldspars in the granite increases (Ward and Robinson, 1990).

The products of the reaction of the weathering of feldspars are solid kaolinite, dissolved silica and potassium sulphide or potassium chloride, depending on whether the acid that dissolved the feldspar was hydrochloric or sulphuric acid. Kaolinite is a clay mineral composed of aluminum, silicon, oxygen and hydroxyl ions (Press and Siever, 1986). Water is used in the reaction as it is absorbed into the kaolinite structure. Hydrogen ion is also used in the reaction. As a result, the solution becomes more basic as the reaction proceeds. The net effect of the weathering process of granites is to buffer the soil solution. An increase in the alkalinity of the soil solution immobilizes metal cations by either forming insoluble compounds, or by the binding of cations to charge sites on micelles that were previously occupied by hydrogen cations (Press and Siever, 1986).

2.2.4 Contaminant movement through the catchment

The distribution of the resulting contaminant seepage from mine tailings is not only a function of soil properties that govern the rate and the amount of pyrite oxidation, but also the hydrology of the catchment area. An understanding of the changes in water quality as it moves through a catchment area requires knowledge of processes that are occurring in the soil. A thorough knowledge of the physical properties of the soil, so that the pathways of soil water movement and residence times can be estimated, is of utmost importance, as is knowledge of the chemical processes that are occurring within the soil itself. The movement of water from the surface through the unsaturated zone to the ground water must be understood as well as the chemical inputs and outputs at all of the soil horizons.

In order to understand the biochemical cycling in a drainage basin, the flux for the entire drainage basin must be partitioned into fluxes of the individual basin components. Soil texture and underlying parent material as well as vegetative inputs contribute to the chemical composition of the outflow. A coarse textured soil having many macropores or root channels never reaches equilibrium with the soil water, as is usually the case in the upper horizons of soils. As soil water percolates towards the water table, texture generally becomes finer, and fewer macropores result in lower soil conductivity. In fact, chemical equilibrium is seldom achieved in the ground water zone, but is more likely to be attained in aquifer systems due to the rate of movement and the higher residence times that occur there. Therefore, the mineralogical composition of these aquifer layers becomes more

important for the determination of the chemical composition of the outflow (Andersson, undated).

Soil texture is one of several factors that influence soil water residence times, and therefore the likelihood of soil water achieving equilibrium with its surroundings.

Topography also plays a role, affecting water potential and residence times. Granitic basements are often massive and unfractured. When these basements are flat and overlying soils are thin, then the ecology of the drainage basin is particularly affected by acid drainage (Englund, 1983).

2.2.5 Factors affecting the availability of metals to plants

A basic explanation of the factors that govern the production and spatial distribution of acid mine drainage and the resulting mobility and transport of metals through a drainage basin have been considered. The effect that these processes can have on the spatial distribution and the availability of metals to plants is extremely complex. A single soil parameter, such as texture, can have numerous effects upon the chemical composition of the soil water as well as its availability to plants. Soil texture governs the rate of acid generation by controlling the speed of soil water movement, by dictating the amount of surface area where the reaction takes place and by limiting the amount of oxygen (Brady and Weil, 1996). The rate of acid generation will have an effect on the pH at a given location, since the rate of acid generation, the rate of acid removal and the rate of buffering will determine soil pH. Soil texture is also the largest single factor affecting soil

conductivity, governing not only the residence time of water in various components of a drainage basin, but also the translocation of water from one component to another (Brady and Weil, 1996). The numerous effects of soil texture on the generation and the distribution of acid mine drainage cannot be considered in isolation of the effects of other soil properties.

Organic matter, base saturation and the concentration of various ions can also affect acid generation and distribution in similarly complex ways. The spatial distribution of acid within a catchment governs both the location and the fraction of soil metals in different forms. These soil properties, as well as the concentration of metals in exchangeable form affect the plants that grow on them in various ways depending on plant species, the nutrient status of the soil and other factors. The explanations of mechanisms affecting acid mine drainage, metal mobilities and metal availability to plants lead to an understanding of the factors that contribute to decline. However, they say nothing of the relative importance of these factors. Interactions between the various components of the soil and the catchment are complex and numerous. As a result, the net effect of a single factor that has both positive and negative feedback effects on plant stress is difficult to quantify.

2.3 Forest Structure

2.3.1 Effects of heavy metal pollution on plants

The literature on the subject of the effects of metals on plants covers a wide range of topics from the effects on crop species to the spectral response of forests. Much of this literature provides consistent observations on some of the responses of plants to metal toxicity. Literature on the subject of forest response to acid drainage is lacking, as some of the morphological responses that take place in trees have not been characterized adequately. This lack of literature is due to the difficulties associated with identifying and characterizing plant stress and its measurement. The primary difficulty in measuring forest damage is that it is difficult to separate structural changes due to stress conditions from structure due to succession or growth stage. A temporal analysis of the spatial variation in forest structure may show variations that are not consistent with successional changes.

There is far more literature on the subject of crop species' response to metal stress than on the effects of metals on forest ecosystems. This is because of the need to determine the amount of metals that are in human food since it is known that elevated levels of metals may cause health problems. A benefit of studying the response of metal stress in smaller plants, including seedlings, is the noticeable changes that take place in plant morphology almost immediately after the application of stress. These studies are usually conducted under laboratory conditions and involve the measurements of tissue concentration of metals, and morphological changes in relation to soil concentrations. The morphological

changes that have been observed include stunted growth, or what is termed dwarfism in trees, thick and stunted roots and changes in spectral response (Page *et al.*, 1981; Milton *et al.*, 1983).

Some, but not all of these symptoms have been observed in trees, though it is not necessarily because they do not exist. Rather, it is because certain measurements like root volume, for example, are nearly impossible to determine accurately for an adult tree. Other measurements such as growth rates in tree rings are difficult to extrapolate to an overall growth rate of a tree, and the detection of a change in growth rate due to stress is even more difficult to measure. The integrated effect of acid drainage on forest ecosystems has seldom been studied in a very scientific way because of some of the above mentioned problems. There are three main types of studies that have contributed to an overall understanding of the effects of acid drainage on forest health; those being: 1. the effects of metal pollution on crop species, 2. the effects of metal pollution on forest structure and spectral response and 3. the effects of mine soil properties on forest productivity.

2.3.2 Effects of metal pollution on crop species

Morphological changes that take place in crop species are worth considering here, since these have been measured in laboratory, and some of the symptoms have also been observed in trees. The effects of arsenic and selenium on soybean plants were measured by Milton *et al.* (1989). They planted seedlings in a greenhouse and dosed them when planted and weekly thereafter. The spectral reflectance of leaves and root length were recorded

weekly to observe the changes due to increasing concentrations of metals. The spectral reflectance was measured perpendicular to the leaf on a spectrophotometer at .5nm spectral resolution to detect changes in the spectral reflectance curve between 690 and 740nm. This area on the reflectance curve is known as the 'red edge', and characterizes the boundary between the absorption of red radiation by chlorophyll and the increased scattering of radiation in near infra-red wavelengths (**Figure 2.1**) (Curran, 1998).

All of the dosed plants exhibited change in their spectral reflectance along the red edge. Root length and mass were also significantly reduced in all of the dosed plants compared to the control plants. According to Milton (1989), the results obtained for the spectral measurements should be used with caution when extrapolating greenhouse results on individual plants to canopy situations imaged from remote sensing platforms. This is because the observed morphological changes alter the spectral characteristics of leaves as their attitude changes on the tree from horizontal to more vertical in stressed vegetation. Also, spectral reflectance of the canopy includes the spectral characteristics of biomass, physiognomy, and water status. In addition, reflectance of soil and rock becomes more important as the plant canopy thins and leaves droop (Milton *et al.*, 1989).

2.3.3 Effects of metal pollution on forest structure and spectral response

Most of the above-mentioned symptoms of metal stress on soybean plants have been observed in trees in the field as well. Changes in the red-edge of the reflectance curve or changes in vegetation indices of canopies have been observed and attributed to metal

Figure 2.1 Typical spectral reflectance curve for vegetation showing the location of the 'red edge' (Curran, 1998)

anomalies in the soil (Singhroy, 1995; Wagner and Howarth, 1989). Dwarfism and early senescence have also been observed in birches suffering from metal stress near Thetford Mines, Quebec (EMR Canada, undated). Though many studies on growth rates of trees under metal stress have proven to be inconclusive for some of the above-mentioned reasons, others have shown a significant decrease in basal area increment related to levels of metal stress. However, because of the lack of consistent results and the inherent variability of growth rates in trees, this method of quantifying stress is not often used for mature forests (Page *et al.*, 1981).

Seedlings and younger trees have been used extensively to determine the effects of metals on site productivity at reclaimed mine sites, which is determined to be a function of soil properties and has been related to seedling growth and survivorship (Jokela *et al.*, 1990; Gale *et al.*, 1991; Dewar and Norland, 1994; Torbet *et al.*, 1988; Burger *et al.*, 1994). Studies on the effects of metal toxicity on tree root volume were not in the literature for obvious reasons, though a decrease in above-ground biomass productivity likely occurs as a result of a decline in root function and rooting volume. Trees will decrease their rooting volume in response to water stress to reduce evapotranspiration as do smaller plants (Brady and Weil, 1996). Because soil metal contamination accompanies a reduction in the capacity of soil to retain water, some of the stress in trees observed near mine sites is likely caused by a lack of available water.

Variation in the spectral reflectance of canopies due to metal stress has been observed in a number of studies using remote sensing and a number of different sensors. The Geological

Survey of Canada used multitemporal Landsat imagery for their geobotanical study near Thetford Mine, Quebec (EMR Canada, undated). They found that spectral reflectance classes corresponded more to the species composition of the stand than to variation in stress. They did observe a tonal discontinuity with boundaries that corresponded to the limits of the ultrabasic outcrops. The infra-red bands 6 (700-800nm) and 7 (800-1100nm) were particularly good at discriminating different species, and the average chlorophyll production of the observed species was directly related to the reflectance in band 7. Various tonal patterns were found to correspond to certain plant communities, and these facilitated the visual interpretation of the images where plant communities exhibited similarly low spectral reflectance. A multitemporal analysis rendered the separability between trees exhibiting different levels of stress more significant, since the spectral reflectance curves of sites located within the anomaly and those located outside changed at different rates. The differences in the absolute change and the rates of change were attributed to lower chlorophyll production in the stressed vegetation. The lower chlorophyll production caused premature leaf colour change and senescence as well as less overall greenness in the early summer.

Studies conducted to determine levels of stressed vegetation using airborne imaging spectrometers such as MEIS II (Multi-detector Electron optical Imaging Sensor developed by the Canada Centre for Remote Sensing) have been conducted by Singhroy (1995). According to Singhroy (1995), changes in the red edge reflectance of stressed vegetation can be attributed to chlorosis. A change in the spectral reflectance peak of metal stressed vegetation in the green band near 570nm has been consistently observed

(Gates *et al.*, 1965; Collins, 1978; Horler *et al.*, 1980; Collins *et al.*, 1983; Singhroy *et al.*, 1986). Changes in the wavelength of the red edge inflection point and slope have been observed, though some have reported changes towards longer wavelengths, while others have reported shifts towards shorter wavelengths. The variation in the changes of reflectance of stressed plants in relation to their background have been attributed to chlorophyll production, canopy architecture and phenology, species etc. (Singhroy, 1994).

The precise effects of individual metals on tree health have been impossible to determine because metals very seldom occur in isolation, and the conditions that must exist for metals to be available to plants are stressful themselves. In natural conditions, no single metal exists by itself, and therefore the influence of a single metal on plant health cannot be isolated. The effect of several metals has been observed in natural conditions.

Laboratory experiments have determined that the effect of several metals can be synergistic on plant health. For example, the effects of cadmium and lead have been measured on small plants, and the individual effects were not as severe as the combined effect of the two metals together (Page *et al.* 1981). Under natural conditions, cadmium is most often found in association with zinc lead and copper ores. This makes it impossible to define a threshold at which cadmium becomes toxic to trees. Another problem has been that the variation within species of metal uptake can be great, as much as 20 - 40%. This variation produces toxic effects of metals in certain genotypes while other genotypes do not exhibit the same effects at a specific level of soil metals.

The effects of certain levels of combined soil metals on plant health have been

documented. The geobotanical study of the Geological Survey of Canada (EMR Canada, undated) reported that the levels of metals observed at a geochemical anomaly were toxic to plants, specifically the levels of nickel at 2600 ppm, the levels of chromium at 2600 ppm and the observed levels of magnesium. The symptoms of such toxicity are dwarfism, chlorosis and early senescence. The symptoms of toxicity of other metals are similar to those of nickel and magnesium. Page *et al.* (1981) reported that zinc toxicity produces a retardation of growth, and stunted and chlorotic plants. They went on to state that these symptoms appear to be similar to those produced by phosphorous toxicity. Dewar *et al.* (1994) reported a decrease in biomass and percent cover of poplar seedlings planted for mine reclamation due to the toxic effects of taconite tailings. The levels of zinc, copper and cadmium that were observed were inert in relatively alkaline tailings. They did not attribute the observed toxicity to any one element, but to the levels of other metals found there such as chromium, observed at 89 ppm, lead; 158 ppm, mercury; 1.1 ppm, and nickel; 32 ppm. Increasing the compost rate of the amendment improved the biomass and stem density of poplar seedling. However, they also reported an increase in the levels of zinc, copper and cadmium with increasing application rate of compost. This was not to suggest that the increasing uptake of these metals had a positive effect on the growth of poplar seedlings, but rather that the improvement in the coarse-textured tailings' soil structure improved growth rates in spite of an increased uptake of toxic metals.

Aluminum toxicity of plants has been observed, but only under extreme acidic conditions. The average concentration of aluminum in the earth's crust is on the order of about 71 000 ppm (Bowen, 1966) making aluminum one of the most abundant elements on earth.

Under alkaline conditions, aluminum toxicity rarely occurs. However, Collier and Greenwood (1977) demonstrated that at a pH of 4.6, soluble aluminum concentrations reached 18 ppm, and before this concentration was reached, the root growth of some crop species was severely inhibited.

2.3.4 Minesoil property effects on forest productivity

Several studies relating soil properties to forest productivity have been conducted, most notably by Torbet *et al.* (1988) at reclaimed mine sites in West Virginia. Standards set by the Surface Mining Control and Reclamation Act (SMCRA) of 1977 require that mine sites be restored to pre-mining crop productivity. The criterion for evaluating site productivity is based only on tree-seedling survivorship, which is a measure of stand density and not of overall stand productivity. A site index estimates the volume of wood that a site will produce when it is ready to be harvested. Site indices were determined for seventy-eight plots ranging in size from 0.02-0.04 hectares, as well as biomass. The research was performed to determine which soil properties to control during mine site reclamation in order to maximize the volume of harvestable wood. Correlations were performed between a productivity index that considered soil pH, cation exchange capacity (CEC), phosphorous and bulk density, and above-ground productivity. Significant correlations showed that the soil properties that were selected for the productivity index had a significant bearing on the productivity of the regeneration. Above-ground productivity can also be used to estimate root growth, and therefore can be used as an

estimate of the level of soil contaminant stress on a tree, since rooting volume is diminished by stressful site conditions (Torbet *et al.*, 1988).

Another study conducted by Torbet *et al.* (1988) determined the separate effects of individual minesoil properties on tree growth to identify limiting factors. Growth performance was determined by measuring the total height and the growth rate using the terminal four-year increment of 10-year-old white pines. Soil properties that were considered were those thought to have an effect on the growth performance of young trees on reclaimed mine sites. These properties included rooting volume and depth, size fractions, pH, soil conductivity, organic matter content and extractable nitrogen, phosphorus, potassium, calcium and magnesium. Multiple regression analysis was used to determine which of the soil properties were significantly correlated to growth rate, terminal four-year increment and total height.

Their results showed that soil depth is significantly correlated to both terminal four-year increment and total height. It was concluded that rooting volume was the most significant factor controlling growth rates. Diminished rooting volume at reclaimed mine sites is due to salt and metal toxicity, which cause rooting volume to diminish either by direct toxicity of one or more elements, or which force roots to propagate in less contaminated soil horizons. A significant negative correlation was determined between soil electrical conductivity and measures of growth performance. This was attributed to the presence of high levels of salts and other cations in contaminated soil layers. The resulting high osmotic potentials in these soil layers reduce water absorption by plants, and require plants

to divert energy from growth to maintain internal osmotic potentials. This hypothesis was supported by the findings of Cummins (1965) who determined that minesoils having electrical conductivities of 3 dS/m were toxic to plants, and that plants growing on soils with CECs of 2 dS/m were adversely affected.

Abrutat *et al.* (1994) tested the effects of several reclamation amendments on the growth rates of alder. Mine wastes contribute to poor soil structure, low nutrient status due to soil acidification and subsequent leaching of nutrient cations, poor water retention and the presence of heavy metals. The application of organic matter to mine sites as a method of reclamation has proven effective in the past since organic matter improves the structure and the nutrient status of the soil. The application of solid municipal waste and other amendment application procedures were tested against biomass generation of various seedling tissues such as roots and leaves in a controlled laboratory experiment. The mine waste that was used for the experiment contained elevated levels of most toxic metals, as well as having a very low CEC, low nutrient status, high levels of pyrite and a pH near 3.7. Various amendments were tested against survivorship, and various growth properties using a method of factor analysis.

Only one of the amendments produced significant positive results for all growth properties. The application of dried sewage sludge produced significant positive effects at $P < 0.05$ for survivorship, height and all biomass measures of productivity were significant at $P < 0.005$. Some of the amendment practices produced deleterious effects on tree survivorship, especially the application of fertilizers. It was hypothesized that phosphate

would combine with aluminum or iron to produce insoluble phosphates. Phosphates combine with calcium and magnesium, which would have reduced their availability thereby lowering the buffering capacity of the soil. Also, some research has shown that phosphates displace arsenic cations on exchange sites, making it available to plants through uptake (O'Neil, 1990).

Dewar *et al.* (1994) also showed that the application of municipal solid waste is an effective method of mine site reclamation. Dewar's growth experiments were performed on a different type of tailings from those used by Abrutat. These tailings were basic, low in metal content, low in organic matter and in major plant nutrients such as nitrogen and phosphorus, and were coarse textured which inhibited the accumulation of organic matter and the retention of nutrients. The municipal waste that was applied contained slightly elevated metal levels. An examination of the plant tissues of poplar seedlings used in the experiment revealed low concentrations of metals in all tissues. Increasing levels of zinc and copper were detected in the seedling stems, and lead and cadmium were detected in leaves with increasing rates of compost application. Growth rates as determined by biomass of regenerating seedlings were significantly higher for the plots that had higher application rates of municipal waste, while survivorship for these plots was lower. The lower survivorship of these seedlings was attributed to increased competition from other ground cover, since survivorship is generally a function of competition. It was concluded that compost improved both the fertility and the structure of the soil. The trace metals that were present in the soils were not considered toxic at the observed levels, and did not pose a threat to vegetation health as long as the pH remained in the neutral to basic levels.

These four experiments show that growth rates and survivorship of seedlings on reclaimed tailings are adversely affected. Torbet *et al.*'s experiments revealed that soil acidity, CEC, nutrient status and bulk density were soil properties that contributed significantly to forest productivity. These findings support those by Abrutat *et al.* and Dewar *et al.*, who found that soil structure and nutrient status were significant contributors to improved forest productivity at reclaimed mine sites. The application of organic matter such as municipal sludge improves the soil structure by lowering the bulk density, and improves both the nutrient status and the CEC of the soil. The largest limiting soil factor to the productivity of seedlings appears to be soil structure and nutrient levels. Soil acidity assumes a greater importance in soil productivity when metal levels are high in the tailings.

The effects of the observed changes in soil chemistry and soil structure described in these four experiments led to a decrease in forest productivity. Decreased productivity is caused by mine site conditions, which produce direct metal toxicity to plants and other stresses due to changes that occur within the soil. Strong acids displace nutrient cations on exchange sites, which may be subsequently leached by the flushing action of precipitation. Decreased organic matter decomposition also reduces nutrient cycling and adversely affects soil structure, which may lead to soil compaction and insufficient aeration. If soil texture is such that water is able to infiltrate, then the lack of organic matter within the soil will decrease the water retention capacity of the soil. Therefore, soil metal toxicity is never the only cause of plant stress at mine sites; rather, metal toxicity occurs in conjunction with nutrient and water deficiencies. Nutrient deficiency symptoms are

described by Stern (1991) as a loss of leaf colour, yellowing of leaves, stunted growth and roots dead or dying in garden bean plants. Many of these symptoms are quite similar to those resulting from metal stress, and given the likely condition of the soil after prolonged acid drainage, it is conceivable that symptoms of metal stress, water and nutrient stress occur in conjunction with each other in forests affected by acid drainage.

2.3.5 Selected soil properties

The above studies have shown that certain soil properties affect mine site stresses on plants. These properties include CEC, organic matter content, pH, soil metal concentrations and soil texture. Some of these soil properties are highly variable in time. A study was conducted on the distribution of soil metals along a transect at the Kam Kotia mine site, and found that soil metal concentrations varied significantly at locations along the transect and between sample dates (May to August in 3 successive years) (Olthof, 1997). When trying to relate morphological changes in the forest to soil metal concentrations, this variation must be taken into account. Soil metal concentrations, which vary quite significantly from month to month, cannot be related to the structural changes in the forest that have been ongoing for at least 25 years. The spectral reflectance of deciduous leaves may relate to soil metal concentrations taken at the same time, since these leaves developed while the tree was under the stressful conditions of a particular level of metal toxicity. However, structural changes that have taken place due to the integrated effect of 25 years of acid mine drainage will likely relate better to more permanent soil properties such as soil texture.

2.4 Structural damage that results from forest stress

The literature review produced some important conclusions about the structural changes that take place as forest health is affected, and their probable causes. The review cited several studies where site health was measured by site productivity. Site health is being affected at the Kam Kotia mine site by soil metal contamination and soil structure degradation due to decreased nutrient cycling as well as numerous micro-climatic changes, and these stress factors were expected to be partly responsible for a decrease in forest productivity. Extreme cases of decreased productivity lead to the dwarfism in trees such as that observed by EMR Canada (undated) near Thetford Mines, Quebec. We have also observed these extreme cases at Kam Kotia.

In the context of forest health, damage can result from a number of different stress factors. These stress factors can be natural such as drought or pathogens, or can result from human activity such as pollution or disturbance. Increasing stress lessens tree vigour by decreasing resilience and growth. A decrease in tree vigour results in changes to tree condition or health (Innes, 1993; Ferretti, 1997). Forest damage can be assessed as a combination of forest structure parameters that measure this decrease in growth or vigour. Regardless of the stress factors, forest damage appears to be universal, and is primarily the result of a decrease in forest productivity (Leak, 1992).

Forest damage can range in scale from the individual leaf to the entire stand (Mageau *et*

al., 1995). Certain symptoms are almost immediate following the application of stress, and some are the result of long-term stress. A direct relationship exists between the scale of damage and the length of time stress has been applied; the longer the application of stress to a forest, the larger the scale of damage. The scales at which damage occur range from the individual leaf to the stand. A tree that is subject to stress will exhibit pre-visual symptoms in its leaves as leaf function breaks down. These symptoms can often only be seen in the red-to-NIR portion of the electromagnetic spectrum, as a decrease in reflectance or a shift in the red-edge (Singhroy, 1995; Wagner and Howarth, 1989). Prolonged periods of stress will produce extreme cases of leaf damage, which result in leaf discoloration due to 1) the actual damage from the stress factor, and 2) the active response by the plant to the stress factor. A tree will begin to shed leaves if foliar dysfunction is severe or prolonged. Since changes in the leaf function tend to occur soon after the onset of stress, this type of damage is most indicative of the current level of stress that the tree is subject to (Stone, 1998).

Changes in crown and canopy structure become more obvious if forest stress continues. The shedding of severely affected leaves results in a decrease in foliage density at the crown and canopy scales. If the stress continues further, a resultant response is that generally a second generation of leaves tend to be fewer and smaller. Continued stress causes defoliation to resume, arising from a shift in foliar production dynamics as the rate of leaf abscission exceeds the rate of leaf replacement over time (Stone, 1998). The branching structure of individual trees will begin to alter as defoliated branches die. As defoliation continues and severe crown dieback occurs, individual trees die and structural

changes at the scale of the canopy become more obvious. These changes occur at the stand level as numbers of standing dead and blown down stems increase. Therefore, damage to an individual tree can be placed on a continuum from moderate chlorosis to defoliation to the extreme case of death or blowdown (Curtiss and Maecher, 1991). Since changes in forest health proceed from leaf damage to the death of trees, the larger scale structural changes that occur at the level of the stand or canopy encompass all smaller scales. Therefore, stand health may be assessed using indicators at different scales from assemblages of trees to individual trees to branches and leaves (Ferretti, 1997). For example, canopy density is the sum of crown densities plus extreme cases of crown damage as dead and blowdown stems (where crown density is zero). Individual crown health is the sum of the health of the branches, and branch health is the sum of the health of the leaves and leaf density. When considering canopy health, one must also consider the health of all components at lesser scales. A complete census of the health of all components at all scales is not possible. However, sampling at scales from groups of leaves to individual trees to entire stands will give a relative measure of damage resulting from past and more recent levels of stress.

2.4.1 Methods of quantifying forest damage

There are a number of methods that exist to quantify the physiological and morphological changes that result from stress on a forest system. The measurement of forest structure parameters such as canopy openness and stem density is one method of monitoring morphological changes that take place due to stress. This method involves the

measurement of parameters that are sometimes difficult to obtain, such as leaf area index (LAI), and forest structure can be highly variable depending on tree age, water availability and site conditions. Structure also changes relatively slowly in a forest (unless subjected to catastrophic conditions such as direct tailings deposition, extreme weather, or fire), and therefore monitoring progressive forest decline as a change in forest structure requires a long temporal scale.

A second method is the measurement of changes in the spectral response of plant leaves as they exhibit chlorosis. This method characterises forest stress using quantifiable measurements that are instrument-based (Curran, 1989). The use of this method in ground surveys using hand-held spectrometers has produced consistent results. However, remotely sensed spectral response does not always relate to field-based measurements. Forest stress often causes structural changes to take place, and these structural changes cause gaps, or holes to form in the canopy. The normal horizontal attitude that leaves assume under normal conditions changes as well, as leaf droop tends to accompany chlorosis. The result is that light from the sun that is reflected by the forest often includes the spectral reflectance of the forest floor covered by litter, understory or bare soil. The contribution of these features to the pixel value often produces varied reflectances that are uncharacteristic of forests (Milton *et al.*, 1989).

A third method of measuring forest damage has been to determine the growth rate of trees that are exhibiting damage in relation to unstressed trees (Dewar *et al.*, 1994; Torbet *et al.*, 1988), since a change in forest health must accompany a change in productivity

(Ferretti, 1997). Again, this method has sometimes provided inconsistent results because of the variability of growth rates due to species, genotype, site, etc., and the capacity for some trees to grow well on contaminated sites. An accurate measurement of overall growth is also difficult to obtain for a canopy tree (Page *et al.*, 1981).

Despite the difficulty of detection and measurement of forest stress at low stress levels, both field and remote sensing methods can be applied when moderate to severe stress is present. The natural variability of the forest and the high level of precision that is required to measure low levels of stress can sometimes make symptoms difficult to detect. Severe damage resulting in structural changes at the crown-to-stand level can be reliably measured as crown contraction (measured by crown radius), crown thinning, decreased LAI, high mortality and blow-down. Symptoms of leaf discolouration can also be measured consistently using within-crown spectral samples to obtain a 'purer' pixel consisting mostly of foliage.

The extrapolation of these ground-based measurements to obtain continuous forest health information over large two-dimensional areas requires the use of some form of remote sensing. An important structural measure of health is LAI, and therefore methods of estimating LAI with remote sensing will be considered in the next chapter with particular emphasis on the use of high-resolution digital imagery and spectral, textural and structural image measures.

2.5 Conclusion

The purpose of this section was to better understand the processes that govern the distribution and availability of metals to plants at sites affected by acid drainage. The forms that metals assume within soils were considered as well as the factors affecting the amount of metals that occur in forms that are available to plants. Next, the hydrology of the drainage basin was considered, since metals travel through the soil and groundwater, and the path and residence time of water affects its final composition. The chemical composition of ground and soil water also determines the level of stress that plants growing on these soils will exhibit.

Research on the effects of metals on plant health fall under one of three categories. First, studies have been conducted at mine reclamation sites to determine the limiting soil factors to plant productivity. Second, laboratory studies have been conducted on crop species to determine the effects of individual metals on plant health. Some of the difficulties of extrapolating these results to field situations were mentioned. The methods of determining levels of tree stress are difficult. This is because it is impossible to pinpoint the exact cause of stress in field situations because of the synergistic effects of metals, and because of the degradation of soil structure that results from the intense leaching of basic cations due to acid drainage. Morphological effects of metals on plants have been studied extensively in the laboratory, and it is probably reasonable to assume that many of these effects occur in trees based on personal observations made at the Kamkotia mine site. Changes in the spectral reflectance of stressed canopies were then considered. However, these changes

are not predictable because of the changes in forest structure that accompany the changes in reflectance of leaves. In the next chapter, the potential of remote sensing for estimating LAI, an important structural health parameter, will be considered with emphasis on techniques involving high-resolution remotely sensed imagery.

3 EVALUATION OF HIGH-RESOLUTION REMOTELY-SENSED IMAGERY FOR THE ESTIMATION FOREST STAND LEAF AREA INDEX

Spectral information, primarily as a shift in red-edge reflectance, is the most common and traditional method of quantifying forest stress using remotely-sensed imagery. The use of spectral information, as a symptom of forest health, was summarized previously in this thesis. It will not be emphasized here as much as newer techniques involving the use of spatial and structural image measures from high-resolution digital multi-spectral imagery.

Based on the previous literature review, it was hypothesized that forest structure is adversely affected at the study site due to several long-term mechanical and chemical stress factors. One measure of structure that is receiving much attention in ecological and remote sensing studies is LAI. It represents vertical structure as a health indicator, and has been found to be well estimated using spectral and spatial variables in satellite and airborne remotely sensed imagery (Spanner *et al.*, 1994; Wulder *et al.*, 1996). To evaluate the utility of spatial analysis of very-high resolution imagery in estimating LAI, an initial experiment was designed. The results from this experiment were expected to indicate whether or not textural information should be included in the multivariate analysis, and which texture measures to include. This experiment was done in parallel with another which evaluated shadow components for the estimation of forest stand structure (Seed and King, 1997). Both experiments used the same imagery from a Kodak DCS 420 Colour Infra-Red (CIR) digital frame camera, and the same leaf area data from a Licor-2000 Plant Canopy Analyzer.

3.1 Potential of remote sensing for estimating LAI

Leaf Area Index is a dimensionless index used to quantify the total single sided vegetation leaf area per unit area on the ground. The determination of leaf area index is currently of great importance to earth scientists such as climatologists who wish to model energy and mass exchange by plant canopies over landscapes, and increasingly to forest managers who are investigating the usefulness of leaf area as a measure of forest structure for monitoring changes in forest productivity and forest health. Forest managers and climatologists are interested in changes in leaf area over a landscape (Chen and Cihlar, 1995). Remote sensing has proven itself to be less expensive and less time consuming than field data collection methods for estimating LAI because it enables scientists and forest managers to collect data over vast areas almost instantaneously. Depending on the scale at which leaf area is to be estimated, various methods using remote sensing have been developed.

3.1.1 Canopy radiation models

The first remote sensing approach to estimating LAI has been the application of canopy radiation models to assess the image expression of forest canopies (Wulder *et al.*, 1996). Such models consider the effects of the viewing geometry of the sensor in relation to the solar elevation to estimate the response of direct and diffuse radiation to various levels of LAI. The image expression of the optical radiation environment of forests is complex, being dependent upon a number of forest structure parameters as well as sun-sensor

geometry. For the purposes of this study, some simplifications could be made about the image expression of the optical radiation environment of the forest. At the Kam Kotia study site, stem density, basal area, canopy closure, and leaf area index varies significantly but generally remains within the middle of the range of possible values for forests of Canada. For example, for the 15 plots of this initial research, Seed and King (1997) obtained canopy closure measurements between 26% and 95%. Tree crowns generally do not overlap, so canopy closure does not reach 100% in any stand, and there are very few locations where trees are so sparsely spaced that the ground can be seen in images to be directly illuminated between crowns. Seed and King (1997) also give values of several other forest structure measures for these plots. The species composition varies from almost pure coniferous to pure deciduous with several mixed compositions in between. They are typical of the broader study area analyzed in later research of this thesis. These data formed the basis for conceptual development of the generalizations described below, while the data of this research provided verification.

For the range of forest structures at the study site, and for an oblique sun angle during image acquisition, the brightest areas in the image represent directly sunlit portions of the canopy. These bright areas generally correspond to the upper portions of crowns where LAI is high relative to surrounding, darker areas. Conversely, the darkest areas where most light is absorbed usually represent gaps or holes in the canopy where LAI is relatively low. The range between these two extremes may represent a gradient from directly illuminated crowns where LAI is highest to increasingly diffuse light where LAI becomes progressively less. An important consideration for these generalizations to hold

true is whether or not sunlit ground can be seen in the imagery for the range of stem densities and crown sizes in the imagery.

To illustrate the image expression of the most common range of stem densities and crown sizes at Kam Kotia, a set of synthetic forest images were created (Figure 3.1).

This figure shows deciduous trees represented as balls on sticks to facilitate the visualization of within-crown shadow. Conifers are also included in these images, although within-crown shadow of conifers could not be represented with the software that was used. Some assumptions are made for simplification. Crowns are completely opaque, which is probably a valid assumption for all but the lowest crown densities imaged at 50cm spatial resolution. If we are to assume that the largest crown diameter in the imagery is between 6-8m, intermediate crowns between 3-4m and small crowns between 1.5-2.5m, then the three images represent stem densities of greater than or equal to 6 stems per 10m-radius plot. This represents a low extreme of stem densities at Kam Kotia, as only 4 of the 70 plots sampled in this research had a stem density lower than 6 stems per plot.

For both the medium and high stem density cases, virtually no sunlit ground can be seen within the forested portion of the imagery. This is the range of stem densities that are most common at Kam Kotia. The absence of sunlit ground in the imagery was also confirmed through placement of 30 targets in the study area beneath large gaps to facilitate plot location in the imagery; none were visible in the imagery. In other words, for 30 sample points of the ground beneath large gaps, all of them were either blocked by canopy elements or fell in deep shadow. Therefore, it was concluded that for this study forest,

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gaps in the canopy were represented by deep shadow in the imagery and sunlit ground was not present.

To illustrate this generalized relation between elevation in the canopy (from crown apexes to gap minima) and image tone (light to dark, respectively), the medium density synthetic image and 50cm pixel green band (550nm) imagery from the study site representing medium-to-high stem densities were thresholded at equal intervals to produce binary images (Figure 3.2). The white arrow corresponds to a gap in the canopy, while the red arrow corresponds to an approximate tree apex. The synthetic imagery illustrates the effect of sun angle on the perceived location of the tree apex. Both images illustrate the two elevation extremes from gap to apex, and the corresponding tonal gradient between these two extremes. This established gradient of image tone and canopy structure was exploited in the research through the use of spectral measures of mean crown brightness and the proportion of several spectral shadow components. They were used as representations of the structure of individual crowns and the forest canopy as discussed above in development of the forest health index.

3.1.2 Spectral reflectance models

In addition to the use of canopy radiation models, a second approach for estimating LAI at the landscape scale has been through the use of spectral reflectance models (Wulder *et al.*, 1996). Spectral reflectance is related to the amount of photosynthetically active radiation that is absorbed or reflected by the canopy. The amount of radiation that is

Figure 3.2 Synthetic imagery representing the medium stem density case and Kamiskotia imagery thresholded at equal intervals to produce a series of binary images representing a gradient of tone. The location of a gap is indicated by the white arrow, while the red arrow points to approximate apex locations.

absorbed or reflected is relative to the amount of biomass that is being imaged. A denser canopy layer will absorb more radiation in the red wavelength of the electromagnetic spectrum, and reflect more in the near infrared. Vegetation indices make use of the information in the difference between the amount of red and NIR radiation that is reflected by the canopy. The amount of radiation that is absorbed or reflected in these two bands can be detected by remote sensing, and related through the use of vegetation indices to the thickness of the vegetation layer, or LAI.

There have been a number of problems associated with the estimation of LAI using spectral reflectance models. Because of its low-to-medium resolution and the absence of spatial information at the crown level, satellite imagery requires the use of the spectral reflectance model to estimate LAI. In global vegetation monitoring, satellite imagery has provided adequate LAI estimations (Nemani *et al.*, 1993). However, when estimating LAI at the landscape level, the inability of low-resolution imagery to capture the within-crown variation has limited its usefulness. When ground resolution exceeds a few meters, the pixel no longer captures information about the variation in spectral reflectance within the crown. In satellite imagery, single pixels typically represent the average reflectance of areas of 10 x 10m on the ground or more. The pixel value may be influenced by the reflectance of soil or litter beneath gaps in the canopy, or branches and trunks, especially in sparse canopies. These features can often contribute spurious reflectance to the pixel value that make the extraction of accurate LAI information impossible. In the research at this study site, and in the broader research program (King, 1997), the appropriate pixel spacing to capture within-crown structure has been determined through empirical studies

(e.g., Lévesque and King, 1999). Typically, 25-50cm pixels are required to provide reliable statistical samples and the resulting models of individual crown structure have been better than those derived from lower resolution imagery.

A second limitation of spectral reflectance models for the estimation of LAI is their dependence on species composition, topography, atmospheric and sensor effects which can make it difficult to isolate LAI information. A third limitation is the saturation of vegetation indices above leaf area indices of 3-4 (Running *et al.*, 1986). The spectral reflectance from above the canopy does not change dramatically when leaf area exceeds 3-4 per unit area on the ground. Incident radiation from above does not penetrate significantly through 3-4 leaf layers, and of the little light that does penetrate these layers, very little finds its way back towards the sensor and thus is available for measurement.

3.1.3 Potential for image texture in the estimation of LAI

The limitations of spectral reflectance models can be overcome to some extent through the incorporation of spatial information in high resolution imagery for the estimation of LAI (Wulder, 1996). Since texture is a measure of the spatial distribution of variations in tone, it possesses spatial information and therefore can be used to quantify various parameters of forest structure related to LAI. Within the range of canopy closures present in the study area, more open canopies exhibit greater brightness variation and therefore more image texture than closed crowns (see Figures 3.1 and 3.2). Image texture contains important information about the structural arrangement of surfaces and their relationship to

surrounding environment (Haralick, 1973). Variations in spectral reflectance can therefore be attributed to the physical texture of the canopy itself.

Image tone and texture are interrelated concepts that can be effectively used in visual interpretation. Image tone is dependent upon the amount of radiation that is reflected from a surface, ranging from dark to bright. Image texture can be described as the variation in brightness or tone across space, giving a visual perception of surface roughness or smoothness (Irons and Peterson, 1981). Commercial remote sensing software has only recently incorporated algorithms to make use of image texture in machine interpretation of surface features. Because a local measure of image texture surrounding a pixel requires a spatial component to capture spatial variation, some form of image sampling is required.

Image texture algorithms use a moving window as a local sample to generate image texture. A texture image is generated from the algorithm where each digital number in the texture image of coordinates (x,y) represents a local texture measure in a window surrounding a centre pixel of coordinates (x,y) in the original image. Window size may be specified to generate a very localized texture measure immediately surrounding the pixel (in the case of a 3×3 window), or a more widespread measure in the case of larger window sizes.

Texture measures may be derived from the frequency distribution of digital numbers (DN) or grey levels within the window sample, or they may be derived using spatial association of DNs. First-order texture measures fall under the former category, and consider the

statistical distribution of DNs in a window, not the spatial distribution. Examples of first-order texture measures are the standard deviation of the sample DNs, or the range measure, which considers the difference between extreme values in the window (Irons and Peterson, 1981). Second-order texture measures form another category, and use a co-occurrence matrix to tabulate the frequency of the spatial association of pixels within the window. Co-occurrence matrices are frequency tables whose entries represent the number of times that pixels of all possible DN combinations occur at a specified distance (in # of pixels) and direction (0, 45, 90, 135 degrees from horizontal to the right) from each other. Thus, they can represent both the statistical and spatial distributions of DNs in a given sample region. The co-occurrence matrix is derived for a sample window, and a texture algorithm is applied to the co-occurrence matrix to generate the texture measure for the window. Higher frequencies along, or near, the diagonal of the co-occurrence matrix represent less image texture, since these entries are proximal pixels with the similar DNs. Higher frequencies away from the diagonal, where DNs of proximal pixels differ more, represent greater image texture (Haralick, 1973) (Figure 3.3).

Equations 3-8 show the six different second-order texture measures that will be evaluated in the initial experiment investigating the potential of texture for the estimation of stand LAI. As an example explanation of the mechanism by which these measures represent

Sample 5 x 5 window

128	129	131	129	132
129	132	132	130	131
130	128	128	128	129
132	129	130	129	129
131	130	130	131	131

co-occurrence matrix (1,0), 0°					
	128	129	130	131	132
128	2	2			
129		1	1	1	2
130	1	1	1	2	
131		1	1	1	
132		1	1		1

co-occurrence matrix (0,1), 90°					
	128	129	130	131	132
128			1		2
129	3	1		1	
130	1	3	1		
131		2			2
132		1	1	1	

co-occurrence matrix (1,1), 45°					
	128	129	130	131	132
128			1	1	1
129		1			
130		1	1		2
131		2			
132	1	1		1	

co-occurrence matrix (-1,1), 135°					
	128	129	130	131	132
128		1			2
129	1		2		
130	1	1		1	1
131		2	1		
132	1	1			

Figure 3.3 Four sample directions 0° , 45° , 90° and 135° are shown at top. A 5 x 5 sample window and co-occurrence matrices for the four sample directions and distances of 1 (0° and 90°) or $\sqrt{2}$ (45° and 135°) are shown below.

image texture, the second-order contrast measure (Equation 4) will be considered. It is based upon the squared difference between sampled brightness values (i, j) multiplied by the normalized frequency of occurrence $P_{(i,j)} / R$ and summed over all sample pairs. The brightness difference between two pixels determines how far they are from the diagonal of the matrix, and consequently, the degree of image texture associated with the

$$Homogeneity = \sum_{N=0}^{Ng-1} \left(\frac{P_{(i,j)}}{1 + (i - j)^2} \right) \quad (3)$$

$$Contrast = \sum_{N=0}^{Ng-1} n^2 \left(\sum_{|i-j|=n} \left(\frac{P_{(i,j)}}{R} \right) \right) \quad (4)$$

$$Dissimilarity = \sum_{N=0}^{Ng-1} (P_{(i,j)} \times |i - j|) \quad (5)$$

$$Mean(i) = \sum_{N=0}^{Ng-1} (i \times P_{(i,j)}) \quad (6)$$

$$Variance(i) = \sum_{N=0}^{Ng-1} (P_{(i,j)} \times (i - Mean(i))^2) \quad (7)$$

$$Entropy = \sum_{N=0}^{Ng-1} (-P_{(i,j)} \times \log_e(P_{(i,j)})) \quad (8)$$

Ng = # of grey levels

i, j = grey level pair i, j

R = normalization constant

$$= \sum_{i=0}^{Ng-1} \sum_{j=0}^{Ng-1} f_{(i,j)}$$

R = total # of frequency – pairs

R = sum of frequencies in co-occurrence matrix

two pixels. The frequency of occurrence of a particular pair $P_{(i,j)}$ is normalized by a constant (R) which is dependent on both the window size, sampling direction and distance. This constant represents the total number of possible pairs, or the summation of the frequencies in the co-occurrence matrix.

The average texture within a window of a forest image represents the spatial distribution of grey levels within the forest. Figure 3.4 shows a number of simplified forest subscenes from a digital image. They correspond to plots of 10-20m on each side where LAI has been measured in the field. The subscenes may be any number of pixels in size, depending on the spatial resolution of the imagery and plot size. Texture within these subscenes is created by the mix of shadow and illuminated portions of the canopy (between trees) and within tree crowns (if resolution fine enough). The subscenes are on a gradient from low to high spectral reflectance and LAI, with the first subscene (1) falling entirely on a canopy gap, and the last (5) falling entirely on sunlit canopy. The examples are presented in binary form to simplify visualization, though one would have to imagine each of the binary cases represented by a range of grey levels in an actual forest image.

The average texture of cases 1 and 5 are low, since both of these have no tonal change within the subscenes. Case 2 represents a case of maximum texture, since each dark pixel representing a canopy gap or hole has an area of sunlit canopy directly adjacent to it. Case 3 represents an area containing a gap that is smaller than the window size, but larger than Case 2. The average texture in this case would be low, though higher than in

Figure 3.4 Hypothetical forest subscenes representing a gradient of leaf area (LAI) and explained by a combination of spectral and spatial information.

Cases 1 and 5. The reason for such a low texture measure in Case 3 is because only the pixels adjacent to the gap would represent areas of texture. The other areas, either directly in the gap, or in larger portions of sunlit canopy are areas of little or no tonal variation. Case 4 is an intermediate case between the second and third, and therefore represents a subscene of moderate texture. The average texture therefore changes from high to low to moderate for the three mid LAI subscenes. These three cases may be used to represent a gradient of mid-LAI values that can be described by a range of texture values.

Because texture represents a change in tone with respect to space, it is similar in concept (but not equivalent) to a derivative measure of slope. An average second-order texture measure within a window represents the variation in grey tones over two dimensional image space in a similar way that the average slope of a variable between two points represents the change in that variable over a given distance. It was hypothesized that the frequency distribution of texture within a subscene must possess more forest structure information than what is captured by the average texture measure. Texture variation, as measured by the standard deviation of texture, represents the average change in the variation of grey tones (texture) with respect to space in a similar way that a second derivative measures rates of change of a variable over space. Texture variation measured by one standard deviation does not take into account distance or direction, since it is based on the average deviation from the mean. A more appropriate measure of texture variation might be a second-order texture measure, which uses a window that is smaller than the entire subscene. This preliminary investigation of texture information did not account for distance or direction in the measurement of texture variation.

This preliminary research was done to see if texture and texture variation were sensitive to changes in LAI in high-resolution imagery so that these variables could be included in a multivariate analysis relating image variables to known stress-induced forest structure changes. Texture variation within a subscene can be related to the size and distribution of gaps, which are both important determinants of LAI. Considering **Figure 3.4** again, it can be seen that the moderate-LAI range is represented by a gradient in texture variation.

Cases 1 and 5 represent subscenes of no texture variation since both are equally smooth throughout. Case 2 has low texture variation as well, since all areas within the subscene are equally rough. Case 3 has some variation in texture in the subscene, since tonally smooth and areas of intermediate texture occur together. Case 4 possesses maximum texture variation since the extreme tonally rough and smooth areas occur together in this subscene. Therefore, a second gradient can be extracted from texture information within subscenes which relates to a gradient along the moderate-LAI range. The two extreme cases (1 and 5) of high and low LAI which both possess equally low texture and texture variation can be separated from one another by their respective spectral reflectances.

Therefore, a combination of spectral and textural information should adequately represent LAI over a range of values.

3.1.4 Potential of image structure for the estimation of LAI

Spectral mixture analysis has been used to estimate stand biophysical attributes by Peddle *et al.* (1995) and Seed and King (1997). Shadow fractions as a measure of image structure were found to be particularly useful in estimating effective stand leaf area in mixed species plots using high resolution digital imagery and linear regression (Seed and King, 1997).

The approach is based on the assumptions that (1) using high spatial resolution multispectral digital camera imagery capable of resolving features within individual crowns will provide additional information on within-crown structure, and (2) the spatial variability of forest structure can be treated by using the shadow fractions as surrogates for stand structure (Seed and King, 1997).

Seed and King (1997) have shown that shadow fractions in high resolution remotely sensed imagery may be used to predict stand structure. The same fifteen image subscenes of 25cm pixel spacing were used in this initial texture study and corresponded to plots where stand structure had been measured in the field. Initially, six shadow fractions were extracted from the image subscenes by thresholding at levels corresponding to approximate valleys in the histogram, with each shadow fraction corresponding to a peak in the subscene histogram. Shadow fractions were iteratively merged to produce three distinct fractions, which were found to be the optimal number in predicting stand structure by representing deep shadow, transitional shadow and light diffuse shadow. The additive combination of the three shadow fractions was determined to be particularly useful at predicting leaf area and canopy closure in mixed stands. The authors obtained a coefficient of determination of .9, with standard errors of 0.3 and 10% for effective LAI and canopy closure respectively.

Since canopy shadow is sensitive to changes in sun angle and sensor-view angle geometry, Seed and King (1997) state that shadow fractions should only be extracted for plots within 10 degrees of nadir. The location of plots in the imagery is also critical, especially in varied

forest since shadow can change significantly from location to location. Peddle *et al.* (1996) used a helicopter mounted radiometer and photography to obtain high positional accuracy for the extraction of shadow fractions over plots. Seed and King (1997) used many ground targets to ensure high positional accuracy of their 15 plots, and confined the analysis to plots within 7 degrees of nadir.

3.1.2 Parameters that can affect image texture measures

Atmospheric and sensor effects can have an influence on image sharpness and consistency, which in turn will affect how the image represents the spatial structure of the imaged objects, and thus image texture. These include atmospheric effects such as variations in path radiance, scattering and absorption and illumination / view angle variations (King, 1992). Sensor-related effects include image blur due to aircraft motion, image noise, image focus and image spatial resolution. Adjustments to the shutter speed and aperture settings, which can affect the dynamic range of the resulting image, will affect first-order texture measures. Second-order texture measures are normalized for image brightness, and are therefore less affected by brightness variations.

3.2 Study site and data acquisition for initial experiment

The effective LAI of fifteen plots along a transect in the western portion of the Kam Kotia mine site was measured in the summer of 1996 and high resolution digital camera images were taken of the forest at the same time by other researchers (Seed and King, 1997).

Each of the fifteen 20 x 20m plots had been thoroughly inventoried and Leaf Area Index estimates were made using a Licor-2000 Plant Canopy Analyzer. This instrument consists of two photoradiometers that are sensitive to blue light (<490nm) and record spectral measurements on separate data loggers. The two data loggers are synchronized, and one is placed in an opening (on the tailings) to record the above-canopy irradiance, while the other is used in the forest to measure the below-canopy irradiance. The instrument takes measurements in five concentric rings of increasing view angle, centred at 7, 22, 38, 52 and 68 degrees, with a maximum view angle of 148 degrees. The narrowest view angle is a point sample of radiation penetrating the canopy and a number of these point samples gives an estimate of canopy closure, while rings 1-3 give the best estimate of effective LAI (Welles and Norman, 1991). The instrument measures effective LAI, which is not a true measure of leaf area since it assumes a random distribution of foliage elements (Chen and Cihlar, 1995). Measurements from the two data loggers were combined in a program to calculate effective LAI and canopy closure for the five different view angles of the sensor based on the difference between above and below-canopy irradiance measurements. Effective LAI ranged from 1.2 to 5.9 for the fifteen plots. For this initial experiment, the fifteen subscenes from the digital image of .25m resolution corresponding to the plots of known LAI were obtained from Seed. The spatial resolution should have resulted in subscenes of 80 x 80 pixels, though some of the subscenes were slightly larger due to the subscene rotation that was necessary in order to be able to perform texture measures. The digital image was obtained from a Kodak DCS 420 CIR camera which generates NIR, red and green channels of 100nm bandwidth. The NIR band was selected to perform the

measures of texture because of its wide dynamic range and sharpness relative to the other two bands.

3.2.1 Extraction of Texture Information

All measures of texture were second order derived from the co-occurrence matrix of a moving window. In the software used, window size, sample distance and sample direction can be specified. The six texture measures (Equations 3-8 in Section 3.1.3) were evaluated. Derived texture channel histograms were generated to determine the texture mean and standard deviations of the texture channels, and these statistics were regressed with effective LAI. Window sizes that were tested were decided upon through previous research at the site using similar imagery and semi-variance analysis (Lévesque and King, 1999). The range of the semivariogram, the approximate distance at which spatial independence is reached, had been shown to be about 8 pixels. This distance was considered as being close to optimum and therefore texture windows from 5 x 5 to 9 x 9 were evaluated. Window sizes that are smaller than the range do not capture the image variation adequately, while window sizes that are larger than the range provide redundant information. Sampling distances from 1 to 3 pixels were evaluated and sampling direction was arbitrarily selected to the right. A perpendicular sampling direction was not considered because initial tests had shown that the image texture was not significantly different for the forest conditions of the study area. Texture subscene histograms were visually checked for normality and to ensure unimodal distributions, and subscene texture means and standard deviations were extracted.

A Pearson correlation coefficient (r) was used to evaluate the relationship between the average texture and effective LAI for each individual texture determination. The texture measure with the highest correlation coefficient was then used in conjunction with other image information to see if the relationship between image variables and effective LAI could be improved. Spectral information was extracted from the red and NIR channels and included the individual spectral band means as well as two vegetation indices; a band ratio (NIR/red) and a normalized difference vegetation index ($\text{NDVI} = (\text{NIR} - \text{red}) / (\text{NIR} + \text{red})$). Of the four spectral variables, the one having the highest correlation with effective LAI was used in subsequent regressions in conjunction with texture. Multiple regression was used to evaluate the relationship between the individual independent variables of texture mean, texture standard deviation and spectral information with the dependent variable effective LAI. The relationship between various combinations of independent variables and effective LAI were evaluated separately. These combinations included 1. texture mean and spectral measure and 2. texture mean, texture standard deviation and spectral measure. Correlation coefficients were then determined for each of the combinations with respect to effective LAI and compared with the correlation coefficients of individual independent variable to see if additional effective LAI information was provided by the average texture of subscenes and the texture variation within those subscenes.

3.3 Results and Discussion

3.3.1 Individual Texture Measures with LAI

Of the window sizes and sampling distances that were used to derive measures of texture for the 15 plots, the three that provided the highest correlation coefficients with effective LAI are shown in Table 3.1. Six of the individual texture measures produced significant relationships at the 5% level ($r > .51$), those being the contrast texture measure and the dissimilarity texture measure for the three window sizes considered. The contrast texture measure consistently had the most significant relationship with effective LAI for the three window sizes and sampling distances shown. A sampling distance of two pixels provided the best results of the distances that were tested. Since the contrast texture measure with a sampling distance of two and a window size of 7×7 provided the most significant relationship with effective LAI, it was chosen for subsequent regressions with effective LAI. In addition, the standard deviation of the contrast texture measure was significantly related to effective LAI ($r = 0.69$).

Table 3.1 Texture measure correlation coefficients (r) with effective LAI for window sizes of 5x5, 7x7 and 9x9 pixels, (n=15)			
TEXTURE	5 x 5 (2,0)	7 x 7 (2,0)	9 x 9 (2,0)
Homogeneity	-0.47	-0.48	-0.43
Contrast	0.56	0.64	0.58
Dissimilarity	0.53	0.52	0.53
Mean	0.27	0.27	0.27
Std	0.28	0.26	0.27
Entropy	0.43	0.44	0.4

3.3.2 Relationships of Individual Spectral Measures with LAI

Both the individual NIR band and the band ratio produced significant correlation coefficients at the 5% level (Table 3.2). The red channel produced the poorest relationship with effective LAI, and therefore introduced increased variability in the ratio and NDVI measurements when compared to the NIR channel alone. The individual NIR band produced the most significant correlation coefficient with effective LAI, and therefore was chosen for subsequent regressions with effective LAI. However, it is a weak relation compared to that found by Wulder *et al.* (1996) ($r = 0.82$) between NDVI and LAI using CASI data.

Table 3.2 Correlation coefficients (r) of spectral measures with effective LAI ($n=15$)				
	Red	NIR	Ratio	NDVI
r	-0.21	0.56	0.52	0.49

3.3.3 Multiple Regression of Spectral and Textural Measures with LAI

Table 3.3 shows the regression results for the best individual spectral and textural variables as given above (contrast texture mean, standard deviation of contrast texture, and NIR band mean) as well as the multiple regression results for the contrast texture mean plus NIR band mean, and these two variables with the addition of the standard

deviation of the contrast texture. The standard deviation of the contrast texture measure was introduced into this analysis based on the conceptual development presented in association with **Figure 3.4**. It is a measure of the variability of texture, determined in a small window at many points within a subscene as the window is passed through the subscene.

Table 3.3 Simple and multiple regression results of the selected independent variables with effective LAI. 'Texture' was derived using the contrast measure (Equation 3), a 7x7 window, and a sample distance of 2 horizontally to the right					
7 x 7 (2,0)	Contrast texture mean	Contrast texture Std. dev.	NIR band mean	Contrast texture & NIR	Contrast texture Contrast texture std. dev., & NIR
r	0.64	0.69	0.56	0.79	0.81
r ²	0.41	0.48	0.31	0.62	0.65
SE	0.94	0.88	1.01	0.79	0.78

When multiple regression was used to relate several independent variables to effective LAI, the NIR channel and the texture mean correlated quite highly with effective LAI at 0.79, and the inclusion of the texture standard deviation to the independent variables improved the relationship to 0.81 (**Table 3.3**). The inclusion of texture from high-resolution digital imagery improves estimation of effective LAI to within a standard error of 0.78 leaf area from 1.01 for the best spectral measure. A coefficient of determination of 0.62 between texture mean, NIR and effective LAI indicated that 62% of the variance in effective LAI is explained by the variance in the NIR band and texture mean combined.

When the texture standard deviation was added to the equation, 65% of the variance in effective LAI was explained. The correlation matrix shown in **Table 3.4** shows that the texture standard provided additional information in the multiple regression with effective LAI. Texture mean and standard deviation were significantly correlated but there was 34% of the variance between them which was not explained. This information contributed to the increase in explained effective LAI when texture standard deviation was added to the multiple regression. Although this increase in correlation was not statistically significant with the small number of degrees of freedom available in this study, it does show potential for improved estimation of effective LAI.

Table 3.4 Correlation coefficients for each pair of variables used in the multiple regressions with effective LAI			
	NIR	tex.std	tex. mean
Tex. mean	0.03	0.66	1.00
tex.std.	0.07	1.00	
NIR	1.00		

This initial study shows the complementary nature of tone, subscene average texture and texture variation for estimating LAI. Texture variation, as a measure of the dispersion of texture, has never before been considered as a potential source of information for the estimation of forest structure. This study suggests that variability in spatial information can capture additional forest structural information over that of a simple average texture measure. These results also suggest that second-order contrast is the most useful texture measure for estimating effective LAI.

3.4 Conclusion

The purpose of this chapter was threefold. First, a review of two methods of extracting LAI information from high-resolution digital imagery was undertaken. Second, an experiment was performed to determine if texture can be used to estimate effective stand LAI, and third, an evaluation of several second-order texture measures was conducted to determine which texture measures are most effective for estimating effective stand LAI. This chapter showed the potential for the use of texture and texture variation within subscenes, combined with simple spectral measures for estimating effective stand LAI. Because of the large number of variables in this thesis, not all texture measures could be included in the multivariate analysis. This initial study determined that the second-order contrast measure was most significant in estimating effective stand LAI; it is this texture measure and its standard deviation that will be used in the subsequent analysis.

4 METHODS

4.1 Field methods

This section gives the field methods used to establish a set of plots in the study area and to measure health-related forest and soil variables. Image acquisition and processing to extract image variables that will be related to forest variables are described, followed by the statistical analysis for determining the spatial distribution of variables and relations between sets.

Six transects labeled A-F from west to east were established along the direction of flow from the tailings' edge to the north creek (**Figure 4.1**). Transects varied from 350 to 900m in length and were parallel to each other, spaced two hundred meters apart. The transects followed survey cut-lines established by Falconbridge. A total of eighty-four plots were established 10m off of these cut-lines. They were spaced along transects to capture much of the variation that was thought to occur along a narrow strip of forest adjacent to the tailings' edge. Plots began at 10m from the tailings' edge and were placed every 25m to a distance of 110m along the transects. From there, plots were spaced every 50m to a distance of 510m where spacing increased to one plot every 100m to the northern creek (**Figure 4.1**). This sampling configuration was chosen because the most significant changes in soil and forest structure were expected to be in the area immediately adjacent to the tailings. Plot centres were staked at 10m from the cut-lines in a southeastern direction from transect A and in a northwestern direction from transects

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Figure 4.1 84 plots were sampled along six transects (A-F) in increasing distance increments from the tailings edge.

B-F. Transect A was positioned on the south-eastern side of the cutline because the cutline was at the western edge of the forest and the transect would have had to have been shortened if plots were located on the north-western side. Similarly, transects B-F were located on the other side for positional reasons.

4.1.1 Vegetation sampling

The forest was sampled in 10m radius plots. The plot radius was measured using a rope that had been cut to length. A field assistant and myself alternated standing at the plot centre while the other extended the rope in one of the four cardinal directions and flagged the nearest branch. The radius of the plot was judged with the centre stake and the flags by the person identifying and measuring the trees as well as the person recording the data. All living trees in the plot above 2m in height were inventoried; tree species was identified and diameter at breast height (DBH) was recorded using a measuring tape. Trees that had died and were also standing were recorded in the same fashion. Notes were made on the perceived health-status of individual trees and of entire stands. Once all standing stems had been recorded, then fallen stems were counted, measured for DBH and species-identified (where possible). Percent cover of alder and other shrubs was estimated in plots where it was judged to be visible from above. Next, the five tallest trees in the plot judged to be closest to the centre were identified and measured for height using a Suunto clinometer.

A Licor-2000 Plant Canopy Analyzer (described in Section 3.2) was used to estimate measures of effective LAI and canopy closure. All measurements were taken at dusk or at

dawn to ensure that the sky was illuminated with diffuse light so that portions of sunlit canopy, clouds or the sun itself did not affect the measurements. Measurements were taken at eight different locations within each plot. Two measurements were taken between the cutline and the centre of the plot in a direction that was parallel to the cutline. Three were taken on a line that ran through the centre of the plot and was parallel to the cut line, and two more were taken on a line parallel again, but halfway between the centre and the far end of the plot. A 45 degree view angle cap was placed on both the above and below canopy sensors to ensure that only diffuse light was striking the sensor and that the operator's shadow would not influence the instrument's measurements. All measurements were taken facing away from the sky where the sun was either rising or setting. Care was taken to ensure that no overhanging branches were within a meter of the sensor during measurement. Because of the short amount of time during which measurements could be taken, measurements were recorded at dusk until the sky was completely dark. As a result, measurements that were taken in almost complete darkness were sometimes influenced more by sensor noise than by irradiance. This produced above-canopy irradiance measurements that were higher than the below-canopy irradiance. These were noted, and these plots were re-recorded under more favourable conditions so measurements were obtained successfully for all plots.

Skyward photographs were taken of tree crowns to obtain a canopy-based measure of structure. Mature trembling aspens in the upper canopy were selected for these measurements because a single species would allow for a more meaningful comparison of individual tree structure. The aspen generally ranged in height from about 25-30m. Not all

plots had mature aspen in them, so only selected plots were used to obtain measurements. Generally, the closest aspen to the plot centre and those that were thought to be visible from the air were selected for skyward photography. Three pictures were generally taken at each plot from different view angles, and sometimes of different trees. The photographs were taken from the base of the trunk looking upwards towards the canopy and facing the sun to minimize the amount of direct sunlit foliage. 100 ASA film was used to ensure a high contrast between the tree canopy and the sky, and to ensure a sufficiently high resolution to capture the details of the spacing between individual leaves.

4.1.1.1 Measurement of crown closure in individual trees using skyward photographs

The skyward photographs were cropped to display only the individual tree crown on which they were centred, and then thresholded to obtain a measure of the tree's crown closure. Care was taken to crop as much of the crown as possible without including any large branches or trunks. Though several photographs were taken of trees at each plot, only a few were selected for thresholding. Many plots did not contain canopy-level trees and other plots only had coniferous species. Thresholding was only performed on mature canopy-level trembling aspen to minimize the variation in canopy closure due to species and age. Other photographs were not used in the thresholding procedure because of poor contrast between the leaves and branches, and the sky. This sometimes occurred when the sky had cloud cover in the scene that was being photographed and when the attitude of leaves was such that direct reflectance made them appear brighter than the sky.

Thresholding was done in an iterative fashion until spatial agreement was visually assessed

to be adequate in a number of areas on the crown between the scanned image of the tree crown and the thresholded image. The resulting measure of crown closure was obtained by dividing the number of leaf and branch pixels by the number of pixels in the cropped portion of the tree crown.

4.1.2 Soil sampling and analysis

Soils were sampled next. Three soil cores were taken at each plot and a sample from each core was taken from the B horizon. The B horizon was chosen because it was assumed that most rooting occurred there and also because it consisted mostly of clay, which has many exchange sites and therefore adsorbs many cations. Therefore, differences in cation concentrations between contaminated and uncontaminated sites would be maximized in the B horizon. The three cores were taken at the mid point between the cut-line and the stake at the plot centre, at the stake and at 5m from the stake in the same direction. The three individual soil core samples were put together into labeled bags and were considered as being representative of the soil for the entire plot. Soil samples were immediately taken out of the bags at the field lab, and air-dried for a few days on newspaper. Soil pH was determined shortly after the soils were dry.

Soil samples were evaluated in the laboratory for a number of different properties. A textural analysis was performed first by sieving the sand fraction and then using a standard settlement method (Gee and Bauder, 1986). The fractions extracted were sand ($>74\mu\text{m}$), sandy-silt ($<20\mu\text{m}$), silt ($<5\mu\text{m}$) and silt ($<2\mu\text{m}$). An estimate of organic matter content

was obtained by loss on ignition. A sample of approximately 5g of soil was weighed, put in crucible and placed in an oven for 8 hours at 400 degrees C. The sample was then cooled and re-weighed. The difference represented the mass of the organic matter lost on ignition, which was divided by the original weight of the sample for percentage organic matter content. The samples were then taken for ICPEs (Inductively Coupled Plasma Emission Spectrometry) analysis to obtain the concentration of metals and nutrient cations in the samples. The samples were split to obtain a representative sub-sample of approximately 15g. These sub-samples were crushed using a mortar and pestle and taken to the ICP lab for digestion. An aqua-regia digestion was used to extract the exchangeable cations from the samples using approximately 3g of soil and a standard digestion procedure (see **Appendix 1**). This technique of digestion extracts elements that may potentially become available to vegetation. The insoluble content of the samples was collected in ashless filter paper during the extraction procedure and this fraction was measured by placing the filter paper and contents in a muffle oven at 450 degrees C for four hours and then re-weighing the sample. Analysis was done to obtain cation concentrations of 10 metal cations; aluminum, boron, barium, copper, iron, manganese, sodium, silicon, strontium and zinc (Al, B, Ba, Cu, Fe, Mn, Na, Si, Sr, Zn) and 3 nutrient cations; calcium, potassium and magnesium (Ca, K, Mg).

4.2 Image acquisition and processing

In the days before the digital camera was flown, targets were placed in the woods beneath openings in the canopy along the cut lines, in the tailings and on the dry creek bed to

facilitate the location of plots in the imagery. White shower curtains were used as targets, because they had been used successfully for locating plots in the past. The distance of these targets along the transects was recorded to the nearest half-meter using a field tape. A total of 30 targets were placed in the study area. Every attempt was made to space the targets evenly along the transects so that a target was placed at each end of the cut line in the tailings and on the dry creek bed, and at every quarter distance of the cut line.

A multispectral digital camera sensor (King, 1995) was mounted in a Cessna 172 aircraft. Eight filters in the visible and along the red-edge in the NIR at 430 (blue), 550 (green), 660 (red), 670 (red), 700 (red-NIR), 730 (red-NIR), 800 (NIR) and 900nm (NIR) were used, each being 10nm in bandwidth except the 430nm filter whose bandwidth was 40nm. 1300 x 1000 pixel format images were obtained for the three flight altitudes corresponding to 25, 50 and 80cm nominal ground pixel spacing. The actual ground resolution would be slightly worse due to atmospheric and optical degradation of the signal. Beyer (1992) provides a complete lab calibration of the Kodak Megaplug 1.4 camera including spatial resolution and radiometric response analysis. The 550, 660 and 900nm bands were obtained for the 25cm pixel imagery. Four bands were obtained at the 50cm pixel spacing including those recorded in the 25cm pixel imagery with the addition of the 430nm band. The 80cm pixel imagery was recorded in all eight bands. Due to image acquisition timing constraints of 6.7 frames/s, eight overlapping spectral bands can only be acquired at the highest altitude. Image histograms were checked for each spectral band while flying over forested areas, and the exposure speed was adjusted to maximize the data dynamic range. Three flight lines were flown for total coverage of the study area in the 80cm and 50cm

data, so that 60% forward overlap and 30% sidelap were obtained. In the 25cm imagery, six flight lines were necessary to obtain similar overlap and total coverage of the study area and only 40% overlap could be potentially achieved.

Multispectral data sets were acquired by pre-programming scripts for the given number of bands, and the time interval between data sets. The operator simply loaded a script for a given flight line and pressed return for the data acquisition to proceed. The locations of the beginning and end of flight lines were specified to the pilot for navigation. The aircraft GPS coordinates, accurate to within 50m, were also noted.

4.2.1 Band-to-band alignment and mosaic procedure

The imagery was examined carefully to try to locate the targets that had been placed in openings in the forest and to assess the actual overlap between images. It was quickly discovered that the actual overlap between images was much less than anticipated due to strong tailwinds, an aircraft velocity that was higher than had been specified to the pilot, and an error in the conversion of altitude above sea level to altitude above ground for aircraft navigation. In fact, some gaps existed between images at the 25cm resolution. Since an image mosaic of the entire study area was required, it was decided that only the 50cm imagery could be used in order to extract enough control and tie points in overlap areas. Only a couple of the targets placed in the forest were visible in the digital imagery. It was thought that perhaps this was due to the fact that many of the targets were in deep shadow on the forest floor. Aerial photographs that were taken at the same time as the

digital imagery showed some targets in the forest, and target location was made easier by looking at these. The targets in both the tailings and on the dry creek bed were easily visible.

Because each spectral band was slightly offset from one another due to aircraft translation between acquisition of successive images, the spectral bands were first registered to each other using a first order transformation (equations 9-10) (Lillesand and Kiefer, 1994) and a minimum of four control points. With one spectral band in a multispectral set as the master, the others were aligned one at a time using the least-squares linear model derived from the control point coordinates.

$$x = f_1^n (X, Y) \quad (9)$$

$$y = f_2^n (X, Y) \quad (10)$$

where

(x, y) = distorted image coordinates (column, row)

(X, Y) = corrected (map) coordinates

f_1^n, f_2^n = transformation functions of n^{th} order

Nearest neighbour interpolation was used in the re-sampling phase of this process. The resulting multi-spectral image was slightly smaller than the original 1300 x 1000 pixel size. A mosaic of the multispectral image sets for the whole study area was then produced using a linear transformation and a minimum of four control points. Spectral matching was performed in the overlap areas between images to account for any differences in image brightness. In this process, the grey level histograms of the two images within the overlapping area are evaluated and matched using a lookup table so that any differences in

overall brightness between the images are removed. Image brightness varied significantly between flight lines.

In order to account for sources of variation in image brightness that were not health related, an examination of the brightness variation between flight lines was conducted (Table 4.1).

Table 4.1 Average digital numbers of image frames on each flight line			
	Image Frame		
	Line1	Line2	Line3
NIR	98.5	81.8	83.9
Red	64.4	64.2	44.2
Green	98.6	103.2	101.5
Blue	93.9	92.8	89.9

The first frame of each flight line was discarded, since each of these frames contained different amounts of tailings, producing variable mean brightness. The flight lines in the green and blue band were most consistent in brightness across the study area from west to east. Of these, the green band was thought more appropriate for texture analysis, since atmospheric scattering effects are lower in the green band than in the blue band. Overall sharpness was also highest in the green band. It suffers from less cross-talk between adjacent photo-sites than longer wavelength bands. Photons are absorbed deeper in the sensor substrate as wavelength increases resulting in increased cross-talk (King, 1995). A shorter wavelength band such as the blue band was not used because of the visible haze effects of atmospheric scattering.

An image of the area that had been geocoded to an Ontario Base Map was then used to georeference the mosaic. Thirteen control points were selected from the perimeter of the study area for correction, and a second-order transformation (equations 9-10) was applied to warp the mosaic to the map base. The output pixel coordinates are related to the input coordinates through a least-squares model fit using linear and squared terms. The image pixels were then coded by both row/column coordinates and UTM map coordinates. Nearest neighbour interpolation was again used in re-sampling of the image values to the new grid. The model fit at all stages of the process of mosaicing had precision of better than 0.5m or 1 pixel RMS. The mosaic was then exported into four separate .tif files for the four separate spectral bands.

4.2.2 Extraction of plot subscenes from mosaic

The green band was imported into a standard graphics software package, and a vector line equivalent to one transect in length and graduated to show the plot centre locations was drawn onto a separate layer. This transect line was copied five times, and the beginning of each was placed over the target corresponding to the beginning of the transect in the tailings. A rotation of the transect line was then performed so that the target on the dry creek bed intersected it. The transect lengths in the imagery were obtained using Euclidean distances and were checked against distances measured in the field. Distortions in distance measurement were negligible as the study area is nearly flat, and the total view angle of the camera-lens system is very small (± 9.1 degrees in North-South direction). The

coordinates in pixels that corresponded to the plot centres were obtained for each plot, and 20 pixels were subtracted from both the x and y to obtain the upper-left corners of 20m x 20m image subscenes that centred directly on the plots. The four spectral bands were then overlaid, and the subscenes that corresponded to the field plots were cropped out of the mosaic (**Figure 4.2**).

4.2.3 Extraction of sunlit portions of the forest canopy

The use of spectral symptoms to quantify forest health has been the most common approach taken by researchers in agriculture, forestry and geobotany. Previous research at the Kam Kotia mine site revealed some spectral differences in trembling aspen (*populus tremuloides*) between six sample plots on a transect downstream from the tailings. The differences were related to distance of the plots from the tailings' edge but they were not statistically significant as high within-crown reflectance variations masked the between plot variations (Lévesque and King, 1999). For this research, direct-sunlit portions of tree crowns were cropped out of each of the image subscenes to obtain the brightness of sunlit portions of canopies. Sunlit portions were determined visually as a group of several to many pixels representing a uniform bright area of a single tree crown. Sunlit bright areas were cropped from the subscene, and the mean of these cropped portions was used as the measure of sunlit brightness.

4.2.4 Image texture extraction

Subscene image texture was then obtained. The green channel was used to measure

Figure 4.2 .5m resolution digital image mosaic of the green band including blow-up of image subscene with field plot dimensions.

texture because it had the least amount of image brightness variation due to exposure differences across the study area (Table 4.1). The previous study relating subscene texture in 25cm pixel digital imagery to effective LAI had shown that the contrast measure of texture with a window size of 7 x 7 and a sampling distance of 2 had performed best of the six texture measures and three window sizes that were tested (Olthof and King, 1997). Because the resolution of the imagery for this project was 50cm, the contrast texture measure with window sizes of 3 x 3 and 5 x 5 and sampling distances of 1 and 2 were tested separately. The first used had a window size of 3 x 3 and a sampling distance of 1, the second, a window size of 5 x 5 and had a sampling distance of 1, and the third, a window size of 5 x 5 and a sampling distance of 2. The previous study had also shown that the variation in texture when combined with average texture and simple spectral measures, was useful in explaining additional variation in effective LAI. For this reason, the mean and standard deviation were extracted from the image subscene texture channels.

4.2.6 Extraction of shadow fractions from the imagery

Subscene mean and standard deviation were obtained for each spectral band. Only the NIR (900nm), red (670nm) and green (550nm) bands were used for shadow analysis. The blue band was excluded because thresholding could only be performed on three 8-bit bands with the software that was used. The subscene's pixel brightness therefore represented the average of the three values from the three spectral bands. The method used for shadow fraction analysis was taken from Seed and King (1997) as summarized in Section 3.1.4. Details pertinent to this research are as follows. A careful examination of

several subscene histograms revealed discrete shadow class boundaries near 38 and 58 DN for most of the image subscenes. Three other class boundaries were chosen at approximately equal intervals between these discrete boundary classes at 20, 75 and 95 DN. These additional shadow classes were added to provide more precision than may be visible in the histogram analysis, and it was recognized that significantly discrete shadow fractions would emerge in the multivariate analysis. This resulted in six separate shadow classes labeled S1 to S6 whose proportions in each plot subscene were then determined.

4.3 The Complete Data Set

This study used several measures of forest structure at both the canopy and crown level. The first set of forest structure variables included the effective LAI and canopy closure measurements that were obtained from the Licor-2000, the individual tree crown closure measurements, the stem counts and basal area for live, dead and blowdown trees (Table 4.2). The second set included the same variables divided by the live stem counts and basal areas. It was thought that the latter set would reveal more information about the health of the forest stand. Absolute blowdown or dead stems will reveal a great deal about forest health if forest structure is similar in all plots to begin with. At the Kam Kotia mine study area, there was a great deal of variation in forest structure across the study area. Plots within the spruce bog area in the centre portion of the study area contained fewer stems than the western mixed forest or the eastern portion dominated by large aspen. A comparison of absolute blowdown numbers between these sites is meaningless in terms of forest health. Leaf area and canopy closure were also related to the total basal area of

standing stems including dead stems. Any variation in forest health can be captured by this relationship since a certain stand basal area is expected to produce a certain leaf area in a mixed forest stand. Any degradation in forest health will produce a lower leaf area per standing basal area either by decline of standing stems or individual branches of live trees. For example, leaf area per standing basal area was included in the set of relative forest structure variables, and can be considered as a measure of change in forest productivity. Beyond the age of 20 years, leaf area per standing basal area is almost constant for healthy Aspen, Jack pine, Black Spruce, Japanese Larch, Birch, Scots Pine and Norway Spruce stands. **Figure 4.3** is a set of sketches illustrating the effects that were derived for these species in the research of Nilson and Peterson (1994), Osawa (1990), Leemans (1991), and Gower *et al.* (1997). Although there is wide variability between species that has been generalized in the sketches, the reduction in variation with age resulting from calculation of LAI relative to standing basal area was distinctly evident in each study. Gower *et al.* (1997) also reported that leaf area per tree was highly correlated to stem diameter for most stands sampled in the boreal forest, with r^2 values ranging from 0.75 to 0.98, the majority exceeding 0.85. A slight decrease in leaf area and standing basal area occurs in older stands for some forest types. However, age effects were not taken into account in this study.

Figure 4.3 Schematic sketches of typical stand development showing leaf area and standing basal area increasing at similar rates, producing leaf area per standing basal area that is almost constant with age, (after Nilson and Peterson, 1994; Osawa, 1990; Leemans, 1991 and Gower et al. 1997).

Table 4.2 Soil, forest structure and image variables for 84 plots and 70 image subscenes.

Soil		Forest structure		Image	
<i>metal cations</i>		Blowba	blowdown basal area	<i>Spectral</i>	
Al	Aluminum	Blowstem	blowdown stem count	Blue	Average blue brightness
B	Boron	Crownclo	Single aspen crown closure / plot	Green	Average green brightness
Ba	Barium	Deadba	dead basal area	Red	Average red brightness
Cu	Copper	Deadstem	dead stem count	NIR	Average NIR brightness
Fe	Iron	Licor1	ring 1 (canopy closure)	NDVI	NIR-Red / NIR+Red
Mn	Manganese	Licor2	rings 1, 2	Sungreen	sunlit green brightness
Na	Sodium	Licor3	rings 1, 2, 3 (effective LAI)	Sunred	sunlit red brightness
Si	Silicon	Licor4	rings 1, 2, 3, 4	SunNIR	sunlit NIR brightness
Sr	Strontium	Licor5	rings 1, 2, 3, 4, 5	<i>Radiometric fractions</i>	
Zn	Zinc	Liveba	live basal area	S1	deepest shadow
<i>Macro nutrients</i>		Livestem	live stem count	S2	deep shadow
Ca	Calcium	Stemba	average stem basal area	S3	Intermediate shadow
K	Potassium	Relative forest structure		S4	Intermediate shadow
Mg	Magnesium	Blowba_l	blowdown basal area / live basal area	S5	bright shadow
<i>Soil fractions</i>		Blowst_l	blowdown stems / live stems	S6	Brightest shadow
Sand	> 74um	Deadba_l	dead basal area / live basal area	<i>Texture (2nd order contrast)</i>	
Sand/silt	< 20um	Deadst_l	dead stems / live stems	Texmean1	average texture 3 x 3 (1.0)
Silt	< 5um	Licor1_l	Licor1 / standing basal area	Texmean2	average texture 5 x 5 (1.0)
Clay	< 2um	Licor2_l	Licor2 / standing basal area	Texmean3	average texture 5 x 5 (2.0)
Insol	insoluble fraction	Licor3_l	Licor3 / standing basal area	Texvar1	texture standard deviation 3 x 3 (1.0)
Orgmat	organic matter	Licor4_l	Licor4 / standing basal area	Texvar2	texture standard deviation 5 x 5 (1.0)
pH	soil acidity	Licor5_l	Licor5 / standing basal area	Texvar3	texture standard deviation 5 x 5 (2.0)

Therefore, by relating forest structure measures to their live counterparts, some of the variation in structure across the study area that was not health-related could be partitioned out from the analysis. This approach is similar to Everham's (1996) suggestion to measure structural loss as a percentage of basal area lost or percentage mortality.

The set of soil properties had a total of 20 variables including texture, pH, organic matter and various nutrient and metal cations. The set of forest structure data had a total of 13

variables. The set of image variables had a total of 20 variables including average spectral reflectance of image subscenes in four bands, six shadow fractions, sunlit canopy brightness in the NIR, red and green as well as the three measures of texture means and texture standard deviations.

4.3.1 Spatial and Map layer analyses

Plots of the forest and soil variables against distance were produced to determine the most appropriate model fit. Correlation coefficients were determined between each of the variables and distance from the tailings edge. Statistical tests in the tables of the results section are reported as either P or F values, depending on if the fit was linear or non-linear, respectively.

A visual analysis of maps that were produced through linear interpolation and triangulation between plot values was then conducted to determine if any other spatial patterns existed in the data. Map layers were done in black and white, with darker shades being symptoms of poorer stand health to facilitate visual comparison between layers. Therefore, black was used to show the highest level of blowdown on the blowdown map, while on the leaf area map, black was used to show the lowest level of leaf area.

4.4 Statistical Analysis

The statistical analysis related to the objectives required the use of two complementary multivariate methods that are somewhat complex. The purpose of this chapter is to

introduce these methods and discuss them to a level that is appropriate to the research.

4.4.1 Canonical Correlation Analysis

The goal of canonical correlation is to analyze the relationships between two sets of variables. It provides a statistical analysis for research where each subject is measured on two sets of variables, and the researcher wishes to know the number and nature of independent ways in which the two sets relate to each other (Tabachnick and Fidell, 1996). It was deemed an appropriate technique for relating multiple vegetation spectral and biotic relations in studies by Jakubauskas (1996) and Korobov and Railyan (1993).

In canonical analysis, it is sometimes useful to think of one set of variables as being independent (IVs) while the other is dependent (DVs). Because the use of independent and dependent terms implies cause and effect, it is sometimes as useful to think of the sets as being neither independent nor dependent, but only related. The use of canonical analysis then allows the user to infer how the two sets are related, i.e. in what combinations among variables within a set, the magnitude of variable weightings, the relation between sets and the significance of that relationship. Different sources in the literature use different terminology to describe the variables and combinations of variables within and between sets. A canonical variate is a linear combination of variables on either side of the equation, while a canonical variate pair is two canonical variates that are related to each other through canonical correlation.

Canonical correlation analysis is similar to multiple regression. Multiple regression seeks to maximize the correlation coefficient between a linear combination of independent variables and a dependent variable. Unlike canonical correlation, regression analysis provides only one possible combination of independent variables that maximizes the correlation coefficient, since there is only one dependent variable. In a canonical analysis, there are several ways to combine and recombine the set of dependent variables so that the number of variate pairs that can be extracted is equal to smallest number of variables in either set.

The canonical correlation procedure finds the first pair of linear combination of variables that maximizes the Pearson correlation coefficient between the two sets. It then searches for a second pair of linear combinations that is orthogonal to the first and has the next highest correlation coefficient, explaining the next highest between set variance. The procedure continues until the number of variate pairs that is extracted is equal to the smallest number of variables in either set. Like multiple regression and principal components, canonical correlation is a maximization procedure that partitions the between-variate association through the use of uncorrelated pairs of linear combinations (Stevens, 1992). A significance test is performed on each of the canonical variate pairs to determine how many pairs are statistically significant.

The significance test is approximately distributed as a chi-square statistic with pq degrees of freedom (p = number of independent variables, q = number of dependent variables).

The significance of the first canonical correlation is determined. Then the largest canonical

correlation is removed and the residual is tested for significance. This procedure continues until all the residual variate pairs have been tested in this manner.

There are a number of criteria that must be met to ensure that the canonical analysis is valid and that the variates are interpretable. A minimum case-to-variable ratio of 10-to-1 is required according to Tabachnick and Fidell (1996) to obtain meaningful relations. A variable is a descriptor of a phenomenon, material, or object whose characteristics change over time or space. Measurement of the variable can be based on sampling of that variable, each sample that is measured being a single 'case'. Stevens (1992) states that a minimum case-to-variable ratio of 20-to-1 is required, and only if the largest canonical variate pair is to be interpreted. Stevens recommends that principal components analysis be performed on both sets of variables first if the case-to-variable ratio is high. The use of principal components has other advantages in this type of analysis. It is important in canonical correlation analysis that the variables in each set and across sets be not too highly correlated with each other. This problem is termed multicollinearity, and applies equally to multiple regression. Since principal components are orthogonal, the problems of multicollinearity are eliminated, which increases the interpretability of the canonical variates.

Although there is no strict requirement that the variables be normally distributed, the canonical correlation analysis is enhanced if they are. Also, the test of significance of canonical variate pairs is based on the assumption of multivariate normality. Multivariate normality is the assumption that all variables, linear combinations of variables and residuals

in regression are normally distributed. Multivariate normality is difficult to test since it requires all possible combinations of the variables, and most tests that are available are too strict. However, the likelihood of multivariate normality is greatly increased if all the individual variables are normally distributed. Outliers can also have a large impact on the outcome of the analysis, and therefore every effort should be made to eliminate them or to minimize their impact (discussed in 4.5.1). If single variables are not normally distributed, then transformations of the offending variables should be considered (Tabachnick and Fidell, 1996).

Interpretation of the canonical variates is accomplished by examining the standardized coefficients and the canonical variate-variable correlations. Eigenvalues are the variate-variable correlation coefficients squared, and explain the amount of variance in the canonical variate that is explained by the variable.

4.4.2 Principal Components Analysis

In this research, principal component analysis (PCA) was used as a variable-reducing method prior to the canonical analysis. This was done to achieve a more desirable case-to-variable ratio, and to ensure that there would be no multicollinearity effects on the analysis. Both of these factors must be accounted for in canonical analysis to increase the interpretability of the variate pairs, and principal components analysis was an elegant solution to the problem.

Variable reduction may be accomplished by examining a correlation matrix of a set of variables. Those variables that are highly correlated may be combined to form a single factor in the analysis. While combining variables that are highly correlated will work as a method of variable reduction, making sense of a correlation matrix to determine precisely what the correlations represent is often quite difficult. For example, there are 435 simple correlations in a set of 30 variables that may reduce to 4 or 5 different constructs. PCA determines if there are a small number of underlying constructs which account for most of the variation in a set of variables (Stevens, 1992).

In PCA, linear combinations of the original variables are derived, and often a small number of these account for most of the variation in the original set. The original variables are transformed into a new set of uncorrelated linear combinations (components) that additively partition the variance of the original set of variables. The total variance that is accounted for in the set of principal components is the sum of the variances in the original set of variables.

PCA first seeks a linear combination of variables that accounts for the maximum variance in the set of variables. The variance of the first principal component is equal to the largest eigenvalue. The analysis then seeks a second linear combination that accounts for the next largest amount of variance in the set and that is uncorrelated (orthogonal) with the first component. Each successive component accounts for the maximum remaining variation in the set, and is orthogonal to all components that preceded it. In this way, a set of

correlated variables is reduced to a set of uncorrelated components, the first few of which usually account for most of the variance in the original set of variables.

Several methods have been proposed to decide how many of components to retain for further analysis. The criterion proposed by Kaiser (1960) is probably the most widely used. He suggested retaining only those components whose eigenvalues are greater than one. A principal component that has an eigenvalue of one accounts for the same variance as a single variable in the original set. This method is deemed valid if there are a small to medium number of variables (10-30) in the analysis and if the communalities are high ($>.70$). Communality is the amount of variance in a single original variable that is accounted for by the variance in the set of principal components.

PCA works well to summarize most of the variance in a set of variables. Interpreting the components is not always as easy. Interpretation can be accomplished by examining the factor loadings in the factor matrix, which are correlations between the variable and the component. Loadings that are significant in a two-tailed test at a stated level are interpreted in this analysis. Interpretation of the component requires insight into what the variables that have high loadings have in common. Interpretability of the components is made easier by rotation, such as the varimax rotation developed by Kaiser (1960), so that each factor tends to load high on a smaller number of variables and low on the others.

Canonical correlation is similar to principal components analysis in a number of different ways. Both are variable reduction schemes that use linear combinations of the original variables. In principal components, each successive linear combination or component is orthogonal to all previous ones. Canonical correlation also extracts linear combinations or variates that are orthogonal. In principal components analysis, the first few components usually account for most of the variance within a set of variables, while in canonical correlation, the first few variate pairs account for most of the between set variance. The interpretation of components and variates is also done in a similar manner. Principal components are interpreted by examining the correlations between the variables and the components, while in canonical analysis, the variates are interpreted by examining the variable-variate correlations.

4.5 Application of Multivariate Analysis

The sets of variables were related to each other using canonical correlation. Specifically, the set of soil properties was related to both the forest structure and the forest structure relative to live densities. The image variables were also related to both sets of forest structure measurements. This resulted in four separate canonical correlation analyses. Canonical correlation was chosen as a multivariate technique because it is capable of dealing with multiple variables from two sets and it provides a numerical and mostly objective means for weighting of forest structure components that explain variation in health.

4.5.1 Transformation of variables and management of outliers

Some of the variables in the four data sets required modification to achieve a significant degree of normality. Elimination of cases that had missing variables was not appropriate for this analysis because of the high case-to-variable ratio that was required, and because many of the cases had at least one missing variable. Elimination of variables was also not desirable since the variables that were chosen were deemed necessary for the analysis. Instead, missing cases were replaced with the mean value of the variable. This treatment of missing cases is appropriate since the analysis is based upon Pearson correlation coefficients which is unaffected by the mean. However, in doing so, caution is required when interpreting the significance of correlation coefficients, since the actual degrees of freedom are slightly less than 82 where some of the cases were replaced with the mean. The set of image variables had 14 cases that were replaced with the mean due to the missing subscene data between flight lines. The image variables should therefore be interpreted with 68 degrees of freedom instead of 82. This difference represents very little in terms of the actual significance because the t-distribution changes very little beyond 30 or 40 degrees of freedom (Olson, 1987). Correlation analysis was done with the variables with missing cases, and significance was interpreted with the actual degrees of freedom. Histograms were checked for each of the variables for normality. The significance of the statistic value (z) for skewness and kurtosis was calculated. The distribution was accepted as normal if the critical z value for both skewness and kurtosis was ± 1.96 , corresponding to the 95% significance level (Hair *et al.*, 1998).

Variables that were determined to be non-normal were transformed and outliers were treated on a case-by-case basis (Table 4.3). According to Tabachnick and Fidell (1996), univariate outliers may be treated in one of four ways. If the outlier is considered part of the target population, then a transformation of the variable should be considered to increase normality. An examination of the frequency histogram is an easy method for determining whether kurtosis is responsible for the outlier, since kurtosis measures the peakedness of the histogram. If kurtosis is deemed responsible, then a transformation of the variable will suffice to deal with the problem of outliers. A second alternative is to eliminate the variable entirely. This method is a good alternative if the variable is highly correlated with others in the analysis, or is judged to be not critical to the analysis. A third method of dealing with outliers is to eliminate them in a case-wise fashion from the analysis. This is appropriate if the cases are judged to be part of a different population than that which the sample was intended (e.g., if its standardized score is in excess of 3.29 in a two-tailed test at $p < 0.001$). The missing cases are then simply treated as other missing cases in the analysis. A fourth way of dealing with outliers is to simply replace the offending value with an extreme that lies closer to the distribution. An outlier is replaced with a raw score that is one unit larger or smaller than the next most extreme case in the distribution. This method is valid in some instances because the measurement of certain variables is somewhat arbitrary or imprecise. The case is still deviant, but less so than before so that the univariate outlier will have less of an impact on the outcome of the analysis. This fourth method is desirable if the outliers are known to contain important information from the same population, but because the sample size is not large enough, these cases appear as outliers.

Table 4.3 Treatment of outliers

Table 4.3 Treatment of outliers											
Soil	transformation	outliers*	treatment**	Forest structure	transformation	outliers*	treatment**	Image	transformation	outliers*	treatment**
Metal cations											
Al		E:360	3	Blowba	log x_i	B60,F:110	3	Spectral		F:35	3
B			Crownelo			E:510	3	Blue			
Ba			Deadba					Green			
Cu			Deadstem					Red			
Fe		C:10	3					NIR		B:110,F:460	3
Mn			Licor1				NDVI				
Na			Licor2				Sungreen				
Si		log x_i	F:260,F:160	3		Licor3		Sunred			
Sr				Licor4				SunNIR		D:260	3
Zn				Licor5				Radiometric fractions			
Macro nutrients											
Ca	log x_i	B:110	3	Liveba	log x_i	F:260	3	S1		E:460	3
K				Livestem			F:35	3		S2	
Mg				Stemba			B:810,F:310	3		S3	
										S4	
Soil fractions											
			3	Relative forest structure							
				Blowba_1	log x_i			S5		B:10	3
				Blowst_1				S6			
				Deadba_1							
				Deadst_1							
Sand		A:85,A:110,A:210	4	Licor1_1	log x_i	A:110	3	Texture (2nd order contrast)			
Sand/silt		E:460,F:610	3	Licor2_1			A:610,F:10	3	Texmean1		
Silt		A:360	3	Licor3_1			A:610	3	Texmean2		
Clay				Licor4_1			A:610	3	Texmean3		
Insol				Licor5_1	log x_i	A:610	3	Texvar1		F:10	4
Orgmat							A:610	3		Texvar2	
							A:610	3		Texvar3	
pH							A:610,F:460	3			
*outliers after transformation of variable											
**treatments - Tabachnick and Fidell (1996)											
† Transformation of variable											

*outliers after transformation of variable

**treatments - Tabachnick and Fidell (1996)

1. Transformation of variable

2. Eliminate variable

3. Eliminate case-wise

4. Replace outlier with extreme that lies closer to the distribution

The set of soil properties had two variables that required logarithmic transformations to achieve normality. These were the concentration of silicon and concentration of calcium, both in parts per million. Cases that were greater or less than three standard deviations from the variable mean were treated as outliers. Outliers were eliminated case-wise and the variable was checked again for normality. The maximum number of cases that were eliminated from a single variable in the soil set was two for silicon concentration. Three cases where sandy soil occurred were identified as outliers. These were not eliminated from the analysis because they all occurred within four plots of each other, and therefore represented a distinct soil texture from the rest of the study area. Instead, these outliers were replaced with an extreme value that fell within the distribution. Two cases that had extreme silt-sand fractions were treated in the same way. Other outliers in the set of soil variables were eliminated since it was unknown if they resulted from experimental error, or if they were from a different population or if they truly represented some extreme case within the sample population.

The set of forest structure parameters also had two variables that required logarithmic transformations to achieve normality. These were stem basal area and dead basal area in square metres. Outliers that were more than three standard deviations from the mean were eliminated on a case-wise basis. A maximum of two cases was eliminated from any single variable. Seven of the relative forest structure variables required logarithmic transformations to achieve normality. These were dead basal area / live basal area, blowdown stems / live stem counts and the Licor 1-5 measures of both effective LAI and canopy closure / standing basal area. Since logarithmic transforms cannot deal with zero

values, all zero values were replaced with an extreme low value prior to the transformation. Outliers were eliminated as before and a maximum of two outliers per variable was detected. Plot A610 was eliminated from all Licor measurements for being high. This plot contained 90% alder 4-7m in height and only two live standing stems. This resulted in an intermediate Leaf Area (3.22-3.52) with very little standing basal area.

None of the image variables required transformations to achieve normality. Outliers were eliminated as before and a maximum of two cases per variable was eliminated. Plot F10 was found to have extreme texture and therefore could have been eliminated from all texture measures. However, an examination of the forest structure and field notes revealed that this plot contained many trees that were noted as unhealthy, broken or leaning. While this case falls outside the normal distribution of image texture, it does so because it represents an extreme case of structural degradation and therefore should be preserved. The fourth option of dealing with outliers was therefore chosen in this particular case to preserve the information in this extreme case.

Plot E460 was also an extreme low outlier in several of the image variables, including average reflectance in the red band, S1 and texture variation for measures 2 and 3. An examination of the field notes revealed that this plot contained 100% alder throughout at 2-4m in height and only one standing dead trembling aspen. This plot was eliminated from further analysis.

Principal components analyses were used to reduce the dimensionality of the soil data set,

the two sets of forest structure data, and the set of image variables. This was done to achieve a more desirable case-to-variable ratio, and to transform the data from a set of correlated variables to a set of orthogonal components. The problem of multicollinearity was therefore eliminated.

4.5.2 Formulation of a health index from the best canonical variate pair

An estimate of forest health based on field measurements was computed as the canonical variate that explained the variation in forest structure-related health symptoms. This field-based estimate was derived from the relative structure variate pair, since the relative structure variate normalized structure due to growth stage and forest type. This variate was a linear combination of objectively weighted structural components, each one representing a different measure of forest structure related to health symptoms.

Multiple regression was used to develop the image-based health index based upon the variate pair that explained the most structural information related to health. The image variables that explained the most variance in the principal components that combined to form the canonical variate pair were regressed against the structural measure of forest health. The criteria for the selection of variables were 1. the variable had to explain most of the variation in the principal component, and 2. the variable had to be simple to extract from the imagery. A variable that explained a small amount of the variance in the field-based health index but was difficult or time consuming to extract from the imagery was not included. The image-based health index was therefore the linear combination of image

variables that explained the most variance in a linear combination of health components from the relative structure variate.

5 RESULTS AND DISCUSSION

5.1 Spatial Distribution

In the following discussion, variables are abbreviated using the same names as in Table 4.2.

The definition for each is given in that Table or the associated discussion of methods.

1.1.1 *Soil properties*

An examination of metal concentrations (Table 5.1) showed that some plots have extremely high concentrations of zinc and copper compared to typical agricultural soil and basic trace element concentrations in uncontaminated soils (Brady and Weil, 1996; Bowen, 1966, Connor and Shacklette, 1975), suggesting that metal toxicity is present at the site.

Table 5.1 Soil metal concentrations in parts per million for 84 plots				
Variable	Mean	Std Dev	Minimum	Maximum
Al	21526	9932.35	0	45654
B	11.02	6.77	2	34
Ba	47.09	20.73	4	102
Ca	9511.44	10478.87	0	61259
Cu	31.73	25.46	2	220
Fe	25372.09	15350.57	1918	57104
K	2725.87	1347.09	2	5609
Mg	9034.77	5811.98	240	40641
Mn	234.18	114.84	13	515
Na	170.11	96.95	13	425
Pb	4.17	4.8	0	21
Si	103.4	73.72	31	354
Sr	11.99	5.47	2	28
Zn	56.32	30.1	3	124

Figure 5.1 Plots of soil variables with distance

Levels of iron, magnesium and calcium are also extreme compared to a White Mountain Forest composed of spruce, hemlock and northern hardwood species (Smith, 1990).

Table 5.2 Correlations of soil properties with distance N=84							
variable	Al	B	Ba	Ca	Cu	Fe	K
r	-0.1454	0.0255	0.0372	-0.2563	0.051	-0.2092	-0.0875
Sign.	P= .187	P= .818	P= .737	P= .019	P= .645	P= .056	P= .429
variable	Mg	Mn	Na	Si	Sr	Zn	
r	-0.2746	0.1406	-0.1165	0.0782	-0.1017	0.0108	
Sign.	P= .011	P= .202	P= .291	P= .479	P= .357	P= .922	
variable	Clay	Silt	Sand/silt	Sand	Orgmat	Insol	pH
r	0.0041	0.0147	0.0649	-0.0661	0.1491	0.1301	-0.083
Sign.	P= .971	P= .895	P= .558	P= .550	P= .176	P= .238	P= .453

Levels of silicon are typically moderate for aqua regia digestion, as the soil matrix is not broken down. Pearson correlation coefficients were determined for each of the soil properties with distance from the tailings' edge (Table 5.2). In the set of soil data, concentrations of calcium (Ca), iron (Fe) and magnesium (Mg) were all significantly negatively correlated with distance at $P < .056$. Of these, iron is the most important as it is easily liberated under acid drainage conditions. That iron content increases closer to the tailings and is reduced further away indicates that acid drainage may exist within the forested study area. Some sample plots (Figure 5.1) reveal moderately significant linear relations of decreasing soil cation concentrations. Significant plots ($p < 0.1$) show both linear and a fifth-order trend lines, the latter of which appeared to fit the data best.

An examination of the correlations between soil properties and distance reveals statistically moderate decreases in calcium, iron and magnesium concentrations with

Figure 5.2 Plots of structural variables that have significant linear relations with distance from tailings edge at Sign. < 0.02.

increasing distance from the tailings' edge. Soil pH and other soil cation concentrations were expected to relate to these properties, but were not significantly correlated with distance. Variations in some of these soil properties with distance was expected because it was assumed that the tailings were the source of cations and soil acidity. However, because the regional groundwater flow is inferred, the actual distribution of the soil properties was very different from what was initially expected. The source of the cations that shows a significant relationship with distance is likely to be the tailings. The decrease in iron with increasing distance from the tailings is easily explained, since iron is contained in pyrite tailings. The source of calcium and magnesium are carbonates present near the tailings (Walsworth, 1998).

5.1.1 Forest structure

Table 5.3 Correlations of forest structure variables with distance N=84							
Variable	Blowba	Blowstem	Crowncl	Deadba	Deadstem	Stemba	
R	0.3479	0.4712	0.1960	-0.2067	0.3362	0.6245	
Sign.	F=0.005	F= .000	P= .074	P= .059	F= .008	P= .000	
Variable	Licor1	Licor2	Licor3	Licor4	Licor5	Liveba	Livestem
R	0.4779	0.4244	0.4182	0.4658	0.4885	0.1929	0.5050
Sign.	P= .000	P= .000	P= .000	P= .000	P= .000	P= .079	F= .000

All of the forest structure variables were significantly correlated with distance (Table 5.3). These included blowdown basal area (Blowba) and blowdown stem density (Blowstem) as well as dead stem density (Deadstem) and live stem density (Livestem), which all decreased with distance and were significant at $<.008$. Variable plots revealed that an exponential fit was most appropriate for blowdown basal area, blowdown stem density, live stem density and dead stem density (Figure 5.2).

All five of the Licor (Licor 1-5) measurements of effective LAI and canopy closure were positively correlated with distance, and were all significant at $P=.000$ (greater than 99.95% of the time). Live basal area (Liveba) was also positively correlated with distance, and was significant at $P=.079$. Live stem basal area (Stemba) was the most significantly correlated with distance of this set of variables, having a Pearson coefficient of 0.62.

Simple correlations between distance and forest structure revealed many changes with increasing distance from the tailings. Average stem size increased significantly with increasing distance from the tailings' edge. Blowdown basal area and stems, dead stems and live stems all decreased significantly with increasing distance. All measures of leaf area and canopy closure as well as live and stem basal area increased with increasing distance. Live stem densities were related inversely to distance. Therefore, more smaller stems grow near the tailings' edge while fewer larger stems grow further away. The result is a small increase in total live volume with increasing distance from the tailings. The reasons for this increase are a combination of factors including decreases in blowdown volume and standing dead stems, and the successional stage of the stand since the area nearer the tailings is populated by younger, smaller trees than further away.

Standing dead stems are a result of either direct toxicity, soil structure degradation due to elevated metal concentrations, senescence or competition from surrounding trees. The increase in stem size and the decrease in dead stems with distance suggest that competition may be at least partly responsible for the observed variation in standing dead stems, since natural thinning will occur more in the denser stands near the tailings. Both

standing dead stem densities and dead basal area are significantly related to distance, suggesting that there may be little variation in the size of dead stems in the study area. This observation is confirmed by the distribution statistics in **Table 5.4**, and also supports the hypothesis that some mortality is occurring as a result of competition, since thinning generally occurs in stands that have a relatively uniform stem size. This is because the seedlings of a sere establish themselves following a disturbance, and develop at a similar rate until they begin to compete for light, water and nutrients. At this point, thinning occurs where generally the smaller stems in the stand begin to die because of a lack of resources.

The relationships between structural variables and distance, as well as those between individual structural parameters suggest that larger stems tend to blowdown more easily than smaller ones. An examination of the distribution of live, standing dead and blowdown stem sizes was conducted to see if the difference in stem sizes was significant. **Table 5.4** shows the results of F-tests of the difference between average live stem circumference and average dead and blowdown stem circumferences. The results show that average dead stem circumference is different from the average live stem circumference at the $F = 0.012$ level. Average dead stem size is greater than average live stem size, which suggests that direct toxicity and senescence are partly responsible for death, since dead stem size would be consistently smaller than live stem size if competition were the only cause of death. The results also show that the average blowdown stem circumference is .15m greater than the average live stem circumference, which represents a difference that is significant at $F = 0.000$.

Table 5.4 Live, dead and blowdown stem circumference distribution descriptives. F-tests were performed between live and dead, and live and blowdown separately							
	<i>Mean</i>	<i>Std Dev</i>	<i>Min</i>	<i>Max</i>	<i>N</i>	<i>Fobs</i>	<i>Sign.</i>
Live	0.34	0.3	0.08	2.59	3622	NA	NA
Dead	0.37	0.25	0.09	1.57	574	6.297	0.012
Blowdown	0.49	0.22	0.1	1.46	828	171.782	0.000

It should be noted that some of the differences between the average measurements of tree circumferences might be attributable to sampling error. Dead and blowdown stems without leaves at or near 2m in height are easily and mistakingly overlooked, while a live tree of the same size is easier to spot. There is evidence of some sampling bias in the minimum stem sizes which show that the minimum stem size that was sampled was less for live stems than for either dead or blowdown stems. The likelihood that smaller stems were possibly overlooked when sampling dead and blowdown stems was further confirmed when looking at the minimum stem sizes that were sampled on each of the six transects. On all transects but one, where the smallest live and dead stems were equal in size, the smallest live stem that was sampled was smaller than the smallest dead stem sampled, and the smallest live stem sampled was smaller than the smallest blowdown stem sampled on all six transects. It was surmised that any possible sampling bias might account for the small difference between average live and dead stem sizes, but would not account for the large discrepancy between live and blowdown stem sizes.

Blowdown and mortality are occurring to stems that are larger than live stems. Because the largest stems in the study area are aspen and balsam poplar, an analysis of variance

was conducted on the proportions of dead and blowdown stems per plot by group (deciduous or coniferous) to determine if either group is more susceptible to mortality or blowdown. Proportions were calculated as the number of coniferous or deciduous dead or blowdown stems divided by the number of corresponding live stems. Results of this analysis are presented in **Table 5.5**.

The proportion of conifers that blow down is significantly greater than the proportion of deciduous blowdown. Across much of the study area, coniferous species are found in the understory, and are therefore sheltered from the wind, being smaller than the deciduous trees which dominate in the overstory. In spite of this, most blowdown occurs to coniferous trees, and these trees tend to be larger overall than live trees. This seemingly contradictory result can be explained by the small variation in the size of blowdown stems compared to live stems (**Table 5.4**). Therefore, uniformly large conifers tend to be most susceptible to blowdown.

Table 5.5 Two separate F-tests between deciduous and coniferous proportions of blowdown and dead						
<i>proportion</i>	<i>Mean</i>	<i>StdDev</i>	<i>Min</i>	<i>Max</i>	<i>F</i>	<i>Sign.</i>
Blowdown deciduous	0.09	0.25	0	2	9.621	0.002
Blowdown coniferous	0.57	1.42	0	12		
Dead deciduous	0.12	0.19	0	0.86	3.261	0.073
Dead coniferous	0.2	0.31	0	2		

A significantly larger proportion of coniferous trees than deciduous trees is standing dead as well. Whether this is because of higher susceptibility of coniferous species to mine site conditions, or because of growth stage or succession is unknown. This observation may

also be a cause of greater blowdown of conifers, since it is unknown whether these trees first die, then blow down or vice-versa.

5.1.2 Relative structure

Table 5.6 Correlations of relative structure variables with distance N=84					
Variable	Blowba_1	Blowst_1	Crowncl	Deadba_1	Deadst_1
R	-0.2568	-0.0343	0.196	-0.0826	-0.0327
Sign.	P= .019	P= .758	P= .074	P= .458	P= .769
Variable	Licor1_1	Licor2_1	Licor3_1	Licor4_1	Licor5_1
R	0.2346	0.2103	0.2109	0.2178	0.1955
Sign.	P= .032	P= .055	P= .054	P= .047	P= .075

The set of forest structure relative to live densities also had several variables that were significantly correlated with distance (Table 5.6). All Licor (Licor 11-15) measurements relative to standing basal area correlated with distance at $P < .075$. Blowdown basal area (Blowba_1) relative to live basal was negatively correlated with distance at $P = .019$ (Figure 5.3). The Licor plot in Figure 5.3 has three high values that may have influenced the slope significantly.

Structure related to live densities considers the variation in the parameters of forest structure while partitioning out the variation in structure across the study area. Though the correlations of these parameters with distance reveals many of the same relations as mentioned previously, others provide additional information on the likely causes of the observed variation. Only blowdown basal area relative to live basal area decreases

significantly with increasing distance. All measures of leaf area and canopy closure relative to standing basal area increase significantly with increasing distance. Blowdown stems relative to live stems (Blowst_1) was expected to produce a significant relation with distance because the large clearing left by the tailings produces higher windspeeds at the tailings' edge. However, Blowst_1 showed no significant relationship with distance. This is likely due to the variation in live stem size and density with distance. The number of blowdown stems in high-density stands is likely controlled by greater windspeeds that exist near the tailings' edge where these high density stands occur. Conversely, low-density stands which are made up of larger stems occur further from the tailings' edge. These stands are usually more vulnerable to blowdown than stands with smaller stems, but similar blowdown occurred in these stands because they were partly sheltered from the wind. Also, stands that occur nearer to the tailings' edge are more uneven-aged than those further in. The fact that blowdown volume relative to live volume is significantly higher nearer to the tailings while blowdown stems relative to live stems is not suggests that most blowdown near the tailings' edge is of the largest stems in the stand. Both blowdown and live densities decrease with increasing distance. As a result, the ratio of blowdown to live density remains almost constant with distance.

The significant increase with distance in leaf area and canopy closure relative to standing (live + dead) stems is attributable to an increase in the number of dead stems, and to a decrease in the crown closure or leaf area that is supporting live stems. This is supported by the nearly significant relationship between crown closure and distance ($P = .074$),

though this result should be interpreted with caution since only single crowns were sampled per plot, and only in a select number of plots.

5.1.3 Image variables

Table 5.7 Correlations of image variables with distance N=70						
variable	NIR	Red	Green	Blue	NDVI	
r	-0.0262	0.1713	0.1983	-0.1252	-0.0757	
Sign.	P= .829	P= .156	P= .100	P= .302	P= .533	
variable	S1	S2	S3	S4	S5	S6
r	0.1646	-0.0791	0.1758	-0.028	-0.028	-0.1
P	P= .173	P= .515	P= .145	P= .818	P= .818	P= .410
variable	SunNIR	Sunred	Sungreen			
r	0.0323	0.1517	-0.2768			
Sign.	P= .791	P= .210	P= .020			
variable	Texmean1	Texmean2	Texmean3	Texvar1	Texvar2	Texvar3
r	-0.2934	-0.2998	-0.3166	-0.1162	-0.1368	-0.2196
Sign.	P= .014	P= .012	P= .008	P= .338	P= .259	P= .068

Of the image variables, five were negatively correlated with distance at $P < .068$ (Table 5.7). These included the spectral reflectance in the green band of sunlit canopies (Sungreen), the three average subscene texture measures (Texmean1-3) and the third measure of subscene variation in texture (Texvar3).

Correlations between the selected image variables and distance reveal significant trends in subscene textural and spectral information. Specifically, all three measures of average subscene texture and the third measure of texture variation decrease with increasing distance from the tailings, as does the measure of sunlit reflectance in the green band.

Average reflectance in the green band shows only a moderately significant increase with increasing distance from the tailings ($P = 0.100$). These results suggest increasing greenness and decreasing texture in subscenes further from the tailings. The reasons for this are that closer to the tailings there are: 1. smaller and more uneven aged stands, 2. less crown closure, 3. more dead stems, and 4. blowdown of larger stems resulting in lower leaf area and canopy closure. As a result of these variations in structure with distance, more openings in the canopy or gaps are formed closer to the tailings due to dieback of branches and entire stems. These gaps appear as darker portions in the imagery which affect the overall subscene reflectance, texture mean and texture variation. It is interesting to note that increasing texture of the green band is accompanied by an increase in the reflectance of sunlit portions of the canopy in the green band. This increased reflectance is due to the openings mentioned earlier, which allow sunlight to directly illuminate larger portions of the canopy. Since average subscene reflectance decreases with increasing sunlit reflectance in the green band, a larger dynamic range or more darker than brighter pixels must exist in subscenes with lower average reflectance for darker portions of subscenes to offset brighter ones. This explains why increasing texture is accompanied by decreasing average subscene reflectance and increasing sunlit reflectance.

Significant brightness increases were observed across three or four images of the mosaic from south to north. Bi-directional corrections were not applied to the data and may account for some of the observed variation, although the view angle of the sensor was small and brightness variations in overlap portions of adjacent scenes along a given flight line were not visibly evident. Whatever the source of variation in these images, the trends

with distance from the tailings were significant enough to mask any other gradients of brightness that may have been present.

5.1.4 Summary of soil and forest structure distributions

Significant decreases in iron, calcium and magnesium concentrations were associated with increasing distance from the tailings' edge. Other cations may be leached from the soil in situ due to high acidity at certain times of the year. A temporal analysis of soil metal concentrations along a transect at Kam Kotia was conducted between months and between years (Olthof, 1997). Soil metal concentrations were found to vary significantly from year to year, and from month to month within a given year. The difficulty in relating soil metal concentrations to structural changes in the forest then becomes one of temporal scale. The observed structural changes are due to the integrated effect of 25 years of acid drainage and mine site conditions, while soil chemistry represents a snapshot in time. An examination of the spatial trends therefore leads to conclusions about the integrated effect of mine site conditions as a function of distance from the source of contamination and all of the associated stress factors, and not from a single stress factor which may vary through time.

Forest structural changes that were associated with the above mentioned variations in soil properties included decreases in dead and blowdown volumes and densities, the results of which were a slight increase in live volume with distance and structural changes in live trees. There were more live stems growing nearer to the tailings, and these stems were

significantly smaller than those growing further away. There was a moderate increase in crown closure with increasing distance which, combined with decreasing death and blowdown, produced highly significant leaf area and canopy closure increases with distance. Blowdown volume relative to live volume decreased with distance, but the density of blowdown stems relative to live stems did not, suggesting that blowdown was occurring to uniformly large stems within the stand. This hypothesis was confirmed with an F-test, which showed that the average blowdown stem is significantly larger than the average live stem, and that there was less variation in blowdown stem size than in live stem size. Greater mechanical forces are responsible for the blowdown of larger stems. These results are consistent with those published by Everham (1996), who states that most researchers have found a positive correlation between stem size and catastrophic wind damage.

The small live stems near the tailings' edge likely have lower growth rates than those further from the tailings' edge, though this has never been confirmed. However, the variation in stem size can more likely be attributed to the opportunity for regeneration near the tailings' edge due to increased openings from death and blowdown. The combination of increased blowdown basal area and stems, standing dead stems and smaller live stems closer to the tailings' edge suggests a very dynamic environment. Because blowdown and mortality present opportunities for regeneration, and because the roots of regenerating stems do not propagate deep into contaminated soil horizons, the small regenerating stems are able to survive for a short period of time.

The spatial variation in forest structure provided some clues about the stress factors that contributed to decline. Mortality was caused by a combination of factors, including competition occurring primarily in denser stands. Senescence and direct toxicity were at least partly responsible for the death of larger trees further from the tailings' edge, since mortality occurred in trees that were significantly larger than live trees overall. The variation in blowdown was controlled primarily by the adjacent clearing, and was compounded by changes in soil structure (Essen, 1994; Everham, 1996). Coarse soil texture and lower soil organic matter content were associated with increased blowdown. This relation confirmed field observations, since most blowdown seemed to occur as a result of stems becoming uprooted and overturned. Less adhesive and cohesive forces in the sandier soils with less organic matter result in poorly anchored stems that are prone to blow down. Trousdell *et al.* (1965) also reported significantly greater damage on coarse-textured soils than on medium to fine textured soils.

5.1.4.1 Map layer analysis from interpolation of the 84 point data set

Visual observation of map layers produced from interpolation between the plots showed similarities in the spatial distributions of soil cations. There did not appear to be any links between soil cation distribution and forest structure. A consistent feature appeared in forest and relative structure map layers, and seemed to be related to both elevation and forest type. At 800m east and between 600 and 900m north was an area of greater blowdown relative to surrounding areas, lower leaf area, lesser live basal area and significantly greater blowdown basal area per live basal area (Figure 5.4). The area

corresponded roughly to a topographic rise (**Figure 5.5**) where mixed stands dominated by black spruce and balsam fir occur. This area might be particularly sensitive to changes in the environment because of the forest type (**Figure 5.6**). Field data revealed these plots to have a low natural stem density dominated by medium to large conifers, which confirmed the results of the analysis of variance showing a significantly higher proportion of coniferous blowdown than deciduous. Unobstructed winds and high mechanical forces on conifer canopies might make these stands particularly sensitive to blowdown. Foster (1988) also found that conifers were more susceptible to blowdown than broadleaf species, and suggested less wind obstruction in winter and greater drag on conifers as possible causes.

The maps are useful visual presentations of the variability evident in plots from **Figures 5.1 and 5.2**. Though significant gradients exist, they are not distinct due to soil type and forest type variations that are naturally occurring. For example, increased blowdown occurs to trees growing on coarse-textured soils and to conifers. Though a significant gradient of blowdown exists from the tailings' edge, it is confounded by these naturally occurring factors. Any gradient from the mine site should be superimposed on map layers of these factors, and may be too subtle to see.

Figure 5.4 Map layers reveal a forested area that is particularly affected by minesite conditions, having high blowdown, low live basal area, high blowdown basal area per live basal area and low leaf area.

Figure 5.5 Severely affected area corresponds to a topographic rise (Walsworth, 1998).

Figure 5.6 Black Spruce and Balsam Fir are dominant in affected area (adapted from OMNR).

5.2 Multivariate Analysis

5.2.1 Principal components

The results of PCA are shown in **Table 5.8**. Final statistics and the rotated factor matrices are in **Appendix 2**.

Table 5.8 Results of Principal Components Analysis (PCA)					
Variable set	Component	Significant variables* ($p < 0.01$)	Interpretation	Variance (%)	Cum. Var. (%)
Soil	SOIL-PC1	B, Ba, Cu, K, Mn, Na, Si, Sr, Zn	Cations	48.1	48.1
	SOIL-PC2	Al, Fe, Ca, Mg	Cations	12.2	60.3
	SOIL-PC3	Clay, -Sand, -lnsol, Orgnat, Silt	Soil texture	8.6	68.9
	SOIL-PC4	PH	Soil acidity	7.5	76.4
	SOIL-PC5	Sand – silt	Soil texture	6.0	82.4
Forest structure	STR-PC1	Licor 1 to 5	Leaf area, Canopy closure	45.8	45.8
	STR-PC2	Blowba, Blowstem	Blowdown	14.7	60.5
	STR-PC3	Deadba, Deadstem, Liveba	Live and Dead volumes, Dead stem density	10.6	71.1
	STR-PC4	-Livestem, Stemba	Live stem size and density	8.6	79.7
Relative forest structure	LSTR-PC1	Effective LAI, canopy closure / standing BA	Leaf and canopy density	41.9	41.9
	LSTR-PC2	Deadstem / live stem, Blowstem / live stem, Deadba / liveba	Dead and blowdown stem densities, Dead volume density	20.0	61.9
	LSTR-PC3	-Blowba / liveba	Blowdown density	11.7	73.6
Image	SUB-PC1	-Green, -NIR, -Red, -S2, S4, S5, S6, Sungreen, SunNIR, Sunred	Spectral	47.5	47.5
	SUB-PC2	Texmean 1 to 3, Texvar 1, Texvar 3	Image texture	21.2	68.7
	SUB-PC3	S1, -S3, Texvar 2	Deep shadow, Texture variation	7.5	76.2
	SUB-PC4	NDVI, SunNIR	Sunlit IR reflectance	6.8	83.0

* -ve sign for inverse relationship

5.2.1.1 Soil components

Principal components analysis was performed on each of the four sets of variables. The set of 20 soil variables was reduced to 5 principal components that accounted for 82.4% of

the variance in the original set of variables. Interpretation of the components was made easier by using the rotated factor matrix (Stevens, 1992), and all variables that had loadings of greater than .572 were considered to contribute some information to that component. A Pearson correlation coefficient of .572 is conservative to control the possibility of at least one false rejection. This threshold was arrived at by using a two-tailed test at $P=0.01$ and 80 degrees of freedom.

The components partitioned the information content of the original variables well. The first component explained the variance in certain cations, specifically boron (B), barium (Ba), copper (Cu), potassium (K), manganese (Mn), sodium (Na), silicon (Si), strontium (Sr) and zinc (Zn). The variance in potassium (K) was not significantly related to the first component according to the criteria mentioned above, but was included because it had its highest loading with the first component, with most of the remainder of its variance in the second component. This first component accounted for 48.1% of the overall variance in the data. A previous analysis of soil metals along a transect at the Kam Kotia mine site produced similarly high correlations between soil cations (Olthof, unpublished).

The second component also explained variance in certain cation concentrations; those being aluminum (AL), iron (FE), calcium (CA) and magnesium (MG). All four had very high loadings on the second component ($r > .79$). The second component accounted for 12.2% of the overall variance in the original set of variables.

This component seems to contain two distinct sets of information that are highly related,

those being plant macro nutrients in calcium and magnesium and toxic metals in aluminum and iron. Three of these four cation concentrations decrease significantly with increasing distance from the tailings' edge. Though these two factors are orthogonal, the variables that explain them are not. An examination of the correlation matrix of the set of variables reveals that most cation concentrations are significantly related to each other, including cations from factors 1 and 2. This is caused by the principal components analysis which forms linear combinations of the original variables to partition the variance in the set. Factors are interpreted by the variable-factor correlation coefficients. This coefficient explains the overlapping variance between the factor and the variable, but tells nothing of the overlap between variables of separate factors. The variables of different factors can therefore be significantly related to each other while the factors they are interpreted as being part of are orthogonal.

The third soil component explained the variance in soil texture, organic matter and insoluble content. Specifically, it explained an increase in clay (CLAY), silt (SILT) and organic matter (ORGMAT) accompanied by a decrease in sand (SAND) and insoluble content (INSOL). All of these variables have significantly high loadings on the third component. This component explained 8.6% of the variance in the original set.

The fourth component explained the variance in soil acidity (pH), which had a very high loading on this component ($r = .92$). The fifth component explained the variation in the sand-silt (SANDSI) size fraction, which had a very high loading on the last component ($r = 0.90$). The fourth and fifth components explained 7.5 and 6.0% of the variance,

respectively, in the original set of soil variables.

Because of the problem of interpreting meaningful relations between variables using principal components only, an examination of the correlation matrix was performed to support the interpretation of the components and to reveal other relations, as was recommended by Stevens (1992). This additional step will also make the subsequent canonical analysis more meaningful. Relations were interpreted as being significant at $P = 0.002$ in a one-tailed test. Significant relations that were not found in the components analysis were between organic matter content and concentrations of beryllium, copper, manganese, and zinc. These relationships were expected, since organic matter is directly related to clay content, and both of these soil fractions possess a large number of exchange sites to which these soil cations can bind.

Though soil pH was the only variable that was interpreted as being significant in the fourth component, there were significant relations between soil pH and other soil variables. Increasing soil pH was related to increasing concentrations of calcium, sodium, strontium and magnesium. Except for strontium, these are base-forming cations and therefore contribute to increasing soil pH. Soil pH was also directly related to the silt soil texture fraction, and inversely related to sand and insoluble content. These relations were also expected since the silt fraction relates directly to the concentrations of base-forming cations, while the sand fraction is primarily composed of insoluble silica-an acidic mineral. Generally, cation concentrations were directly related to the amount of silt and clay fractions, and inversely related to the sand fraction and insoluble content. Cations bind to

the exchange sites of negatively charged particles of the smaller soil texture fractions. A sandier soil has fewer exchange sites, is more acidic and is more readily leached than a finer textured soil. Therefore, cations were found in higher concentrations in a fine-textured soil than in a sandier one.

5.2.1.2 Forest structure components

A principal components analysis on the forest structure data reduced 13 variables to 4 principal components that accounted for 79.6% of the variance in the original set of structural variables. The variance in the set was partitioned nicely into interpretable components. The same criteria for the inclusion of a variable in the interpretation of a component was used for this set of variables as was used for the set of soil variables.

The first forest structure component explained the variance in Licor measurements (LICOR 1-5) which represent leaf area and canopy closure. All five of these variables had very high loadings on the first component ($r > 0.86$). The first component accounted for 45.8% of the variance in the original set of variables.

The correlation matrix also revealed a direct relationship between live basal area and leaf area, and an inverse relationship between leaf area and live stem density. These relationships were expected, since more leaf area is required to support a greater live volume. Also, denser stands are made up of smaller stems, which generally have less canopy thickness than stands with larger stems, and therefore less leaf area. An inverse

relation between live stem basal area and live stem density is explained in the fourth factor.

The second component clearly explained the variance in blowdown. Both blowdown stems (BLOWSTEM) and blowdown basal area (BLOWBA) had very high loadings on the second component ($r > 0.89$). This component explained 14.7% of the variance in the set of forest structure variables.

Since blowdown stem numbers and blowdown basal area are so highly related, it can be inferred that tree blowdown is predominantly occurring in a trees of similar stem size. Blowdown in a forest stand tends to occur to the larger stems, simply because the force of the wind is greater on a larger crown, and because of the increased leverage that the wind has about a fulcrum at or near the base of a taller tree. The correlation matrix also reveals significant inverse relations between all Licor measures of leaf area and canopy closure and blowdown basal area and stems. These relationships are expected, especially if much of the blowdown had occurred recently so that the gaps that were formed did not have the time to become occupied by understory or surrounding stem and branch leaves.

The third component explained the variance in the amount of standing dead trees. Specifically, it explained the variance in dead basal area (DEADBA) and dead stems (DEADSTEM). Both of these variables had significantly high loadings on the third principal component ($r > 0.81$). Variance in live basal area (LIVEBA) was also included in the third component, though it did not meet the criteria mentioned above for the inclusion of a variable in the interpretation of a component. Live basal area had a loading of 0.52 on

the third component, which was the highest loading that this variable had on any of the components. The third component therefore explained 27% of the variance in live basal area, with much of the remainder of the variance being explained by the first component. The third component explained 10.6% of the variance in the set of forest structure variables.

An increase in dead volume in these stands is likely the result of greater live volume and greater competition. Dead basal area and dead stem numbers are highly related because mortality tends to occur to stems of a uniform size. The relationship between blowdown basal area and blowdown stem density is more significant than the relation between the two measures of dead volume. This suggests that while mortality is occurring to stems of a uniform size, there is greater variability in the size of dead stems than in the size of blowdown stems.

The probable causes of mortality of small and large stems are different. A large proportion of smaller stems in the stand likely die as a result of competition that causes thinning. Senescence is likely responsible for the mortality of some of the larger stems in the study area. Direct toxicity and soil structure degradation usually cause smaller stems to die first, provided that the toxicity and soil degradation is evenly distributed throughout the soil profile. Smaller stems tend to be less able to cope with prolonged periods of stress because they do not have the reserves of larger stems to propagate their roots into more hospitable soil horizons (Milton *et al.*, 1989).

The fourth component explained the variance in the number of live stems (LIVESTEM) as well as the variance in average stem basal area (STEMBA). Both of these variables had significant loadings on the fourth principal component and were inversely related. The fourth principal component accounted for 8.6% of the variance in the original set.

The fourth forest structure factor explains an inverse relation between live stem numbers and average live stem basal area. This relationship is expected, since a site is capable of supporting a certain amount of live biomass, which is a function of both stem density and stem basal area (as a measure of tree volume). At any given site, stand basal area establishes itself shortly after a disturbance and maintains itself until the next disturbance through death by competition as average stem basal area increases.

5.2.1.3 Relative structure components

The set of 11 variables that described forest structure relative to live densities was reduced to 3 components through principal components analysis. These three components accounted for 73.6% of the variance in the original set of variables. The same criteria were used for the inclusion of variables in the interpretation of a component as before. The components analysis partitioned the variance nicely into interpretable factors.

The first component clearly explained the variance in leaf area and canopy closure. All five of the Licor (LICOR1-5_1) measurements relative to standing (live and dead) basal area had very high loadings on the first component ($r > 0.81$). This component explained 41.9% of the variance in the original set of variables.

The measurements that formed the first component were expected to be highly related to each other. The correlation matrix revealed a significant direct relationship between leaf area relative to standing basal area and blowdown basal area relative to live basal area. This relationship was interpreted as high density stands (where blowdown volume per live volume is less) having less standing volume per leaf area. Therefore, leaf area increases at a lesser rate than standing volume from high to lower density stands. A significant inverse relationship also existed between effective LAI relative to standing basal area and dead relative to live basal area. This relationship was expected, and was interpreted as greater dead volume per live volume having less leaf area per standing volume. A similar relationship existed between dead stem density and effective LAI. Measures of leaf area per standing volume were also inversely related to average stem basal area, as they were in the forest structure relations.

The second component explained the variance in dead and blowdown stems relative to live stems (DEADST_1), (BLOWST_1) as well as variance in dead basal area relative to live basal area (DEADBA_2). All three of these variables had significant loadings on the second component ($r > 0.73$). This component explained 20.0% of the variance in the set of structural variables relative to live densities.

Blowdown basal area relative to live basal area was not included in this component but was included in the third. It has already been determined that absolute blowdown stems relate to blowdown basal area, and this led to the conclusion that blowdown was occurring to a uniform stem size across the study area. However, it was also determined

that live basal area was not related to live stem density. Because this set of variables considers the forest damage variables relative to live basal area and live stem density, and because these two measures of live volume were not related, then the two measures of blowdown density were also not related in this set.

The third principal component explained the variance in live stem basal area (STEMBA_1), crown closure (CROWNC_1) and blowdown basal area relative to live basal area (BLOWBA_1). Crown closure did not have a significant loading on the third component ($r = 0.569$), but was deemed sufficient considering how conservative the test level was and how close the loading was to the test level. Both crown closure and live stem basal area were inversely related to blowdown basal area. The third component accounted for 11.7% of the variance in the original set of variables.

In addition to explaining the variation in blowdown per live basal area, the third component also explained the variation in average stem basal area. An inverse relationship between these two variables existed because higher density stands tend to have more blowdown volume per live volume. Again, this relationship is explained by the fact that larger stems blowdown more easily in high-density stands located near the tailings' edge.

5.2.1.4 Image components

Principal components analysis reduced the set of image variables from 20 variables to 4 components that accounted for 83% of the variance in the original set. The criteria for the

interpretation of a variable as part of a component were the same as in prior components analyses.

The first component clearly explained the variance in spectral information. Specifically, it explained the variance in average green, red and NIR image brightness of the subscenes (GREEN), (RED) and (NIR). It also explained the variance in certain shadow fractions (S2, S4-S6) as well as the variance in the sunlit reflectance of canopies in green, red and NIR (SUNGREEN), (SUNRED) and (SUNNIR). The average reflectance of the subscenes in the three bands and S2 were inversely related to shadow fractions S4-S6 and to the sunlit reflectance of canopies in the three bands. This first component explained 47.5% of the information content in the original set of image variables.

All of these measures that formed the first component were directly related to the first component except for S2 and average subscene reflectance in the three bands, which were inversely related. Sunlit and average subscene reflectance are inversely related because direct illumination of the larger stem canopies increases in uneven and lower average reflectance sites. It was thought that increases in sunlit reflectance were offset by large contiguous dark fractions to produce lower average subscene reflectance. The combination of bright sunlit fractions and large dark fractions were expected to produce high texture. However, the correlation matrix revealed less texture in subscenes with high sunlit reflectance and low average reflectance.

The association between these variables that explained the decrease in texture was found by examining the variation in shadow fractions. Shadow fractions S4-S6 generally have very high positive correlations with sunlit reflectance. Shadow fractions S1 and S2 are inversely related to sunlit reflectance. The relationship, however, is less significant than that which exists between brighter shadow fractions and sunlit reflectance, indicating more variability in the size of deep shadows. Though generally bright and dark shadow fractions are inversely related, greater variation in deep shadows likely produces large contiguous bright and dark areas simultaneously in subscenes with the greatest sunlit reflectance. It was therefore hypothesized that large bright contiguous fractions must accompany large dark shadow fractions for sunlit reflectance to be inversely related to average reflectance, texture and texture variation. In this case, texture only occurs along edges where two shadow fractions meet, with little or no texture within bright and dark fractions. The decrease in texture variation indicates a gradual change in tone along edges producing a small amount of texture in these areas, while low texture occurs in large contiguous bright and dark fractions.

It should be noted that texture and sunlit reflectance are both inversely related to distance, and therefore were expected to be directly related to each other. However, as mentioned previously, texture and sunlit reflectance are inversely related as well. Therefore, while measurements of texture and sunlit reflectance decrease with distance over the entire transect, one measure must increase while the other decreases over shorter distances. This suggests that sunlit reflectance and texture may be able to provide complementary orthogonal information about variations along the transect. The variation in texture is

explained in the second component, and therefore is orthogonal to the spectral information that is explained in the first component.

Shadow fractions S1 and S2 represent the deepest shadow fractions in the imagery. The variation in these fractions can therefore be attributed to the variation of gap size in the canopy. These shadow fractions were directly related to texture variation in the correlation matrix. This supports the hypothesis that texture variation can provide additional structural information to texture by explaining some of the variance in gap size relating to deep shadow fractions. Shadow fractions S3 to S6 represent brighter fractions corresponding to direct and diffuse sunlit portions of canopies. These shadow fractions are generally inversely related to darker fractions, and therefore also inversely related to texture variation. Therefore, brighter subscenes with larger sunlit fractions generally possess relatively uniform texture. Shadow fraction S3 was inversely related to texture. This fraction represents intermediate shadow, which is generally located closest to the subscene mean. Therefore, a larger intermediate shadow fraction indicates that more of the subscene brightness falls closer to the subscene mean. The standard deviation of these subscenes is therefore generally lower, producing less texture.

The second component explained the variation in textural information of subscenes. The three measures of average texture (TEXMEAN1-3) as well as the three measures of texture variation (TEXVAR1-3) were all significantly correlated with the second component. It should be noted, however, that the second measure of texture variation (TEXVAR2) also had a significant (and greater) loading on the third component. The

variation in TEXVAR2 was therefore almost equally partitioned between components 2 and 3, but was included in the third component because of its higher loading on it.

TEXMEAN1-3 all had very high loadings on the second component ($r > 0.96$), each one explaining almost all of the variation in the second component. The second component accounted for 21.2% of the variance in the original set.

The third component contained a combination of spectral and textural information. It explained the variation in shadow fractions S1 and S3, as well as the variation in the second measure of texture variation (TEXVAR2). Shadow fraction S1 and TEXVAR2 were inversely related to shadow fraction S3. All of these variables had significant loading on the third component ($r > 0.62$). The third component explained 7.5% of the variance in the original set of variables.

Shadow fraction S3 was inversely related to the third component as well as to S1 and texture variation 2. The correlation matrix revealed that S3 was inversely related to all measures of texture variation. Therefore, there is less texture in subscenes that have a large intermediate shadow fraction, and there is less variation in that texture. The subscenes having high S3 fractions are therefore generally relatively smooth throughout. The fourth component explained the variation in the NDVI, as well as the variation in sunlit reflectance in the NIR. The correlation matrix revealed that the NDVI was significantly related to sunlit reflectance in the NIR, and nothing else, while the sunlit reflectance in NIR was significantly related to sunlit reflectance in other bands as well as texture and certain shadow fractions.

Component four explained the variation in the normalized difference vegetation index (NDVI), as well as the sunlit reflectance of canopies in the NIR (SUNNIR). Both of these variables had significant loadings on the fourth component ($r > 0.69$). The fourth component only accounted for 6.8% of the variance in the original set of image variables.

5.2.2 Canonical correlation

Four separate canonical analyses were conducted to determine relationships between the four sets of principal components (Table 5.8). The first canonical analysis was between the set of soil property components and the set of forest structure components. The second was between the set of soil components and the set of relative structure components. The third was between the set of forest structure components and the set of image components and the fourth was between the set of relative structure components and the set of image components. Only the first variate pair was determined to be significant in each of the four canonical analyses, and therefore these variate pairs were the only ones that required interpretation.

Table 5.9 First variate pair of soil – forest structure canonical analysis				
<i>Analysis</i>	<i>CV1</i>	<i>CV2</i>	<i>Sign.</i>	<i>R</i>
1	-.932 SOIL-PC3	.898 STR-PC2	0.083	0.46

5.2.2.1 Soil – forest structure canonical analysis.

The first canonical correlation analysis sought relationships between the set of soil principal components and the set of forest structure principal components. Four canonical variate pairs were extracted, of which only the first was significant ($P = 0.083$) in a chi-square test with 20 degrees of freedom. The correlation between this variate pair was $r = 0.46$, and explained an inverse relationship between the third soil principal component (SOILPC3) and the second forest structural component (STRPC2). Both of these components loaded equally and highly on their respective canonical variates.

This variate pair (**Table 5.9**) was interpreted as a change in soil texture towards larger soil fractions and a decrease in soil organic matter content, which were associated with an increase in both blowdown basal area and blowdown stems. Therefore, more blowdown occurs on sites that have sandier soil and less organic matter. This relation confirmed field observations, since most blowdown seemed to occur as a result of stems becoming uprooted and overturned. Less adhesive and cohesive forces in the sandier soils with less organic matter result in poorly anchored stems that are prone to blow down. Trousdell *et*

al. (1965) also reported significantly greater damage on coarse-textured soils, where there was 30% damage from wind than on medium to fine soils, where there was only 5% damage.

Table 5.10 First variate pair of soil – relative structure canonical analysis.

<i>Analysis</i>	<i>CV1</i>	<i>CV2</i>	<i>Sign.</i>	<i>r</i>
2	.782 SOIL-PC4 - .427 SOIL-PC3 - .410 SOIL-PC1	- .974 LSTR-PC3	0.112	0.428

5.2.2.2 Soil – relative structure canonical analysis.

The second canonical analysis was between the soil principal components and the forest structural components related to live densities. Three variate pairs were extracted, however, only the first was moderately significant ($P = 0.112$) (Table 5.10). The correlation between this variate pair was $r = 0.43$, describing a relationship between the first, third and fourth soil components (SOILPC1, SOILPC3 and SOILPC4) and the third structural component (LSTRPC3). The loading of the fourth component on the soil variate was nearly twice that of the first and third components in absolute terms. The first and third soil components were inversely related to the fourth, and directly related to the third structural component. The third structural component explains almost all of the variance in the structural canonical variate, having a correlation of $r = -0.974$ with the variate or an eigenvalue of 0.95. The soil component related to soil pH (SOILPC4)

explains more than three times the variance in the soil variate as either soil component 1 or 3.

This variate pair related relative blowdown volume to soil texture, soil acidity and soil metals. Specifically, this variate pair explained a relationship between increasing soil pH, accompanied by a change in soil texture towards a sandier soil and a decrease in certain metal cations with increased relative blowdown basal area. Sandier soils have fewer exchange sites, and therefore fewer cations are retained. However, sandy soils are also generally more acidic, and an increase in soil acidity usually accompanies a decrease in soil cations.

This relationship may not be reliable due to the moderate significance of the variate pair ($p = 0.112$), or simply because of flaws in the multivariate analysis. An example of the latter may be that the use of such data transforms of the original variables into orthogonal components does not account for the overlapping variance between variables that are assigned to different components. In some instances, this can produce meaningless results.

There appeared to be no significant relationships between soil cation concentrations, pH and forest structure. The soil concentrations that were measured represented a snap shot of soil chemistry at a particular time, while the variation in forest structure is caused by the integrated effect of 25 years of acid mine drainage and windblown effects. It was shown that soil chemistry at the Kam Kotia mine site can vary significantly from month to month

and from year to year (Olthof, unpublished). It was therefore hypothesized that forest structure would relate better to more stable soil properties such as soil texture. This has been shown to be the case. However, it is unclear whether this relation is due to soil degradation causing less cohesion in the soil, or if this relation is simply due to the adjacent clearing. It should also be stated that although there is no apparent relationship between soil cations and forest structure, both show a significant gradient with distance from the tailings.

Table 5.11 First variate pair of forest structure - image canonical analysis

<i>Analysis</i>	<i>CV1</i>	<i>CV2</i>	<i>Sign.</i>	<i>r</i>
3	.646 STR-PC1 - .537 STR-PC2 - .525 STR-PC3	-.56 SUB-PC1 - .748 SUB-PC2 + .357 SUB-PC3	0.096	0.462

5.2.2.3 Forest structure – image components canonical analysis.

The third canonical analysis (Table 5.11) described the relations between the set of forest structure variable components and the set of image components. Four canonical variate pairs were extracted, of which only the first was quite significant ($P = 0.096$). The variate pair was correlated at $r = 0.462$ and described a linear relation between image components 1,2 and 3 (SUBPC1-3) and structural components 1,2 and 3 (STRPC1-3). The third component in the image variate was inversely related to components 1 and 2, and had less than half of the loading of the second component in absolute terms, explaining more than four times the variance in structure. The loadings of the components on the structural side

were almost equal in magnitude, while the second and third structural components were inversely related to the first.

This analysis (**Table 5.11**) produced a variate pair relating image textural, spectral and structural information to the measurements of effective LAI and canopy closure, as well as blowdown and dead volume and density. Specifically, the structural variate that explained increasing leaf area and canopy closure, and decreasing blowdown and dead volume and density, was related to the image variate explaining increasing average spectral brightness, decreasing sunlit brightness and decreasing texture. Sunlit and average subscene brightness are inversely related because direct illumination of the larger crowns increased in plots of uneven and lower average brightness.

Shadow fractions S1 and S2 represent very deep shadow fractions. The variation in these fractions can therefore be attributed to the variation of gap size in the canopy. Correlation revealed that these shadow fractions were directly related to texture variation. This supports the hypothesis that texture variation can provide additional structural information to texture by explaining some of the variance in gap size relating to deep shadow fractions (Olthof and King, 1997), and thus to forest structural measures such as LAI and canopy closure.

5.2.2.4 Relative structure – image components canonical analysis.

The fourth canonical correlation analysis provided a similar relation between the set of

structural components related to live densities and image components as the third (**Table 5.12**). Three canonical variate pairs were extracted, of which the first was very significant at $r = 0.477$, $P = 0.02$. It described a relation between three subscene components (SUBPC1-3) and the first three structural components related to live densities (LSTRPC1-3). On the structural side, the three components had similar loadings on the variate, and components 1 and 3 were inversely related to the second component. On the image side, the second component related to texture had a moderately higher loading on the variate than components 1 and 3 (0.672 vs 0.507 and 0.540, respectively), explaining 16% more variance in the structural variate than either of those two components. The third image component was inversely related to image components 1 and 2.

Table 5.12 First variate pair of relative structure – image canonical analysis

<i>Analysis</i>	<i>CV1</i>	<i>CV2</i>	<i>Sign.</i>	<i>r</i>
4	-.594 LSTR-PC1+.608 LSTR-PC2 - .526 LSTR-PC3	.507 SUB-PC1+.672 SUB-PC2 - .54 SUB-PC3	0.02	0.477

The fourth analysis, first variate pair revealed a relationship between relative structure and the image spectral and textural components. Specifically, the relative forest structure canonical variate described a decrease in relative leaf area and canopy closure, an increase in dead and blowdown basal area and stems relative to their live counterparts, and a decrease in stem size. This forest structure variate related to an image variate that explained an increase in texture and texture variation and a decrease in average subscene brightness with increasing sunlit brightness. Since the components in the relative structure

variate partitioned out some of the variance due to differences in structure related to forest type, and because the relationship between the variates was highly significant, this variate pair was selected as the starting point for the image-based health index.

5.3 Health Index

5.3.1 Defining the field-based health estimate

The field-based health estimate was taken as the structural canonical variate from the fourth canonical correlation analysis because it explained a natural variation in health. This variate was formed from the linear combination of structural components 1, 2 and 3 related to live densities. These three components had almost equal loadings on this variate used as the field-based health estimate, explaining some variation in effective stand LAI and canopy closure, dead and blowdown density and volumes as well as average tree size. An examination of the component loadings reveals that effective LAI and canopy closure explain between 64 and 90% of the variation in the first component – depending upon which Licor measurement is used. The second factor explains between 52 and 62% of the variance in dead and blowdown stems relative to live stems, as well as dead basal area relative to live basal area. The third factor explains 56% of the variation in blowdown basal area relative to live basal area and 45% of the variation in stem size. The third factor also explains 32% of the variation in crown closure (which had been excluded from the interpretation of this component because of lack of significance).

The field-based health estimate explains the variation in the canopy density component as

well as the variation in the canopy gap component, as measured by numbers of blowdown and standing dead stems. These two separate components of the field-based health estimate are related since an increase in blowdown and death will decrease canopy density. However, canopy density also takes into account the density of the live crowns in the stand, and therefore provides additional information to blowdown and dead stems by giving some indication of the condition of remaining live crowns. The field-based health estimate therefore quantifies canopy condition as canopy gaps and overall canopy density relative to live volume. Since the estimate is formed by the addition of orthogonal components, a large contribution from a single component can provide an equal health estimate to smaller contributions from three separate components.

5.3.2 Development of the image-based health index

Variables that had high loadings on the components that formed the image variate in the fourth canonical analysis were chosen as the independent variables for regression with the field-based health estimate. The components that formed the field-based health estimate do not explain all of the variance in the variables themselves. The variance of a single variable might be partitioned among several components. For these reasons, the variables with the highest loadings on the individual components that form the image variate do not always explain the maximum amount of variance in the structural variate (field-based health estimate). Therefore, several image variables were tested in the multiple regression with the field-based health estimate to form the image-based index.

The image-based health index performed best as a linear combination of sunlit brightness of the green band, contrast texture mean and contrast texture variation with a window size of 3 x 3, and a sampling distance of 1 to the right. A stepwise regression was performed so that all the variables that were entered into the equation contributed significant information to the index at $P_{out} = .100$. A summary of the stepwise procedure is presented in **Table 5.13**. A full statistical report is in **Appendix 2**.

Table 5.13 Summary of stepwise regression					
<i>Step</i>	<i>Variable</i>	<i>r</i>	<i>SE</i>	<i>% resid. var.</i>	<i>Sign. F</i>
1	Sungreen	.33	.94	NA	0.0052
2	Texmean1	.54	.84	20.5	0.0000
3	Texvar1	.58	.82	5.8	0.0000

The sunlit brightness in the green band explained 11% of the variance in the field-based health index. The F-statistic shows that the sunlit brightness by itself is significant at the .0052 level. This test is a quotient of the variance along the regression line divided by the residual variance, or the variance in the direction that is perpendicular to the regression line. It is a measure of the dispersion of the residuals around the regression line. The second step included the measure of average texture into the regression. The inclusion of this variable explained 20.5% of the residual variation from the previous regression. The dispersion of the residuals decreased so that the F-statistic became significant at the 0.0000 level. The inclusion of texture variation in the third step explained 5.8% of the residual variance from the previous regression. This amount of variance is significant at the .05 level. Therefore, texture variation explains a significant amount of information

beyond that accounted for by the linear relationship of the field-based health index with average texture and sunlit brightness in the green band. The standard error decreased consistently from .94 in step 1 to .84 in step 3 of the regression. An examination of the residual plot confirmed that the linear-fit was the appropriate choice of model (Figure 5.7).

The sunlit brightness of the green band was chosen as the spectral measure from the first component in the image variate because it performed slightly better than average brightness. Sunlit brightness was originally included as an image variable because it was hypothesized that it would relate to chlorosis or foliar chemistry. However, this did not prove to be the case. An examination of the correlation matrix of the image variables shows that sunlit green brightness is highly and inversely related to average green brightness. It is thought that sunlit brightness provides some additional information about forest health because it relates to the unevenness of the forest stand. More direct, and less diffuse reflectance occurs in stands that have less overall brightness. This increase in directly sunlit portions of the canopy is likely caused by the unevenness of the stand.

The image variables that form the image-based health index were all extracted from the green band. Therefore, no information from the difference in reflectance between bands was used to explain the observed variation in forest health. This was due to the nature of the data that was acquired. Aperture settings could be changed independently for individual bands. The aperture settings that were used to acquire these data resulted in inconsistent brightness between flight lines. The resulting spectral data were judged to be

Figure 5.7 Residual plot from multiple linear regression of image-based health index

of poor quality. Better quality spectral data could certainly add to the image based health index.

5.3.3 Accuracy assessment

An accuracy assessment of the image-based health index was conducted to see how well the index would perform in an operational setting, and to determine where its limitations lie. The field-based forest health measure was assumed to be the most correct integrative reference measure. Both the field-based measure of forest health and the image-based health index were classified into three classes with equal ranges representing low, medium and high damage. The accuracy assessment was conducted by subtracting the rank of the field-based health from the image-based health index rank. An analysis of the frequency distribution of the differences in ranks was conducted to see how well the image-based index performed.

The results of the accuracy assessment show that 52.9% of the plots were classified into the same health class by the image-based health index as the field-based health estimate. If this index were to be used in an operational setting, where some treatment were to be applied to remedy poor health, a forest manager might be interested in using the image-based health index to predict the same or worse health on the ground. He or she might be interested in doing so to be conservative in order to minimize the amount of times that a site of poor health is overlooked for treatment. In this case, he or she would be correct in predicting the same or worse health 77.2% of the time.

The field-based health estimate provides a great deal of information about forest stand structure. The cause of the variation in forest health for any particular stand cannot be inferred from this health estimate by itself. An examination of the rankings of the individual structural parameters that contribute to the forest health index confirms this. These rankings are from 1-84 as unhealthy to healthy. Therefore, effective LAI was ranked in ascending order since more leaf area is a symptom of greater health, while blowdown stems was ranked in descending order since greater numbers of blowdown stems indicate poorer health. Image variables were ranked in a similar way from 1-70. The plots where extreme differences in the field-based measure of forest health and the image-based health index existed were examined for their rankings of structure related to health to determine under which structural conditions the image-based health index did not perform well, and why.

There were two plots (A410 and E360) where the image-based health index severely over-estimated the field-based measure of health. Both of these plots had a large amount of live standing volume relative to other plots, and relatively low effective LAI and canopy closure. Both plots also had a great deal of blowdown stems per live stems or dead stems per live stems and an intermediate amount of blowdown volume per live volume. Therefore, both of these plots had many, relatively small blowdown or dead stems. The reason that the image-based health index severely over-estimated health in these two cases was the 50cm spatial resolution of the imagery. At this spatial resolution, both average texture and texture variation indicate relative smoothness and high average reflectance because of a large amount of live volume. The low effective LAI, the great number of

blowdown stems and their small size result in small (sub-50cm) within-crown or canopy gaps. This suggests that higher resolution imagery would likely provide better health information related to the measured structural parameters for these extreme cases.

The single case (C210) where the image-based health index severely under-estimated field-based health did so because of a combination of low average reflectance, rough average texture and texture variation. The reason for the severe under-estimation is unknown, since the rank of all the structural parameters falls somewhere near the median rank.

6 CONCLUSIONS

6.1 Spatial Variation

An examination of the spatial variation in soil, forest structure and image variables has led to a better understanding of the combined effects of mine site conditions on forest structure and on resulting high-resolution digital imagery. Stress factors that were responsible for the observed variation in forest structure were inferred based on the processes governing the stress factors, and on the spatial variation of forest structure itself. Proximity to the tailings has a significant effect on forest health, with plots nearer to the tailings having less leaf area, and more blowdown and mortality. The spatial patterns indicate that variation with increasing distance is due more to wind effects, competition, stand type and soil texture than to soil toxicity, which is above toxic thresholds throughout the site for some metals and may simply be contributing to overall decline.

6.2 Health Index

The field-based estimate of forest health is a measure of canopy condition. It is the linear combination of three complementary and orthogonal components; those being mortality, blowdown and effective leaf area. The contribution of mortality and blowdown is a measure of gaps or holes in the canopy, while effective leaf area is a measure of overall gap area plus the condition of the remaining live crowns. The field-based estimate provides an objective and relative measure of overall stand health.

It was hypothesized that the use of texture variation in the estimation of a forest structure parameter such as effective LAI would provide additional information that is not captured by average texture. This thesis demonstrates that there is information in the texture variation within subscenes that can be related to the size and distribution of gaps in the canopy as measured by effective LAI, blowdown and mortality. Measures of the frequency distribution of texture other than the mean should be considered as potential sources of information when texture from high resolution digital imagery is being used for the estimation of any forest structure parameter. This thesis shows that texture standard deviation can increase the accuracy of estimation of a combination of health-related forest structure parameters when combined with a simple spectral measure and texture mean.

The combination of spectral and spatial image information in the formulation of a forest health index for remote sensing-based mapping and monitoring has been demonstrated. In the highly complex and natural setting of the study site, significant spatial variations were found in field and image variables in relation to the contaminant source. Mechanical and chemical causal factors of forest stress were evident in the data proving that the open tailings are a major source of degradation in forest adjacent to the mine site.

6.3 Limitations

The accuracy of plot locations within the imagery is difficult to assess properly with the data collected for this thesis. Some 30 targets were laid out in the forest under canopy

openings and more were laid out in the tailings. The targets on the tailings were clearly visible, but few targets in the forest were visible in the digital imagery. Plot location was probably not in error by more than a few metres in most cases, which would not have significantly affected the analysis unless those few metres consistently represented some significant change in forest structure.

High spatial accuracy was not considered to be essential for these results to be meaningful. The spatial analysis of forest structure variables showed progressive trends in forest structure with increasing distance from the tailings. The spatial analysis of image variables showed similar trends. Gradients of forest structure and image variables coincide, and therefore some variation in forest structure can be explained by the variation in image parameters, even if plot and subscene locations do not align exactly. Tighter control over the spatial accuracy of plot locations would have likely produced slightly better results than those obtained here.

Spectral intensity information in sunlit green brightness accounts for only 11% of the variance in the field-based health measurement, while spatial information in texture and texture variation explains the additional 23%. This demonstrates the strong link between image spatial information and forest structure changes resulting from stress due to soil structure, the adjacent tailings clearing, and soil contamination. The forest health index could have been improved had the spectral data been better, since all bands showed significant differences in brightness across the study area. These differences were thought to have been caused by changing camera settings during the

flight by the operator. Subsequent spectral matching in overlapping areas improved the data considerably, but brightness variations persisted. Since the data were mosaiced one frame at a time, it was thought that the spectral matching may have accumulated a small error at each matching, producing significant error at the end of the mosaicing process from one side to the other. In addition, camera system parameters were known to have adversely affected image quality. It was beyond the scope of this research to evaluate all aspects of image formation, but the camera system suffers from the following limitations that should be improved upon for further research. The shutter speed of 0.003-0.005s resulted in image motion during exposure of about 0.2m at an aircraft velocity of 40m/s. This was about $\frac{1}{2}$ a pixel and may have degraded image texture information through image smear, although $\frac{1}{2}$ a pixel image motion is generally considered acceptable in practice. The interference filters used in front of the camera lens do not stop during exposure due to the inertia of the filter wheel. Instead, they move about 1-2 steps, equivalent to 3.6 degrees, or about $\frac{1}{5}$ of the angle of view of the sensor during exposure. This may cause some additional image smear and vibrational distortion. The lens utilized was a standard low cost Nikkor lens. It undoubtedly contributed to: 1. radiometric distortion such as vignetting and $\cos^4$ type fall-off and 2. spatial distortion including degraded resolution from a poorer point spread function and modulation transfer function, greater radial and tangential geometric distortions, and poorer focussing capability than would be achieved with an expensive corrected lens. The design of the sensor purposely included a small view angle ($\pm 9.7 \times 7.9$ degrees) to minimize the above effects, but it is recognized that they are present to some degree (King, 1995).

All image-based measurements of forest damage were derived from the green band since it appeared to be the most consistent across the study area. The variation in brightness from one side of the mosaic to the other was thought to produce less variation in textural response than spectral response since texture is a local measure of relative brightness differences. Shadow fractions were derived from an additive RGB composite, and therefore the variation in brightness likely accounted for the lack of relations between forest structure and shadow components. More consistent multi-spectral data across the study area would have contributed more information on spectral symptoms of damage.

6.4 Potential Applications

This study has demonstrated that high-resolution remote sensing can allow forest and ecological managers to quantify variations in stand structure, which can be related to forest health. Forest health assessment is becoming increasingly important in global studies of climate change and sustainable forestry. The Montreal Process, outlined in 1995, requires that countries who participate report annually on criteria and indicators of forest health and sustainability. The Kyoto Protocol, established in 1997, will force countries to budget carbon emissions with carbon fixation or sequestration in their carbon sinks. Carbon credits will be traded on a world market based on surpluses and shortages of carbon emission and sequestration by forests. The establishment of this trade will require that the participating countries keep an inventory of carbon sinks, rates of sequestration

and rates of carbon emissions. Forest health information plays an important role in this inventory, since rates of carbon sequestration are directly affected by forest health.

In an operational sense, the methodology that was developed in this thesis can be used to assess localized variations in forest health and structure resulting from different stress factors. This methodology may also be particularly useful to assess localized forest health variation in areas where there are known 'edge effects'. This study was conducted in an area where considerable damage has been observed due to the effects of the adjacent clearing on micro-climate, producing significant blowdown. Other studies, by Odin (1976), for example, have also shown that edge effects may extend more than 175m into stands that are unaffected by other stress factors, and perhaps more where multiple stress factors exist. Along the edges of clearcuts where considerable blowdown is known to occur, forest managers can assess not only the direct and immediate impacts of the cut on the forest, but also the impacts on the adjacent forest environments. If this information were routinely used in forest management decisions, then it would force logging companies re-consider their choice of cutting practice. Another example for the practical use of this type of information would be in the establishment and maintenance of protected areas, where edge effects are a concern to the ecological health of the protected area. Logging and salvage companies can also benefit from this type of information. Salvage operations are routinely conducted to make use of trees that have been blown down or affected by disease or infestation. Forest health information can be used to make salvage

operations more efficient by allowing managers to locate the affected areas quickly and precisely.

Although sensors do not yet exist to acquire high resolution (1-2m) multi-spectral digital imagery over large areas for forest inventory, satellite sensors capable of acquiring such information will be operational in the near future. They may be suitable for some of the canopy level texture and forest structural analysis presented here, but individual tree analysis will still require higher resolution airborne imaging. In the meantime, scaling of inventory and health information from airborne sensors to medium resolution satellite sensors is required to extend this information to large areas.

The methodology for the development of a forest health index is being adopted by government organizations worldwide. State Forests of New South Wales in Australia is currently investigating methods of mapping forest stress and damage from Bell Miner (*Manoria melanophrys*) activity. Indicators of canopy condition and vigour, including most of those used in this thesis as well as leaf chlorophyll fluorescence and spectra, will be incorporated into a field measure of forest stress based on relations with image variables from high-resolution digital multi-spectral video. The Ontario Ministry of Natural Resources has also initiated research into forest damage assessment resulting from the ice storm that struck Eastern Ontario in 1998. Their main objective is to test various fertilizer treatments to determine if stand recovery of forests in Eastern Ontario can be accelerated and improved. In order to achieve their objective, methods of monitoring the recovery of stands subject to different treatments will have to be developed. This research

will include the use of the methods developed in this thesis to assess the health of individual trees in treatment plots.

6.5 Recommendations for Further Work

Other work should include an examination of the spatial variation in structure adjacent to a clearing, without mine site stress contributing to the variation. Additional conclusions could then be made about the importance of individual stress factors associated with mine site conditions on forest damage, and their contribution to the observed variation at Kam Kotia.

Subsequent work will incorporate other measures of field-based forest damage such as chlorophyll fluorescence and spectral response of individual leaves. Multi-spectral data will be acquired for the evaluation of spectral measurements in estimating forest damage. An evaluation of other texture measurements will also be conducted, since the contrast texture measure was selected based upon its performance in the estimation of effective LAI from 25cm data and therefore might not be an optimal measurement of texture for 50cm data. Temporal trends in changes to the forest health index will then be assessed and modeled. The methodology for the development of a forest health index will also be employed on an individual tree basis to monitor trees subject to different treatments to improve their recovery from ice storm damage.

7 REFERENCES

- Abrutat, P.H., Edwards, R.P., and C. Wilkins (1994). The potential of in situ amendments to improve alder establishment in pots of metalliferous mine waste. National Meeting of the American Society for Surface Mining and Reclamation, Pittsburgh, PA, April 24-29, 1994.
- Andersson, F. (undated). Hydrological and hydrochemical mechanisms and model approaches to acidification of ecological systems - a workshop introduction.
- Ardo, J., Pelesjo, P. and A. Skidmore (1997). Neural networks, multitemporal Landsat Thematic Mapper data and topographic data to classify forest damages in the Czech Republic. *Canadian Journal of Remote Sensing*, 23(3): 217-230.
- Beyer, H.A. 1992. Geometric and radiometric analysis of a CCD-camera based photogrammetric close-range system. Institut für Geodäsie und Photogrammetrie, Zurich, Switzerland, Doctoral dissertation. 186pp.
- Brady, C. and R.R. Weil (1996). The Nature and Properties of Soils. New Jersey: Prentice Hall.
- Brockhaus, J.A., Khorram, S., Bruck, R.I., Campbell, M.V. and C. Stallings (1992). A comparison of Landsat TM and SPOT HRV data for use in the development of forest defoliation models. *International Journal of Remote Sensing*, 13: 3235-3240.
- Bowen, H.J.M. (1966). Trace elements in biochemistry. New York. Academic Press, 241pp.
- Bowers, W.W., Franklin, S.E., Hudak, J. and G.J. McDermid (1994). Forest structural damage analysis using image semivariance. *Canadian Journal of Remote Sensing*, 20(1): 28-36.
- Chen J. M., and J. Cihlar (1995). Plant canopy gap-size theory for improving optical measurements of leaf-area index. *Applied Optics*, 34: 6211-6222.
- Chen J.M., and J. Cihlar (1996). Retrieving leaf area index of boreal conifer forest using Landsat TM images. *Remote Sensing of Environment*, 55: 153-162.
- Collins, W.E., (1978). Remote sensing of crop type and maturity. *Photogrammetric Engineering and Remote Sensing*, 44(1): 43-55.
- Collins, W.E., Chang, S.H., Raines, G.L., Canney, F. and R. Ashley (1983). Airborne biogeochemical mapping of hidden mineral deposits. *Economic Geology*, 78: 699-710.

- Connor J.J. and H.T. Shacklette (1975). Background geochemistry of some rocks, soils, plants and vegetables in the conterminous United States. USDI Geological Survey 574-F, Washington D.C., 168pp.
- Curran, P., Jago, R.A. and M.E.J. Cutler (1998). Red-edge research: Estimating Canopy Chlorophyll Concentration From Both Field And Airborne Spectra, Proc. 9th *Australian Remote Sensing and Photogrammetry Conference*, Sydney, Australia, July 20-24, 1998.
- Curtiss B. and A.G. Maecher (1991). Changes in forest canopy reflectance associated with chronic exposure to high concentrations of soil trace metals, Proc. 8th *Thematic Conference on Geologic Remote Sensing*, (ERIM), Denver, Colorado, April 29 - May 2, pp. 337-347.
- Dewar, S.W., and M.R. Norland (1994). Growth and trace metal content of poplars planted on tailings treated with municipal solid waste compost. *National Meeting of the American Society for Surface Mining and Reclamation*, Pittsburgh, PA, April 24-29, 1994.
- Ekstrand, S., (1993). Assessment of forest damage using Landsat TM, elevation models and digital forest maps. Ph. D. thesis, Royal Institute of Technology, Stockholm, Sweden.
- EMR Canada (undated). Prospecting in Glaciated Terrain: an Approach Based on Geobotany, Biogeochemistry, and Remote Sensing. Geological Survey of Canada, Bulletin 387.
- Englund, J.O., and S. Haldorsen (1983). The Astadalen catchment, southeastern Norway; geology and general hydrology. Institutt for Geologi, Norges Lantbrukshogskole, Rapport no 18.
- Environment Canada (1992). Canada's environment today: the state of Canada's environment.
- Essen, P.A., (1994). Tree mortality patterns after experimental fragmentation of an old-growth conifer forest. *Biological Conservation*, 68: 19-28.
- Everham, E.E., (1996). Forest damage and recovery from catastrophic wind. *The Botanical Review*, 62(2): 113-185.
- Ferretti, M. (1997). Forest health assessment and monitoring - Issues for consideration. *Environmental Monitoring and Assessment*, 48: 45-72.
- Foster, D. R., (1988). Species and stand response to catastrophic wind in central New England, USA. *Journal of Ecology*, 76: 135-151.

- Franklin, S.E., M.B. Lavigne, M.J. Deuling, M.A. Wulder and E.R. Hunt Jr. (1997). Landsat TM derived forest covertypes for modelling net primary productivity, *Canadian Journal of Remote Sensing*, 23(3): 243-251.
- Franklin, S.E., Waring, W.H., McCreight, R.W., Cohen, W.B. and M. Fiorella (1995). Aerial and satellite sensor detection of western spruce budworm defoliation in a subalpine forest. *Canadian Journal of Remote Sensing*, 21(3): 299-308.
- Franklin, S.E. and A.G. Raske (1994). Satellite remote sensing of spruce budworm forest defoliation in western Newfoundland. *Canadian Journal of Remote Sensing*, 20(1): 37-48.
- Gale, M.R., Grigal D.F., and R.B. Harding (1991) Soil productivity index: predictions of site quality for white spruce plantations. *Soil Science Society of America*, 55: 1701-1708.
- Gates, D.M., Keegen, H.J., Schleter, J.D., and V.R. Weidner (1965). Spectral properties of plants. *Applied Optics*, 4(1): 11-20.
- Gee, G. and J. Bauder (1986). Particle-Size Analysis, in A. Klute (ed.) *Methods of Soil Analysis: Physical and Mineralogical Methods*, 2nd Edition. ASA: Madison, Wis. 399pp.
- Gerylo, G, R.J. Hall, S.E. Franklin, A. Roberts and E.J. Milton. (1998). Hierarchical image classification and extraction of forest species composition and crown closure. *Canadian Journal of Remote Sensing*, 24(3): 219-231.
- Gong, P., R. Pu, and J. Miller (1992). Correlating leaf area index of ponderosa pine with hyperspectral CASI data. *Canadian Journal of Remote Sensing*, 18(4): 275-282.
- Gower, S.T., Vogel, J.G., Norman, J.M., Kucharik, C.J., Steele, S.J. and T.K. Snow (1997). Carbon distribution and aboveground net primary production in aspen, jack pine and black spruce stands in Saskatchewan and Manitoba, Canada. *Journal of Geophysical Research*. 102(D24): 29029-29041.
- Hair, J.F., Anderson, R.E., Tatham, R.L. and W.C. Black (1998). *Multivariate Data Analysis*. New Jersey. Prentice Hall. 730pp.
- Haralick, R.M., Shanmugam, K. and I. Dinstein (1973). Textural features for image classification. *IEEE Transactions on Systems, Man and Cybernetics*, 3(6): 610-621.
- Horler, D.N.H., Barber, J., and A.R. Barringer (1980). Effects of heavy metals on the absorbance and reflectance spectral of plants. *International Journal of Remote Sensing*, 1: 121-136.

- Hosking, G.P., (1994). Evaluation of forest damage using airborne video. *Resource Technology*, 286-293.
- Innes, J.L., (1993). Methods to estimate forest health. *Silva-Fennica*, 27(2): 145-157.
- Irons, J.R. and G.W. Peterson (1981). Texture transforms of remote sensing data. *Remote Sensing of Environment*, 11: 359-370.
- Jakubauskas, M.E., (1996). Canonical correlation analysis of coniferous forest spectral and biotic relations. *International Journal of Remote Sensing*, 17(12): 2323-2332.
- Jakubauskas, M.E., (1997). Effects of forest succession on texture in Landsat Thematic Mapper imagery, *Canadian Journal of Remote Sensing*, 23(3): 257-263.
- Jokela, E.J., Smith, W.H., and S.R. Colbert (1990) Growth and elemental content of slash pine 16 years after treatment with garbage composted sewage sludge. *Journal of Environmental Quality*, 19:146-150.
- Keller, C. and J.C. Vedy (1992). Heavy metals in the environment: distribution of copper and cadmium fractions in two forest soils. *Journal of Environmental Quality*, 23: 987 - 999.
- King, D.J. (1992). Evaluation of radiometric quality, statistical characteristics, and spatial resolution of multispectral videography. *Journal of Imaging Science and Technology*, 36(4): 394-404.
- King, D.J. (1995). Airborne multispectral digital camera and video sensors: a critical review of system designs and applications. *Canadian Journal of Remote Sensing, Special Issue on Aerial Optical Remote Sensing*, 21(3): 245-273.
- King D. J. (1997). Low cost multispectral camera imaging for forest modelling and topographic mapping. *Third International Airborne Remote Sensing Conference and Exhibition*, Copenhagen, Denmark, July 7-10.
- Korobov, R.M. and V.Y.Railyan (1993). Canonical correaltion relationships among spectral and phytometric variables for twenty winter wheat fields. *Remote Sensing of Environment*, 43: 1-10.
- Lambert, N.J., Ardo, J., Rock, B.N. and J.E. Vogelmann (1995). Spectral characterization and regression based estimates of forest damage in Norway Spruce stands in the Czech Republic using Landsat Thematic Mapper data. *International Journal of Remote Sensing*, 16: 1261-1287.

- Leak, W.B. (1992). Vegetation change as an index of forest environmental impact. *Journal of Forestry*, 90(9): 32-25.
- Leemans, R., (1991). Sensitivity analysis of a forest succession model. *Ecological Modeling*, 53(3-4): 247-262.
- Lévesque, J. and D.J. King.(1999). Airborne digital camera image semivariance for evaluation of forest structural damage at an acid mine site, *Remote Sensing of Environment*, 68(2): 112-124.
- Lillesand, T.M. and R.W. Kiefer (1994). *Remote Sensing and Image Interpretation* 3rd edn. John Wiley and Sons Inc.
- Mageau, M.T., R. Costanza, and R.E. Ulanowicz. (1995). The development and initial testing of a quantitative assessment of ecosystem health, *Ecosystem Health*, 1(4): 201-213.
- MEND (1991). Annual report. Canada Centre for Mineral and Energy Technology.
- Milton, N.M., Ager C.M., Eiswerth B.A., and M.S. Power (1989). Arsenic and selenium induced changes in spectral reflectance and morphology of soybean plants. *Remote Sensing of the Environment*, 30:263-269.
- Milton, N.M., Collins W., Chang S.H., and R.G. Schmidt (1983). Remote detection of metal anomalies on Pilot Mountain, Randolph County, North Carolina. *Economic Geology*, 78(4): 605-617.
- Ministry of Natural Resources (1997). Bioindicators of Forest Health and Sustainability. Forest research information paper, ISSN 1319-9118 ; no.138.
- Miyanishi, K., Hoy, A.R. and D.B. Cavers (1979). "A generalized law of self-thinning in plant populations", *Journal of Theoretical Biology*. 78:438-442.
- Mohammed, G.H., Sampson, P.H., Colombo, S.J., Norland, T.L. and J.R. Miller (1997). Bioindicators of sustainability: development of a forest condition rating system for Ontario. Forest Research Information Paper no. 137. Ontario Forest Research Institute.
- Natural Resources Canada (1997). The State of Canada's Forests, Learning from History. Canadian Forest Service, Hull QC.
- Natural Resources Canada (1994). The State of Canada's Forests, A Balancing Act. Canadian Forest Service, Hull QC.

- Nemani R., L. Pierce, S. Running, and L. Band (1993). Forest ecosystem processes at the watershed scale: sensitivity to remotely-sensed leaf area index estimates. *International Journal of Remote Sensing*, 14: 2519-2534.
- Nilson, T. and U. Peterson (1994). "Age dependence of forest reflectance: analysis of main driving factors", *Remote Sensing of the Environment*, Vol. 48, pp. 319-331.
- Odin, H., (1976). Studies of wind and evaporation in forests and clear-felled areas. Department of Reforestation, *Swedish University of Agricultural Sciences*, report no. 73.
- Olson, C.L., (1987). *Statistics, Making Sense of Data*. Boston. Allyn and Bacon, Inc.
- Olthof, I. and D.J. King (1997). Evaluation of textural information in airborne CIR digital camera imagery for estimation of forest stand leaf area index. *Proc. 1st North American Symposium on Small Format Aerial Photography (American Society of Photogrammetry and Remote Sensing)*, Cloquet, MN, Oct. 14-17, pp. 154-164.
- Olthof, I., (1997). (unpublished). Determination of spatial distribution of soil metals along a transect at the Kam Kotia mine site.
- Olthof, I. and D.J. King (1999). Determination of soil property and forest structure relations with airborne digital camera image spectral and spatial information. *Canadian Journal of Remote Sensing*. Accepted 03/1999.
- Osawa, A., (1990). Reconstructed development of stem production and foliage mass and its vertical distribution in Japanese Larch. *Tree Physiology*, Vol. 7, No. 1-4, pp. 189-200.
- Outridge, P., (1997) Personal communication.
- Page, A.L., Bingham F.T. and A.C. Chang (1981). The Effects of Heavy Metal Pollution on Plants: Pollution Monitoring Series, 77 - 109. Applied Science Publishers, New Jersey.
- Paine, P.J., (1987). Historic and geographic overview of acid mine drainage. *Proceedings Acid Mine Drainage Workshop*, Halifax, N.S., March 23-26, 1987.
- Peddle, D.R., Hall, F.G., and E. LeDrew (1995). Spectral mixture analysis and geometric-optical reflectance modeling of boreal forest biophysical structure, Superior National Forest, Minnesota. In *Proceedings of the 17th Canadian Symposium on Remote Sensing*, Saskatoon, Saskatchewan, June 13-17, 1995.

- Press, F., and R. Siever (1986). *Earth*. New York. W.H. Freeman and Company. 656pp.
- Rock, B.N. (1988). Comparaison of in-situ and airborne spectral measurements of the blue shift associated with forest decline. *Remote Sensing of the Environment*. 24: 109-127.
- Running S., D. Peterson, M. Spanner, and K. Teuber (1986). Remote sensing of coniferous forest leaf area. *Ecology*, 67: 273-276.
- Seed, E. and D.J. King (1997). Determination of mixed boreal forest stand biophysical structure using large scale airborne digital camera imagery. *Proc. GER '97 / 19th Canadian Symposium on Remote Sensing*, Ottawa, Ontario, May 26-29.
- Singhroy, V., Stanton-Gray, R., and J. Springer (1986). Spectral geobotanical investigation of mineralized till sites. *Proc. International Symposium on Remote Sensing of Environment, Thematic Conference on Remote Sensing for Exploration Geology*, Environmental Research Institute of Michigan, Ann Arbor: 523-543.
- Singhroy, V. 1995. Spectral characterization of vegetation at mine tailings. In the *Proceedings of the Sudbury 95 Mining and the Environment – An Integrated Approach to Planning and Rehabilitation for the 21st Century*, 28 May - 1 June 1995, Sudbury, Ontario. pp. 193-197.
- Smith, W.H. (1990) *Interaction between air contaminants and forest ecosystems*, 2nd edn. New York. Springer Verlag. 618pp.
- Spanner, M.A., Johnson, L., Miller, J., McCreight, R., Freemantle, J., Runyon, J. and P. Gong (1994). Remote sensing of seasonal leaf area index across the Oregon transect. *Ecological Applications*, 4: 258-271.
- Stern, K.R., (1991). *Introductory plant biology*. New York. Wm.C. Brown Publishers. 467pp.
- Stevens, J. M., (1992). *Applied multivariate statistics for the social sciences*, 2nd edn. New Jersey. Lawrence Erlbaum Associates. 629pp.
- Stone, C., (1996). The role of psyllids (Hemiptera: Psyllidae) and bell miners (*Manorina melanophrys*) in canopy dieback of Sydney blue gum (*Eucalyptus saligna* Sm.). *Australian Journal of Ecology*, 21: 450-458.
- Stone, C., (1998). Personal communication. Forest Research & Development Division, State Forests of New south Wales, Australia.

- Tabachnick, B.G. and L.S. Fidell (1996). *Using Multivariate Statistics*. New York. HarperCollins College Publishers. 746pp.
- Torbet, J.L., Tuladhar, A.R., Burger, J.A., and J.C. Bell (1988). Minesoil property effects on the height of ten-year-old white pine. *Journal of Environmental Quality*, 17(2):189-192.
- Trousdell, K.B., Williams, W.C. and T.C. Nelson (1965). Damage to recently thinned Loblolly Pine stands by Hurricane Donna. *Journal of Forestry*, 63: 96-100.
- Twery, M.J. and K.W. Gottschalk (1996). Forest health: Another fuzzy concept. *Journal of Forestry*, 94: 20-28.
- Wagner C.L., Howarth P.J., and V.H. Singhroy (1989). A spectral geobotanical study at Natal Lake, northern Ontario. *International Journal of Remote Sensing*, 10(11): 1721-1734.
- Walsworth, N.A., and King, D.J. 1999. Image modelling of forest changes associated with acid mine drainage. *Computers and Geoscience*. 25: 567-580.
- Ward, R.C., and M. Robinson (1990). *Principles of Hydrology*. Maidenhead. McGraw - Hill Book Company Limited.
- Welles, J.M. and J.M. Norman (1991). Instrument for indirect measurement of canopy architecture. *Agronomy Journal*, 83:818-825.
- Wulder, M. A., S. E. Franklin, and M. B. Lavigne, (1996). High resolution optical image texture for improved estimation of forest stand leaf area index. *Canadian Journal of Remote Sensing*, 22: 441-449.
- Wulder, M.A., Lavigne, M.B., Franklin, S.E. and E.F. LeDrew (1997). Refinement of GIS forest polygon content with classified remotely sensed data. *Proc. Canadian Remote Sensing Society Annual Conference*, Ottawa, Canada, May 24-30.
- Yuan, X., D.J. King and J. Vlcek. 1991. Sugar maple decline assessment based on spectral and textural analysis of multispectral aerial videography. *Remote Sensing of Environment*, 37 (1): 47-54.

8 APPENDICES

8.1 Appendix 1 Soil digestion for Inductive Coupled Plasma Emission Spectrometry(ICPES)

Sample size per session

1 batch consists of :	21 soil samples
	1 repeat
	1 standard
	1 blank
total:	24 samples

ICP Analysis: Al, B, Ba, Cu, Fe, Mn, Na, Si, Sr, Zn, Ca, K, Mg
Standard every 10 samples

Equipment:

2mm sieve and pan
1 mortar and pestle
100ml teflon beakers
medium sized plastic funnels
11cm qualitative filter paper
50ml calibrated plastic tubes and caps
250ml beaker (label: HCl, Waste acid)
1 100ml beaker (label: HNO₃)
balance (0.0001g)
small spatula for soil transfer
kim wipes for cleaning spatula
2 or 3 poly tube holders
fumehood
hot plate
label pen
pair of gloves and glasses
ICPE Spectrometer and technician
spray bottle (distilled water)
pipette 1 to 5ml capacity
70ml HNO₃ (concentrate)
190ml HCl (concentrate)
spray bottle (1M HCl) with fine nozzle

PROCEDURE:**Soil Preparation**

Air dry soil samples in warm dry area by breaking them up and letting them sit on paper for two to three days
 Sieve through 2mm mesh
 Split soil to obtain representative sample of approximately 8 cubic cm volume
 Grind sample to a fine powder with mortar and pestle
 Place sample in a clean dry labelled bag

Digestion

Label 24 teflon beakers

For each sample:

Weigh 2g of sample into a teflon beaker, transferring sample with spatula
 Record beaker#, weight
 Clean spatula
 Wash soil that may have collected on the upper rim onto the bottom of the beaker with distilled water. Water should just cover sample, swirl to disperse particles

In fumehood:

Transfer 75ml of concentrated HNO_3 into 100ml ' HNO_3 ' beaker
 Rinse pipette with 4ml HNO_3 discharge into 'waste' beaker
 Add 3 x 1ml HNO_3 (conc) using pipette, deliver down sides to avoid splashing and to wash ions. Stir gently
 Let sit 1 hour, rinse pipette with distilled water
 Transfer 190ml of HCl (conc) into 250ml beaker
 Rinse pipette with 4ml HCl
 Pipette 3 x 2ml + 3ml = 9ml total of HCl (conc)
 Let sit 1 hour and clean up
 Put on hot plate (2 pos) overnight, wash down sides to increase volume with 1M HCl or HNO_3 as needed < 10ml
 Let cool for an hour and set filters up

Filter:

Filter sample into a 50ml polytube, wet transfer with 1M HCl usually taking three washes of beaker. Continue rinsing filter paper with distilled water
 Volume should be approximately 25 to 27ml, increase to 30ml volume with distilled and store. Wash up.

8.2 Appendix 2 Statistical Reports

Principal Components Analyses

Soil

Final Statistics:

Variable	Communality
AL	.86481
B	.74205
BA	.92658
CA	.82881
CLAY	.72715

Factor	Eigenvalue	Pct of Var	Cum Pct
1	9.61125	48.1	48.1
2	2.43256	12.2	60.2
3	1.71771	8.6	68.8
4	1.50588	7.5	76.3
5	1.19889	6	82.3

Rotated Factor Matrix:

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
AL	0.39551	0.78835	0.28227	-0.04356	-0.07294
B	0.85233	-0.00755	-0.04422	-0.11385	0.02477
BA	0.78226	0.28693	0.44737	0.15726	-0.08636
CA	0.03025	0.79326	0.13125	0.39211	0.16629
CLAY	0.3355	0.29589	0.70896	0.08106	-0.1336
CU	0.73749	0.19861	0.31555	0.32294	-0.21683
FE	0.29534	0.91243	0.12013	-0.17205	-0.00159
SAND	-0.26602	-0.23379	-0.73333	-0.2079	-0.46631
INSOL	-0.32386	-0.3653	-0.65809	-0.29391	0.05643
K	0.53417	0.46088	0.32431	0.16195	-0.21081
MG	0.16673	0.91445	0.13846	0.24838	0.09389
MN	0.80474	0.24942	0.32905	-0.08751	0.0841
NA	0.75676	0.26058	0.16302	0.48657	-0.08286
ORGMAT	0.07348	-0.01164	0.82931	-0.17223	-0.09154
PH	-0.05996	0.08368	0.05624	0.92089	0.10958
SAND-SILT	-0.04643	0.03147	-0.02213	0.05851	0.90494
SI	0.74894	0.12946	0.02538	-0.12571	0.13805
SILT	0.09813	0.18093	0.60595	0.32942	0.39612
SR	0.71843	0.36006	0.13399	0.49954	0.01152
ZN	0.85258	0.20928	0.3412	-0.00802	-0.05695

Forest structure**Final Statistics:**

Variable	Communality
BLOWBA	0.90078
BLOWSTEM	0.92317
CROWNCLO	0.10535
DEADBA	0.7666

Factor	Eigenvalue	Pct of Var	Cum Pct
1	5.95743	45.8	45.8
2	1.90465	14.7	60.5
3	1.37994	10.6	71.1
4	1.11155	8.6	79.6

Rotated Factor Matrix:

	Factor 1	Factor 2	Factor 3	Factor 4
BLOWBA	-0.17744	0.9278	0.03647	-0.08459
BLOWSTEM	-0.241	0.88742	0.1745	-0.2171
CROWNCLO	0.25794	-0.1906	-0.0125	0.04831
DEADBA	-0.0982	0.10408	0.85379	0.13103
DEADSTEM	-0.11235	0.15702	0.81272	-0.26832
LICOR1	0.85518	-0.2045	-0.08947	0.15802
LICOR2	0.93473	-0.21497	-0.02406	0.09327
LICOR3	0.95926	-0.16302	0.01704	0.10499
LICOR4	0.94839	-0.11584	-0.03386	0.17251
LICOR5	0.93564	-0.08361	-0.0589	0.21537
LIVEBA	0.46728	-0.35249	0.52347	-0.05124
LIVESTEM	-0.12901	0.08693	0.18329	-0.92571
STEMBA	0.4196	-0.27711	0.13973	0.71558

Relative structure**Final Statistics:**

Variable	Communality
BLOWBA_1	0.76238
BLOWST_1	0.63285
CROWNC_1	0.32966

Factor	Eigenvalue	Pct of Var	Cum Pct
1	4.60789	41.9	41.9
2	2.2015	20	61.9
3	1.29017	11.7	73.6

Rotated Factor Matrix:

	Factor 1	Factor 2	Factor 3
BLOWBA_1	0.25295	0.49752	-0.67147
BLOWST_1	0.15518	0.72787	-0.28103
CROWNC_1	0.02736	-0.07404	0.56871
DEADBA_2	-0.29852	0.76287	-0.00859
DEADST_1	-0.1871	0.79348	0.22578
LICOR1_1	0.80634	-0.11689	0.18366
LICOR2_1	0.94078	-0.16709	-0.07483
LICOR3_1	0.95695	-0.12804	-0.11941
LICOR4_1	0.95367	-0.06922	-0.1622
LICOR5_1	0.90442	0.1224	-0.16257
STEMBA_1	-0.08078	0.20834	0.75858

Image

Final Statistics:

Variable Communality

BLUE	0.16722
GREEN	0.9366
NDVI	0.97491
NIR	0.91672

Factor	Eigenvalue	Pct of Var	Cum Pct
1	9.49135	47.5	47.5
2	4.24464	21.2	68.7
3	1.50634	7.5	76.2
4	1.35963	6.8	83

Rotated Factor Matrix:

	Factor 1	Factor 2	Factor 3	Factor 4
BLUE	0.04186	0.39111	-0.05823	0.09544
GREEN	-0.92578	0.04505	0.25009	-0.12232
NDVI	0.12985	0.02902	-0.04826	0.97718
NIR	-0.86194	0.06805	0.16252	-0.3778
RED	-0.92165	0.0567	0.2545	0.00144
S1	-0.47324	0.07805	0.78134	0.00587
S2	-0.88771	0.08723	0.02894	-0.1924
S3	0.01012	-0.16779	-0.77446	0.01766
S4	0.86534	-0.03851	-0.23283	0.04747
S5	0.94237	0.03344	-0.04336	0.10898
S6	0.9188	-0.11855	0.05586	0.26716
SUNGREEN	0.72865	-0.21461	-0.18422	-0.00407
SUNNIR	0.64588	-0.18242	-0.01818	0.69225
SUNRED	0.80022	-0.3251	0.03597	-0.22898
TEXMEAN1	-0.09158	0.97325	0.09686	-0.03655
TEXMEAN2	-0.10281	0.96113	0.17156	-0.03335
TEXMEAN3	-0.08256	0.95514	0.14455	-0.00596
TEXVAR1	-0.22797	0.8333	0.15876	-0.17136
TEXVAR2	-0.24028	0.57686	0.62395	-0.13428
TEXVAR3	-0.23541	0.76355	0.53647	-0.08531

* * * * MULTIPLE REGRESSION * * * *

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. HIFIELD

Block Number 1. Method: Stepwise TEXMEAN1 TEXVAR1 SUNGREEN

Variable(s) Entered on Step Number

- 1.. SUNGREEN
- 2.. TEXMEAN1
- 3.. TEXVAR1

Multiple R .57730
 R Square .33328
 Adjusted R Square .30297
 Standard Error .82469

Analysis of Variance

DF	Sum of	Mean
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		Squares	Square
Regression	3	22.43832	7.47944
Residual	66	44.88733	0.68011

F = 10.99738 Signif F = .0000

----- Variables in the Equation -----

Variable	B	SE B	Beta	T	Sig T
TEXMEAN1	0.006357	0.00148	0.763134	4.295	0.0001
TEXVAR1	-0.00203	0.001003	-0.36118	-2.021	0.0474
SUNGREEN	0.024482	0.006209	0.422188	3.943	0.0002
(Constant)	-4.14165	0.870082		-4.76	0

End Block Number 1 All requested variables entered.