SUDBURY AREA RISK ASSESSMENT

CHAPTER 5.0
ANALYSIS OF VEGETATION CHANGES BY REMOTE SENSING

Table of Contents

Tables

Figures

PLEASE NOTE THAT THIS CHAPTER HAS NOT UNDERGONE TECHNICAL REVISION SINCE DRAFT 1.0

GLOSSARY OF ABBREVIATIONS

MSS - Multispectral Sensor

NDVI - Normalized Difference Vegetation Index

NIR - Near-infrared

PCA - Principle Component Analysis

PC - Principal Components /Pulse Code/Personal Computer

RGB - Red, green and blue colours

ROI - Regions of Interest

TCT - Tesseled Cap Transformation

TM - Thematic Mapper

USC - Unsupervised Classification

This page left blank intentionally.

5.0 ANALYSIS OF VEGETATION CHANGES BY REMOTE SENSING

5.1 Introduction

The Greater Sudbury area is defined by its unique geological landscape and the mixed boreal forest it supports. For more than a century, this landscape has provided prosperity to the community through timber harvesting and the extraction of minerals and base metal deposits. However, the exploitation and growth of these industries in Sudbury has not been without impact on the local environment.

Forestry and mining operations have severely altered the landscape and ecosystems in the Greater Sudbury area. Physical and chemical changes resulting from forest fires, tree harvesting, agriculture, and smelting have contributed to a decline in the ecosystem health of the region. In particular, historical smelting operations in the communities of Copper Cliff, Coniston and Falconbridge have resulted in the aerial dispersion of sulphur dioxide and metal-containing particulates. These emissions have resulted in a dramatic denudation of the vegetation across the region.

However, as described in the previous chapter, the Sudbury community, government agencies, and the mining industry have worked together to change operational practices, implement monitoring and emission controls, and improve the local environment. The result has been a reduction in fumigation, and the instigation of on-going monitoring and reclamation work. Great efforts by both the mining community and the municipal government, in part with federal support, have been made in restoring the landscape and improving ecological health. This chapter assesses the re-greening process described in Chapter 4 using remote sensing information to evaluate the program's effectiveness.

In the context of this project, remote sensing is the analysis of satellite-based images over a broad geographic area. The unique aspect of this information, and what makes it different from standard aerial photographic images, is that it provides calibrated images at discrete wavelengths or bands. The calibration minimizes internal and external influences to reduce errors or biases in the signature and can improve the ability to conduct temporal comparison of imagery. Referred to as spectral information, these bands are located in the visible to near-infrared (NIR) part of the spectrum. A relationship can be established through mathematical processes to relate particular spectral bands to land cover types. For example, water, forest, grassy fields, and bedrock will have their own unique spectral signatures.

For the Sudbury Soils Study, a multi-temporal remote sensing analysis has been conducted to examine changes in vegetation between Regions of Interest (ROI) for the period 1976-2003. The ROI are defined as areas of vegetation defined both by impacts of emissions and by restoration efforts (see Section 5.3.2). A generalized land cover analysis was done for recent (*i.e.* 2003) images to provide a classification of the vegetation types to support a "Decision Tree Analysis". To quantify the change in vegetation, a number of ROI were used to assist in separating areas of significant interest and further study. Temporal analysis applied to the images used vegetation indices and spectral transformation to examine regreening over these ROI. The details of the methodology and the results are provided in Section 5.3.

5.2 Objective

The remote sensing component of the Sudbury Soils Study supports the regreening review (Chapter 4) and ecological risk assessment (Volume III). Remote sensing methods have been applied to evaluate large geographic areas at a broad scale to assess land cover types and conduct a temporal analysis. The objectives of the remote sensing component are as follows:

- Provide a current generalized land cover description over a broad geographic region as a reference in further vegetation analysis;
- Quantify vegetation cover over the Sudbury region and within the selected ROI using remote sensing techniques both temporally and spatially;
- Compare naturally occurring vegetation recovery and assisted vegetation recovery in the areas of interest; and
- Provide information that can be integrated with the ecological risk assessment.

The remote sensing information provided in this chapter compliments the historical review and the regreening programme described in Chapters 3 and 4 of this volume as it documents the areas where historic damage was apparent as well as the success of the replanting, liming and regeneration efforts. In addition, this information was used for the ERA presented in Volume III. In particular, the remote sensing information was used to address Objective 1 of the ERA (Evaluate the extent to which the COCs are preventing the recovery of regionally representative self-sustaining terrestrial plant communities). Field study sites were established to help address Objective 1. The locations of the study sites were determined in part based on images provided from the remote sensing data. The ecological information collected during the field component was then used as a ground truthing approach for the land cover mapping classification presented in this Chapter. The spectral signatures established during the analysis stages described in this Chapter were also used to extrapolate vegetation types from the field study sites to the entire study area. This approach formed the basis of mapping to provide guidance for future ecological risk management activities in the study area.

5.3 Methods

5.3.1 Introduction

The Sudbury ecosystem is described as a transition between northern boreal forest and the Southern Ontario deciduous range, referred to as the Great Lakes - St. Lawrence Forest Region. Mixed forests of jack, red and white pine, maple, red oak, trembling aspen and white birch dominate the landscape interspersed with wetlands and rock barrens (Freedman and Hutchinson, 1980). In areas where smelting operations have been ongoing, the impacts to the natural vegetation have been significant and are well documented in the literature (Winterhalder, 2002).

For this remote sensing analysis, the primary areas of interest are the “Semi-Barren” and “Barren” areas (Struik, 1973). In the Semi-Barren areas, vegetation is present but has been impacted by emissions and deposition from the smelters. Nested within the Semi-Barren area, there are geographic areas where the landscape is devoid or depleted of natural vegetation (Winterhalder, 1996). These areas have been termed the “Barren areas”. There are three Barren areas; each surrounds one of the historic smelter sites at Copper Cliff, Coniston and Falconbridge.

Recovery of the vegetation in the Semi-Barren/Barren areas has been improving at a rapid rate since the introduction of changes in smelting practices (Gunn *et al*., 1995), and regreening efforts by the community and the mining companies (Winterhalder, 2002). This has resulted in an improvement in air quality and the reduction in emissions and deposition of metals into the surrounding areas (Hutchinson and Gunderman, 1998). Remote sensing is well suited for assessing vegetation recovery over the geographic extent of the Sudbury area, particularly from satellite-based observations. Acquired images reveal both temporal and spatial changes in the landscape cover and provide a valuable assessment tool in managing vegetative biodiversity at the population, ecosystem and regional landscape scales (Franklin, 2001).

Remote sensing has been used in the Sudbury Soils Study to qualitatively and quantitatively illustrate patterns of vegetation change across the Semi-Barren/Barren areas and to examine changes within natural and assisted recovery areas over the past 30 years. Time series analysis of images during different temporal periods was used to derive information on changes of surface land cover related to vegetation. Remote sensing sensors on satellite platforms acquire digital data at discrete regions of the light spectrum known as bands, over large areas. Image processing is used to manipulate the bands to model or apply mathematical techniques. These techniques can be used to determine land cover types and vegetation cover through the inverse process of relating surface radiometric properties with biophysical properties.

The species composition and structure of each plant community alters the way in which sunlight reflects. In the visible part of the spectrum, the pigment content of leaves is dominated by chlorophyll resulting in absorption features which are characteristic of the materials (Peterson and Running, 1989). In the near-infrared (NIR) part of the spectrum, cell structure of mesophyll layers where the cell walls contain CHL (cellulose – hemicellulose - lignin) and water content in the vacuole, dominate changes in spectral signature due to scattering and absorption (Ustin *et al*., 2001). Figure 5-1 shows the spectral signature of a leaf as a function of wavelength.

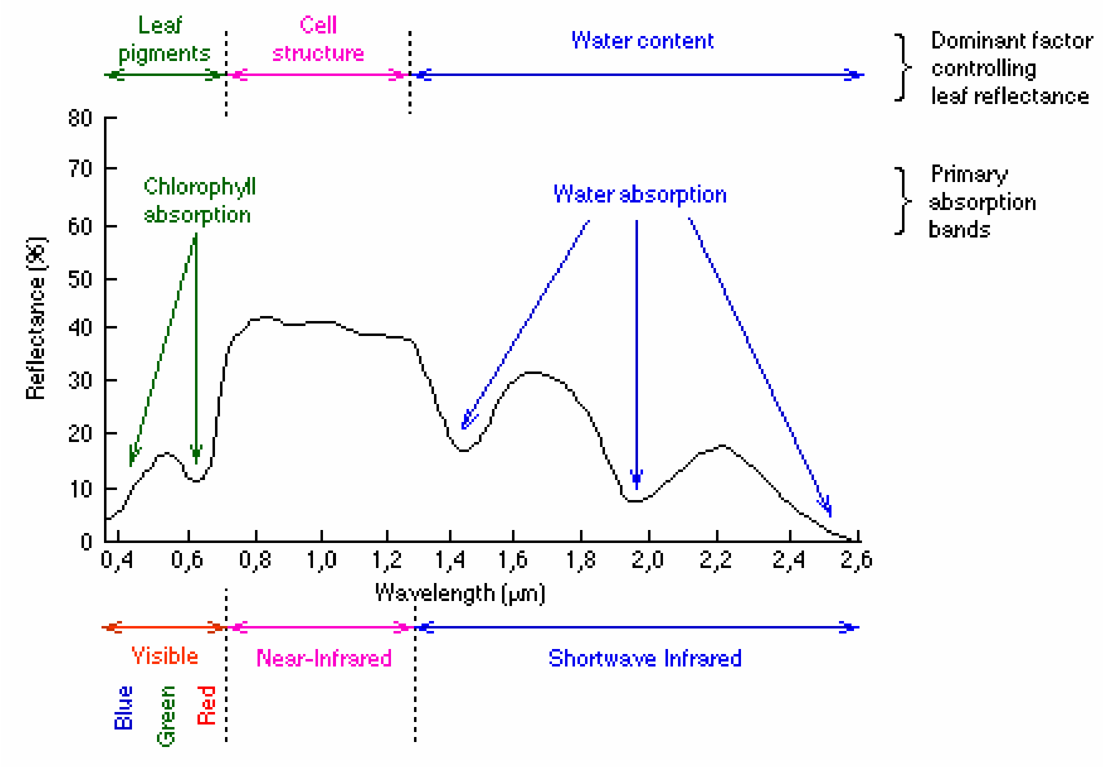


Figure 5-1 Spectral Reflectance Signature of a Leaf as Function of Wavelength

The physical constituents of vegetation result in a unique spectral characteristic between the red and NIR part of the spectrum known as the “red edge effect”. The cause is related to the dominant change in reflectance from the chlorophyll absorption well usually around (660 nm) to the NIR shoulder (750 nm) from scattering of light from the cellular structure. Different types of vegetation have slightly different spectral reflectance signatures. The shape and magnitude of the spectral signature is an intrinsic property and can be used to reveal the presence of different types of vegetation.

For other surfaces, their spectral signatures are defined by their chemical and physical properties. For example, the reflectance of water will depend on the amount and type of constituents in the water column. Similarly, soils will have different signatures depending on the amount of organic material and their surface texture. These unique spectral signatures allow remote sensing techniques to distinguish one from another. Figure 5-2 illustrates examples of common surface types showing their spectral signature and the location of Landsat Thematic Mapper (TM) and Ikonos bands. The gaps in the spectra shown in Figure 5-2 represent regions where there is water absorption in the atmosphere, which blocks the reflectance signal from the earth.

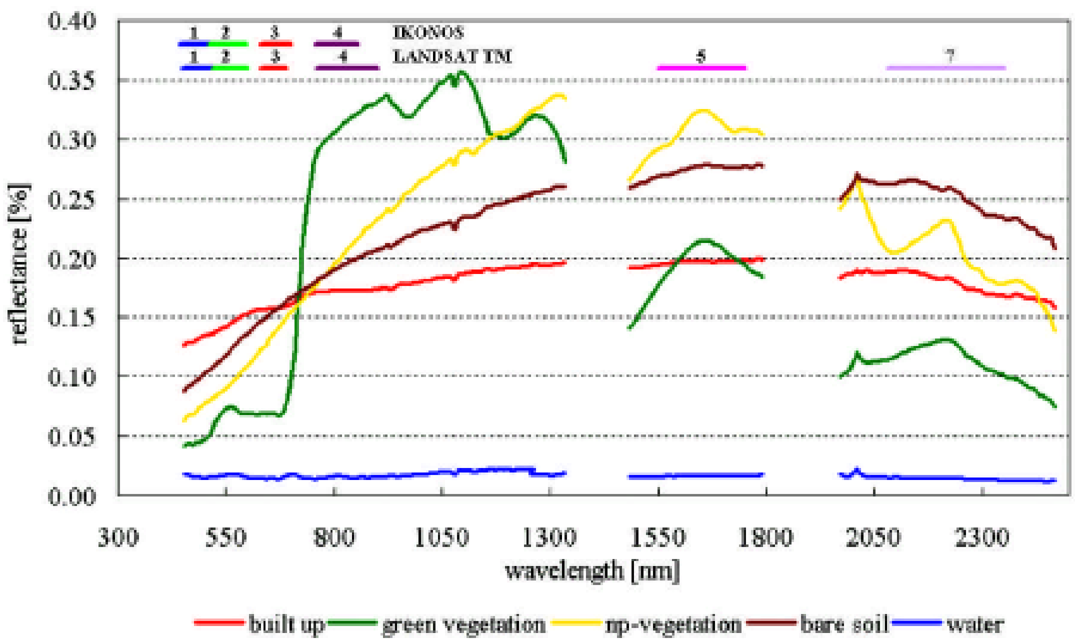


Figure 5-2 Spectral Reflectance of Different Surfaces Types

Figure 5-2 illustrates the distinct difference between each surface's reflectance property in both magnitude and shape. The green vegetation reflectance between Landsat TM Band 3 and Band 4 illustrates the "red edge" by showing a rapid rise in reflectance in the NIR. Surfaces with green vegetation will show similar shapes but may vary with magnitude. Vegetation types such as grass fields, lawns and golf courses tend to have greater magnitudes when compared to forests, which have a more dominant shadow component.

Remote sensing does not directly measure reflectance but a quantity referred to as radiance, which can be interpreted as a surface brightness. Radiance has an angular dependency and is affected by scattering and absorption of particles in the atmosphere. To minimize effects due to attenuation of the light propagating through the atmosphere, a correction process using radiative transfer equations to model the interactions in the atmosphere is applied to normalize the image to values known as reflectance. Reflectance describes how much light reflects off a surface, compared to how much light hits the surface, and is expressed as a percent. Thus reflectance can vary from 0% (the object looks black because none of the light reflects off) to 100% (the object looks white because all the light reflects off).

The physical properties of a surface (for example the chlorophyll content of vegetation) determines the proportion of sunlight that will be reflected, absorbed, and/or transmitted and in what region of the spectrum. A spectral signature is just reflectance expressed as a function of wavelength. Therefore, there is a spectral signature change in solar energy distribution across the electromagnetic spectrum. A spectral signature is uniquely related to the physical properties of an object (*e.g*. type and state). The magnitude and shape of the spectral signature can therefore be used by image processing software to correlate and extract physical features.

For the Sudbury Soils Study, atmospheric correction was applied to normalize the images using radiative transfer model (MODTRAN) and information from the 6S model for a Standard atmosphere (Champagne, 2004). Cross calibration using pseudo-invariant targets was applied to normalize the difference between each corrected image, using the summer 2003 image as the base. Figure 5-3 shows the spectral signatures for some land cover types from an image pixel used in this project (an image pixel is the smallest spatial unit or resolution of an image). Further details on the atmospheric correction process are provided in Appendix A of this Volume.

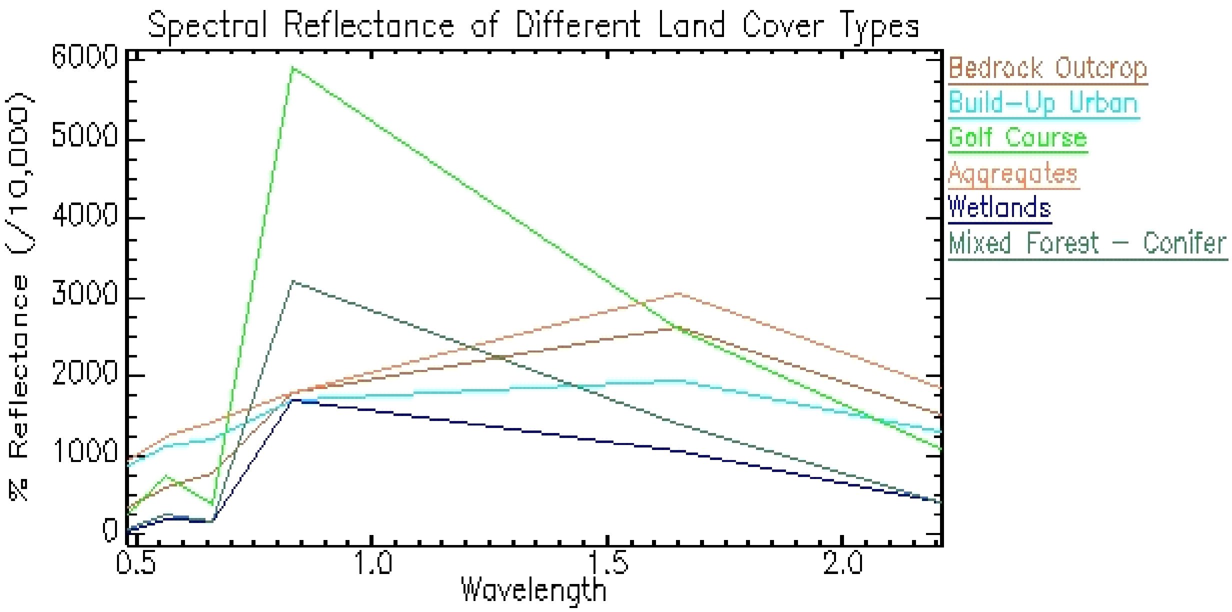


Figure 5-3 Spectral Reflectance of Land Cover Types from 2003 Landsat TM Summer Image

The spectral reflectance shapes as illustrated above provide a distinct means of separating land cover types. When remote sensing bands are displayed on a computer screen, only three bands can be displayed at once. Each band is assigned to a Red, Green or Blue (RGB) colour of the monitor to create a colour image. This image is referred to as a “false colour image” because reassigning different bands to the RGB colours can alter how the spectral bands are displayed and can provide insight into visual interpretation of land cover and enhance our understanding of changing landscape patterns.

In the case of Sudbury, historical satellite imagery has been acquired by the Landsat series of sensors since 1972. Images reveal a sequence of landscape changes from early periods of environmental damage to the regreening of the smelting areas. As a benchmark example, the image in Figure 5-4 represents a false colour image that was acquired by Landsat Multispectral Sensor (MSS) orbiting 720 km above the earth on September 6, 1976. The NIR spectral Band, Band 3, was assigned red, Band 2 was assigned green and Band 1 was assigned blue.

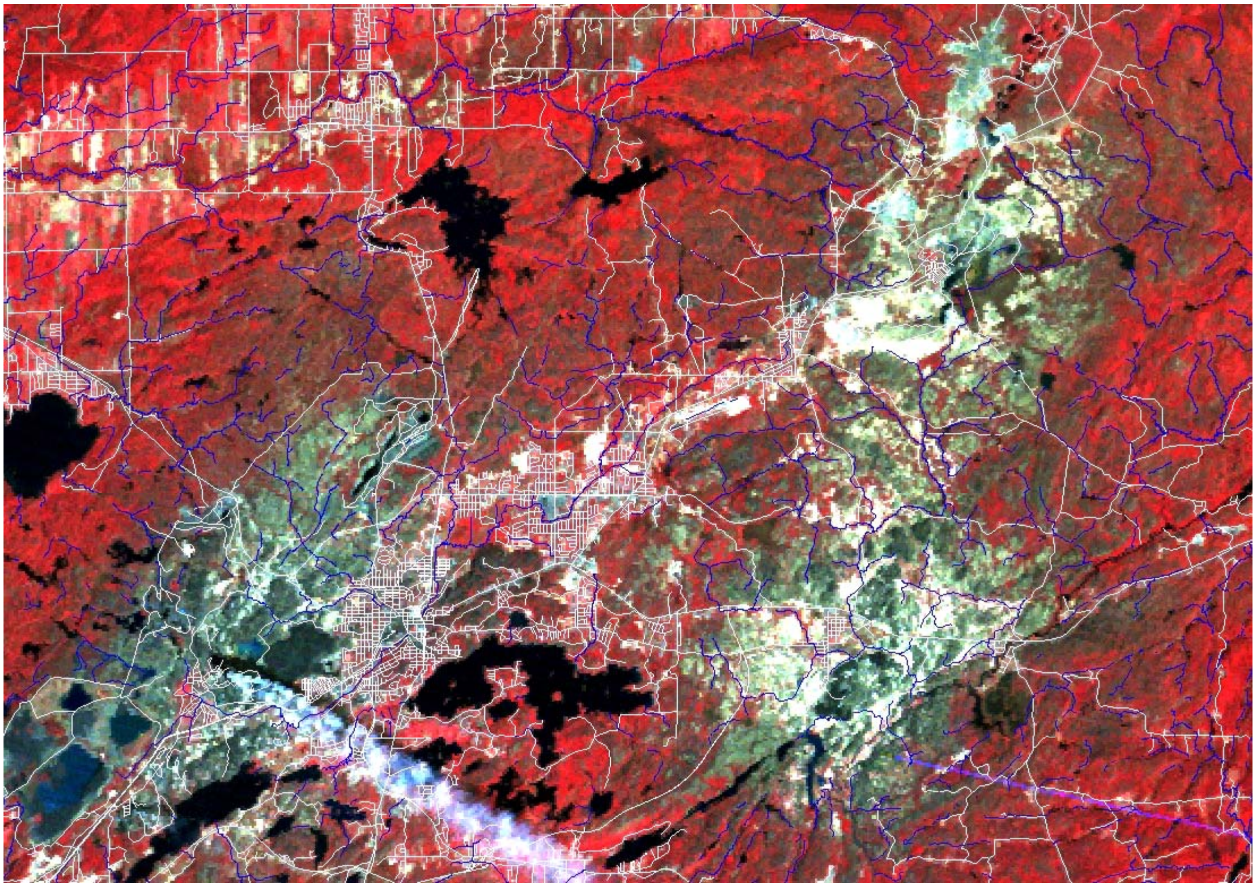


Figure 5-4 Landsat MSS September 6, 1976: Copper Cliff, Sudbury, Coniston, Garson and Falconbridge

The image distinctly shows the release of emissions from the Copper Cliff smelter (bottom left). It also shows distinct grayish-white to grayish-green areas where there is a lack of or minimum vegetation in the area of Copper Cliff, Coniston and Falconbridge. The reddish areas in the image represent vegetation cover, which is very bright in the NIR band, displayed in red.

The three areas around the smelting sites have similar land cover pattern both in magnitude and direction. Visual interpretation shows there is an elliptical pattern oriented in a southwest to northeast direction around each of the three smelting facilities. This observation is also supported by aerial photography (McCall *et al*., 1995) suggesting that the surfaces surrounding the smelting facilities are of similar nature and that their lack of red colour indicates that the land cover is not dominated by the presence of vegetation. Most likely the white to green areas are indicating mixed aggregate, bedrock or bare soil surfaces.

Figure 5-4 also provides a temporal benchmark for investigating changes in land cover types in the Sudbury region. More recent images were acquired to see if change is occurring and to what degree by conducting time series comparison analysis. The goal of this study was to quantify the change in vegetation cover in Semi-Barren/Barren areas and to examine natural and assisted recovery due to liming and planting in the affected areas.

5.3.2 Defining the Study Area for Analysis

To quantify the presence of vegetation change for the comparison analysis, it was necessary to create ROI that would address the objectives outlined. A combination of references from previous work and satellite observations were used to define the geographic extent of the study area used for analysis. Seven ROI areas were selected based on: the impact areas around the smelting locations, a transition zone, assisted recovery locations and a natural area. The areas that were selected were based on deposition of metals and not on fumigation effects from SO_2. In summary, the selection of the ROI included the following:

- Areas where both liming and tree planting occurred as a result of the City of Greater Sudbury's Land Reclamation Program (Concentrated Recovery area);
- Total combined area that was limed and/or tree planted under the Land Reclamation Program (Entire Recovery area);
- Elliptical-shaped areas around the Copper Cliff, Coniston, and Falconbridge (Barrens);
- An area defined as Semi-Barren that includes the refinery locations (Barren) but not the natural area; and,
- A natural area that represents the surrounding area minus the Semi-Barren area.

The data source for the limed and tree planted areas was provided by the City of Greater Sudbury's Land Reclamation Program. It must be noted that the City does not possess records of rehabilitation efforts performed on land owned by either Vale Inco or Xstrata Nickel. The data provided by the City, therefore, represent the efforts of its Land Reclamation Program only and do not include initiatives undertaken by the individual mining companies.

The data were provided as two digital layers, one showing tree planting areas and the other showing areas where liming occurred. Locations where these two layers intersected are referred to for the purposes of this report as the "Concentrated Recovery area", which represents areas where both reclamation activities have occurred. The total area that has either been limed, planted or both is referred to as "Entire Recovery area" and contains the Concentrated Recovery area. The data for the Barren and Semi-Barren areas come from Canadian Geographic 2001 edition (Lees, 2000). The natural area was arbitrarily selected to extend over a large enough geographic region to be considered representative of the surrounding area. Table 5.1 below represents the approximate areas in square kilometres based on Landsat pixels.

Table 5.1 Area of ROI used in Sudbury Soils Study Remote Sensing Project

Reference Areas	Landsat TM Pixels	Sq. Kms
Entire Recovery Area*	201,940	181.75
Concentrated Recovery Area*	29,906	26.92
Falconbridge Barren	53,814	48.43
Copper Cliff Barren	82,280	74.05
Coniston Barren	75,698	68.13
Semi-Barren	896,524	806.87
Natural Area	3,831,500	3,489.45

Figure 5-5 illustrates the ROI used for analysis. The brown area represents the Semi-Barren region, the red area is Copper Cliff Barren area, purple is Falconbridge Barren area, and beige is Coniston Barren area. Yellow represents the Concentrated Recovery area, while green refers to the Entire Recovery area. The Natural area is defined as the lighter blue area of the image excluding the Semi-barren area. It is assumed that the selected Natural Area has received the least impact of any of the ROI from smelter deposition.

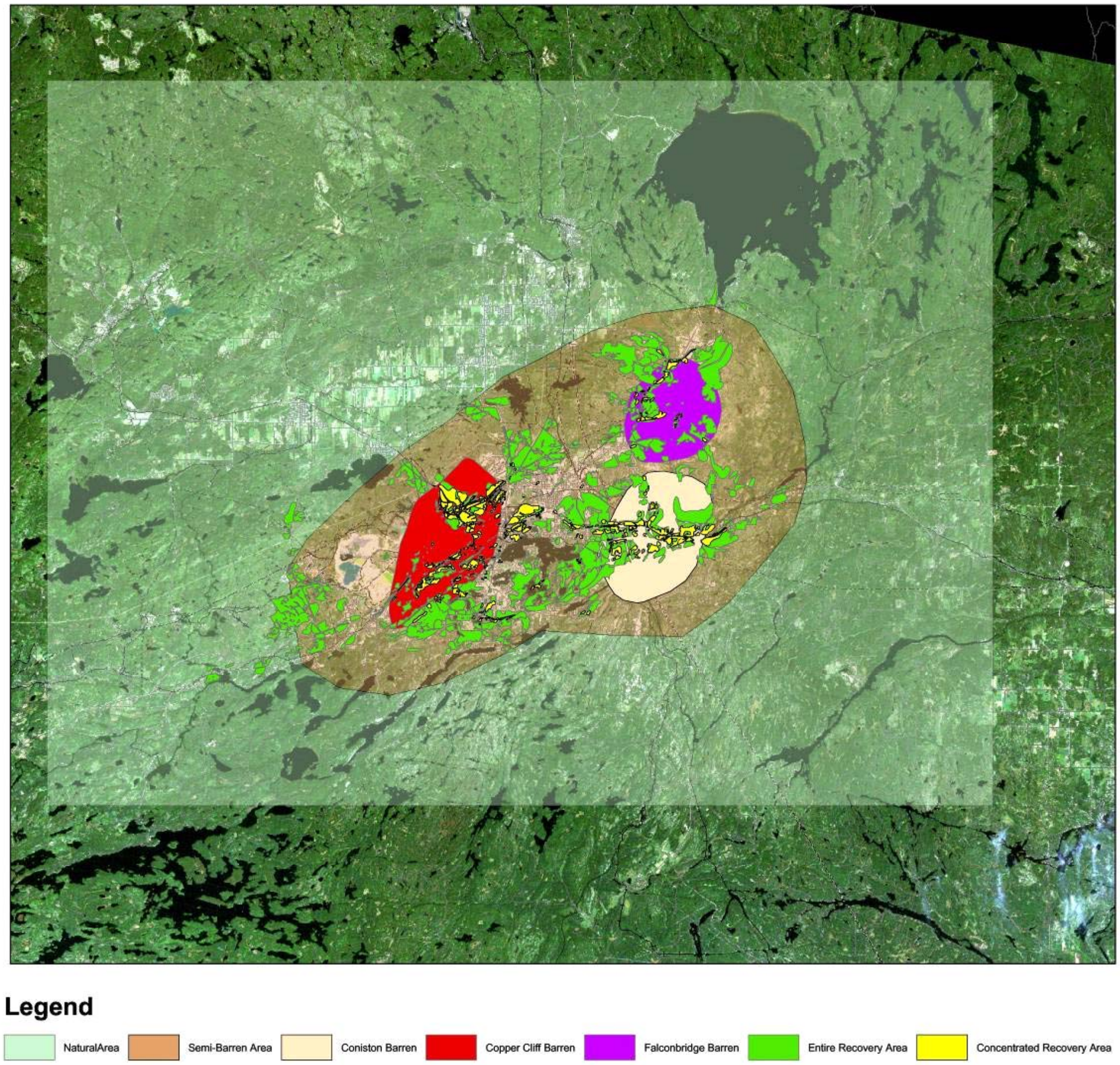


Figure 5-5 Regions of Interest for the Comparison Analysis

5.3.3 Applying Remote Sensing Techniques

Once the ROI were defined, the selection of appropriate data sources and techniques was determined. The following criteria were used to determine the appropriate type of images and analysis techniques:

- Appropriate spectral information should be available to permit vegetation cover detection using discrete spectral bands in the optical (visible) and NIR;
- Calibrated data should be available with a historical archive extending at least 30 years;
- There should be small and similar spatial resolution between consecutive images to separate different land cover types;
- Images should be from similar times of the year (for spring early May and summer early August);

- Images should have clear sky conditions for stable atmosphere;
- Selection of image data should use similar satellite sensor characteristics; and,
- Data should be of reasonable cost.

Two sets of remote sensing data were acquired for use in this study. Landsat 1, Multispectral Sensor (MSS) and Landsat 5TM. The pixel resolution for Landsat TM is 30 m x 30 m with 6 Bands between visible to shortwave infrared; for Landsat MSS the pixel resolution is 60 m x 60 m with 4 Bands between visible and NIR. Details of the sensors are provided in Table 5.2 and Appendix A of this Volume.

Table 5.2 Image Data for SARA Project

Date	Solar Zenith Angle (SZA)	Solar Azimuth Angle (SAA)	Sensor Type	Spectral Bands	File Name
August 12, 2003	52.5	137.5	TM	7	Summer 2003
May 5, 2003	55.16	137.6	TM	7	Spring 2003
July 13, 1998	58.39	130.6	TM	7	Summer 1998
August 18, 1988	50.1	137.8	TM	7	Summer 1988
May 12, 1987	54.6	137.8	TM	7	Spring 1987
September, 6 1976	38.8	128.86	MSS	4	Summer 1976

For the analysis, optical and NIR bands from Landsat remote sensing data were used. This region of the spectrum is ideal for discriminating land cover, in particular vegetation. It is a non-invasive method for characterizing the physical state and type of land cover by means of measuring the interaction that takes place between sunlight and the surfaces.

For the Sudbury analysis, images required processing before being used for temporal analysis, as described in Appendix A of this Volume. The purpose of processing the images was to spatially reference or "tie" the images together to common mapping coordinates and normalize external effects such as the atmospheric scattering and absorption of sunlight, so that the reflected light received at the satellite could be attributed to the surface of interest. Once normalized, remote sensing techniques were applied to examine differences between spectral signatures. Analytical techniques using statistical cluster routine, spectral ratios, and spectral transformations were applied. These techniques are further described in more detail in the following sections.

5.3.4 Techniques for Mapping Vegetation Change

Mapping Land Cover

Assessment of the recovery process in Sudbury through remote sensing was focused on determining changes in vegetation and land cover. At this resolution scale, vegetation analysis focused on the total vegetation over the temporal period (1976 - 2003) and producing a generalized land cover map of the area. A quantitative and qualitative analysis was conducted to determine the condition state.

Qualitative Variation in Land Cover

Analysis of qualitative land cover changes utilized a Principal Component Analysis (PCA) for visual interpretation. PCA is a statistical transformation which separates the information in an image from the noise. The original image data is repackaged so the first few bands of the new PCA image are mostly information, and the last few bands are mostly noise. PCA provides a method of reducing the dimensionality of remote sensing data for visual discrimination of surface cover types (Ashutosh, 2002). Visual interpretation of the PCA images can identify different areas of similar surface reflectance within the image and provide a means of comparing multi-temporal images. When displaying PCA bands, the result of combining the first three spectral bands is a brilliant colour image. The unique colour variation produced by PCA is a rapid means of providing qualitative land cover identification and pattern recognition between normalized scenes from different time periods. Using scenes from different temporal periods, PCA can highlight areas of change due to natural and anthropogenic activities such as fire, clear cutting, urban expansion, and land use changes.

For this project, the reflectance images from the different temporal scenes were transformed using an Ordinary PCA transformation, which uses a covariance matrix to calculate the eigenvalues and eigenvectors. This resulted in the greatest variance of the information being captured in the first component. Visual interpretation of PCA was applied to provide qualitative land cover change between 1988 - 2003 summer images.

Identification of Current Land Cover

A generalized land cover map of the Sudbury area was created using a clustering technique to identify different surface types. A spectral clustering routine was applied to the image using 6 Bands of the summer 2003 Landsat TM image. The purpose of the clustering routine was to identify and group surfaces of the same type with those of similar spectral signatures. The process is referred to as Unsupervised Classification (USC) because it requires no prior knowledge of the area. USC produces a map whose pixels of similar colour are grouped. After that, the analyst decides which land use class each colour group belongs to. To the extent that the same land use classes have the same colour, and different uses have different colours, USC maps can be interpreted to make good land cover maps.

The algorithm used for this process was an ISODATA routine, which is an iterative procedure that initially assigns cluster groups based on a statistical parameter such as standard deviation from the mean and threshold change in the mean value. The number of land cover classes must be initially provided for this iterative process. The iteration process continues until the change in the cluster groups becomes less than the defined threshold.

For the Sudbury Soils Study, USC was applied using an ISODATA algorithm for 20 iterations. A 5% threshold change was used for one standard deviation. A range of five to 40 classes was provided representing the possible range of land cover types. The advantage of USC was that homogenous areas such as large agricultural areas, golf courses, and water bodies, where the spatial extent of the surface was sufficiently large, would group easily in the process. Surfaces of similar types such as urban features and aggregate areas would have minor overlap when separating buildings from parking lots or aggregate sites from bedrock outcrop.

Heterogeneous areas, where the image pixel resolution results in mixed surface types such as roads, shorelines, and wetlands, can result in multiple classes of the same type. These represent transition areas between different land cover types. The dependency to resolve the unique characteristic of the surface is a combination of the spatial and spectral resolution and algorithm used.

In the case of the Landsat TM, the spatial resolution for each pixel covers an area of 900 m^2. In the Sudbury area where the landscape changes dramatically over short distances, the change in land cover can also be rapid over this distance and therefore discriminating these surfaces is difficult.

USC was applied to the summer 2003 images, where 40 classes were generated. A post classification procedure was then performed using ancillary data sets. Vector mapping, including Forest Resource Inventory data from 1996 and Ontario Base Mapping, was used as a reference. Visual interpretation was also applied by geolinking the satellite imagery with the Sudbury Digital Orthophoto (http://www.city.greatersudbury.on.ca/pubapps/ortho/index.cfm?lang=en). The image and the orthophotos lined up well (*i.e.* alignment was estimated to be within two to three pixels). Refinement of the visual interpretation of the land cover classes was conducted with the assistance of an experienced field ecologist with detailed *in-situ* knowledge of the area. The objective was to assign a type of land cover to each of the USC classes. Additional post classification was conducted to combine the 40 USC classes into

19 classes based on similar land cover types to further generalize the land cover maps. Appendix A of this Volume provides a listing of the land cover types.

Quantifying Vegetation Change

To quantify vegetation change over the Sudbury area, two methods were used. The first was based on a spectral index referred to as Normalized Difference Vegetation Index (NDVI) and the second was an applied algorithm that is based on a statistical transformation known as Tesseled Cap Transformation (TCT).

The first method, NDVI, provides a means of inferring the presence of vegetation by utilizing a unique relationship between vegetation physiology and its reflectance property. In the red part of the spectrum, chlorophyll causes the sunlight to be absorbed, while in the NIR, leaf cellular structure and water content cause light scattering and increase the spectral reflectance. The magnitude of the spectral reflectance slope between red and NIR is known as the "red edge" and is used by NDVI to indicate the presence of vegetation. In the Landsat TM image this corresponds to Band 3 and Band 4 as shown in Equation 1.

Equation 1. NDVI

$$\frac{NIR(Band\,4)_{ij} - RED(Band\,3)_{ij}}{NIR(Band\,4)_{ij} + RED(Band\,3)_{ij}} = \phi\,(NDVI) \quad where\ \phi\ \ is\ constrained\ -1 \le \phi \le 1$$

The value of NDVI is unitless. It has a range of minus one to one and standardizes the mapping of vegetated and non-vegetated surfaces. Application of NDVI was used to quantify the seasonal variation in the total vegetation cover using a spring 2003 and summer 2003 image. It was also applied to determine the change in conifer forest by using spring 1987 and spring 2003 images, and to conduct a trend analysis for three temporal periods using summer 1988, summer 1998 and summer 2003 images. Although NDVI provides an indication of the presence of vegetation, its value is influenced by the effect of mixed image pixels, directional reflectance, and remnant atmospheric effects. Therefore, the same land cover surfaces will have a range in NDVI values. For example, for the summer 2003 scene, the range in NDVI values for various land cover types is listed below.

Clouds, snow, artificial surfaces	0 to 1
Deciduous Trees	0.70 – 0.90
Grass Fields	0.75 – 0.95
Rock Barren	0.30 – 0.55
Urban	0.05 – 0.30
Mixed Forest – Sparse	0.65 – 0.80
Roads - highway	0.15 – 0.40

Gravel	0.20 – 0.45
Conifer Forest	0.65 – 0.80
Wetland	0.55 – 0.75

The TCT is a spectral enhancement method aimed primarily at analyzing vegetation in a scene. The principle behind the TCT is based on a modified PCA and dependent on the characteristics of the sensors. There are two TCT that have been applied in this project. The first one is designed for Landsat Multispectral Scanner (MSS) data. This TCT is a technique which produces a transformation of the original data to a four-dimensional space. The transformation does this by identifying four new axes including soil brightness index (SBI), green vegetation index (GVI), yellow stuff index (YVI) and a non-such index (NSI) associated with atmospheric effects. Generally, the first two indexes (SBI and GVI) represent significant portions of the scene information.

The second TCT was designed for Landsat TM data. As a result of the different spectral and spatial bands, this data contains different information than the MSS, and therefore requires a different transformation. The transformation for TM data is commonly called the Brightness, Greenness and Wetness index. For comparison analysis, TM images need to be resampled to a similar resolution as MSS images. TM Brightness and Greenness indices are similar to SBI and GVI. For this project, TCT was applied to the 1976 Landsat MSS and Landsat TM images using the relationships by Crist and Richard (1984).

5.3.5 Comparison Analysis

Vegetation change in the Sudbury area was assessed by conducting a comparison analysis for the ROI applied to different temporal periods using NDVI and TCT. Two categories were used in the analysis that correspond to Natural vs. Assisted Recovery areas and Barren vs. Semi-Barren areas. Summer image scenes were used to examine the overall change in vegetation and spring images were used to determine the variation in seasonal cover and conifer species presence.

Variation in Seasonal Land Cover

Seasonal variation of land cover observed from Landsat TM can show the spatial distribution of vegetation in a scene by comparing the spring and summer scene within the same year. Changes in surface reflectance between these two image scenes will be caused by the appearance of new growth on vegetation such as deciduous trees, understory growth, and herbaceous plants. It will also identify any negative impacts such as recent anthropogenic activities related to subdivision development or mining operations. It was anticipated that areas such as conifer trees and non-vegetated surfaces related to urban surfaces and bedrock outcrop would represent areas of minimal change over a season.

For the Sudbury Soils Study, the seasonal variation was performed to provide a visual representation of the overall seasonal change in land cover, and to use the information to identify areas of conifers. In addition, the mapping of seasonal variation in land cover was related to natural and assisted recovery areas to compare the differences.

NDVI was applied to map the seasonal land cover change as related to vegetation by comparing the ratio between the summer 2003 and spring 2003 image scenes.

Equation 2. Seasonal Variation

$$\frac{NDVI \quad Summer2003_{ij}}{NDVI \quad Spring2003_{ij}} = \alpha \quad \textit{where } \alpha \textit{ is constrained } 0 \leq \alpha \leq 1$$

The ratio was then density sliced into Ratio Classes by intervals of 0.5 (*e.g.*, 1, 1.5, 2, 2.5, *etc.*). Interpretation of the size and location of the ratio class can be used to identify changes in vegetation. Image pixels with a ratio between 0 - 0.5 indicate areas where NDVI values decreased over the season. This could be the result of urban expansion, or other anthropogenic activities. Natural changes may be the result of increased wetland areas due to more abundant precipitation resulting in more water, or vegetation dieback. Ratios between 1 - 1.5 are considered relatively unchanged and can include urban features, water, bedrock, and conifer forest areas. A ratio of 1.5 – 2 might reflect areas of sparse conifer forest mixed with other vegetation. Sparse vegetation on outcrop areas and urban pixels mixed with vegetation would also have similar ratios. The remaining ratios indicate the presence of deciduous vegetation (*e.g.*, vegetation on bedrock outcrop, understory growth, deciduous forest and grass fields).

Variation in Spring Vegetation Cover

Image analysis in this section focused on providing a broad understanding of the success of the planting program by using NDVI to relate changes in conifer presence over a temporal period from 1987 to 2003 through two scenes. Both images were acquired in mid May (12th and 8th, respectively) since the vegetation signature should be dominated by conifers in early May, and there would be negligible changes as a result of early growth of deciduous vegetation. Spring images can therefore be used to analyse the vegetation change as a result of natural and assisted recovery. Since vegetation growth is at a minimum in the early spring, any changes can therefore be attributed to a change in the amount of conifer cover as a result of assisted or natural recovery.

To quantify this change, a percentage difference of NDVI between the spring 2003 and spring 1987 images was calculated for each pixel in the image scene as shown in Equation 3.

Equation 3. Percentage Difference

$$\frac{NDVI \quad Spring2003_{ij} \text{ - } NDVI \quad Spring1987_{ij}}{NDVI \quad Spring1987_{ij}} \times 100 = \%\alpha$$

Percentage difference NDVI values were then grouped into classes, as follows:

-25 to 0%	no change
0 to 25%	no change
+25 to 50%	modest increase
50 to 100%	significant increase

Vegetation Trend Analysis

To examine the temporal change in overall vegetation, two analyses were conducted. NDVI values were used to perform a vector analysis for summer images from 1988-1998-2003. TCT was applied to the images to create Brightness and Greenness index values for the 1976-1988-1998-2003 images. TCT provided a visual qualitative measurement of change in the vegetation landscape through interpretation of the resulting colour composite image and TCT values. Brightness and Greenness index images were displayed using RGB colour with the -1976 image assigned to the red, the 1988 image assigned to the green and the 2003 image assigned to the blue colour. TCT Brightness and Greenness Index values were extracted for the Semi-Barren and three Barren areas.

A vector analysis of NDVI values in both magnitude and direction was applied by plotting NDVI value as function of time (years) for each spatial image pixel in the four scenes. A straight trend line was fitted through the NDVI values using a least square routine and a slope value was determined. An R^2 was derived for each pixel. For $R^2 > 0.66$, one is 90% sure that the correlation is significant and not just due to chance.

Those pixel values below 0.66 were excluded from the image. The analysis technique was applied as a first order method to examine the existence of a trend and where it is located in the image. A rigorous treatment would be required with additional data and further statistical analysis to define the vegetation relationship. The intent of using this methodology was to identify geographic areas that were experiencing positive trends, negative trends or areas that remain unchanged over the temporal period using the slope magnitude, direction of the slope and how well the values correlated to the trend line as indication of trends.

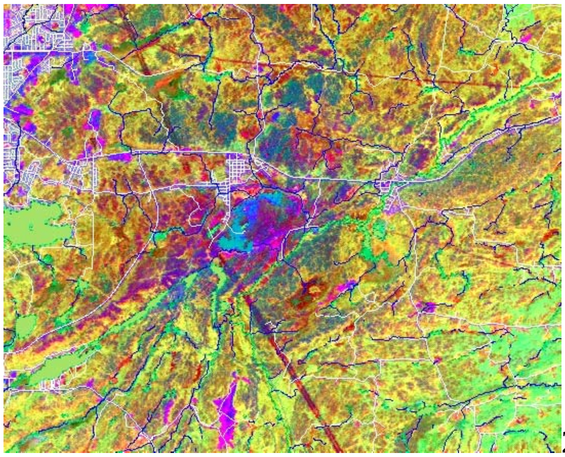
5.4 Results

5.4.1 Qualitative Variation in Land Cover – Principal Analysis

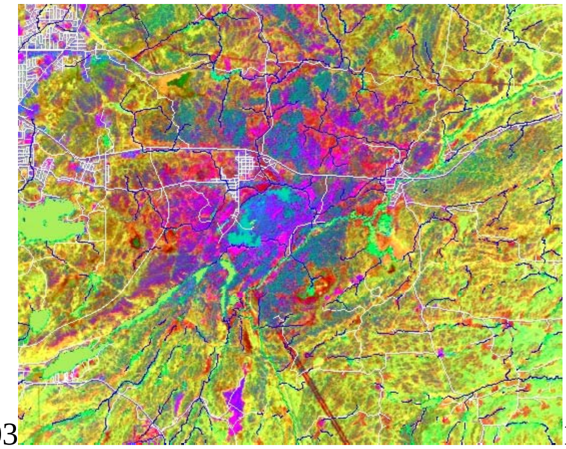
PCA applied to summer images reveals variations in land cover, both spatially and temporally (Figure 5-6). Spatial colour patterns are the result of displaying PC Band 1, PC Band 2 and PC Band 3 in RGB. The data is uncorrelated and reveals patches of similar land cover due to similarities in their surface reflectance.

For the three smelter areas, interpretation of the PCA is not obvious because of the complexity of surface types ranging from vegetation, industrial, urban, rock outcrops, and wetlands within a small area. However, close examination shows that subtle changes in surface pattern are present in the images. The Coniston area shows the greatest transition in colour towards the surrounding area, primarily to the west and the north, between the 15-year period and a decrease in intensity to the east. In the Falconbridge area the transition is not as pronounced but transitions in colour are apparent in the vicinity of the airport, on the northern edge of the image clip. Changes in the Copper Cliff area are noticeable near and to the northeast of the tailings area, on the lower left of the image clip. There is also a change in colour to the west of the Sudbury area.

Coniston

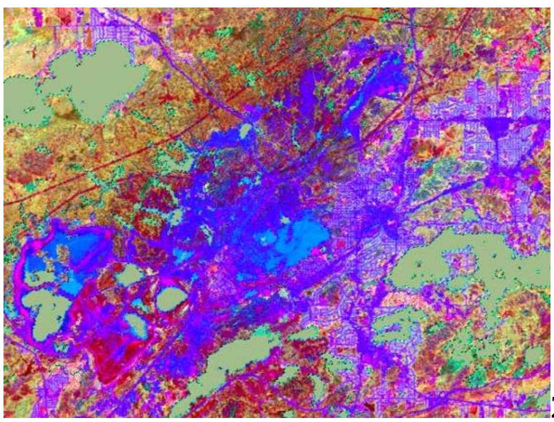


2003

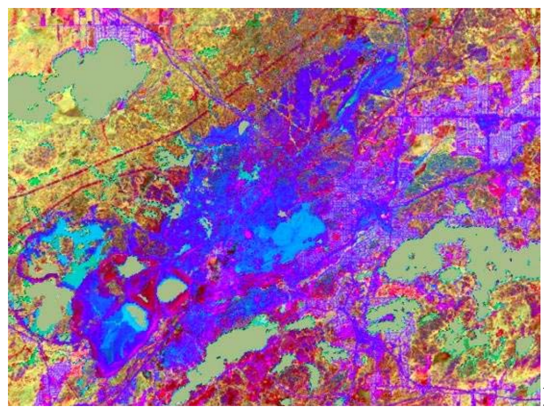


1988

Copper Cliff

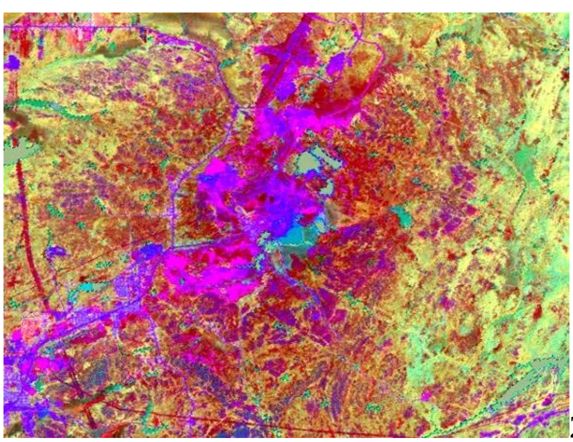


2003

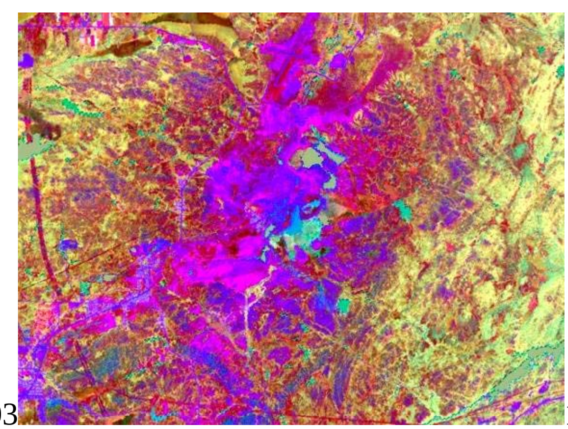


1988

Falconbridge



2003



1988

Figure 5-6 PCA Imagery for 2003 and 1988 for Coniston, Copper Cliff and Falconbridge, with PC1 in red, PC2 in green, and PC3 in blue.

5.4.2 Generalized Land Cover of the Sudbury Region

The generalized land cover created from the summer 2003 image provides a strong visual representation of the different land cover types in the Sudbury area (Figure 5-7). The USC routine was applied and the result of combining the 40 classes to 19 in a post-classification process provides a map-like image of the different land cover types such as water, industrial, barren/outcrop, and field areas, *etc.* A list of class names was created from local interpretation of the land cover type. The complexity of some surfaces such as industrial, mixed forest and wetlands included some inherent variation due to the heterogeneous nature of these land cover types, resulting in mixed image pixels. A random process was used to provide a confidence value in the classification by sampling locations in the orthophoto and examining the classification pixels for 40 classes in the USC. Seventy-five points were sampled providing an 83% confidence based on photo interpretation.

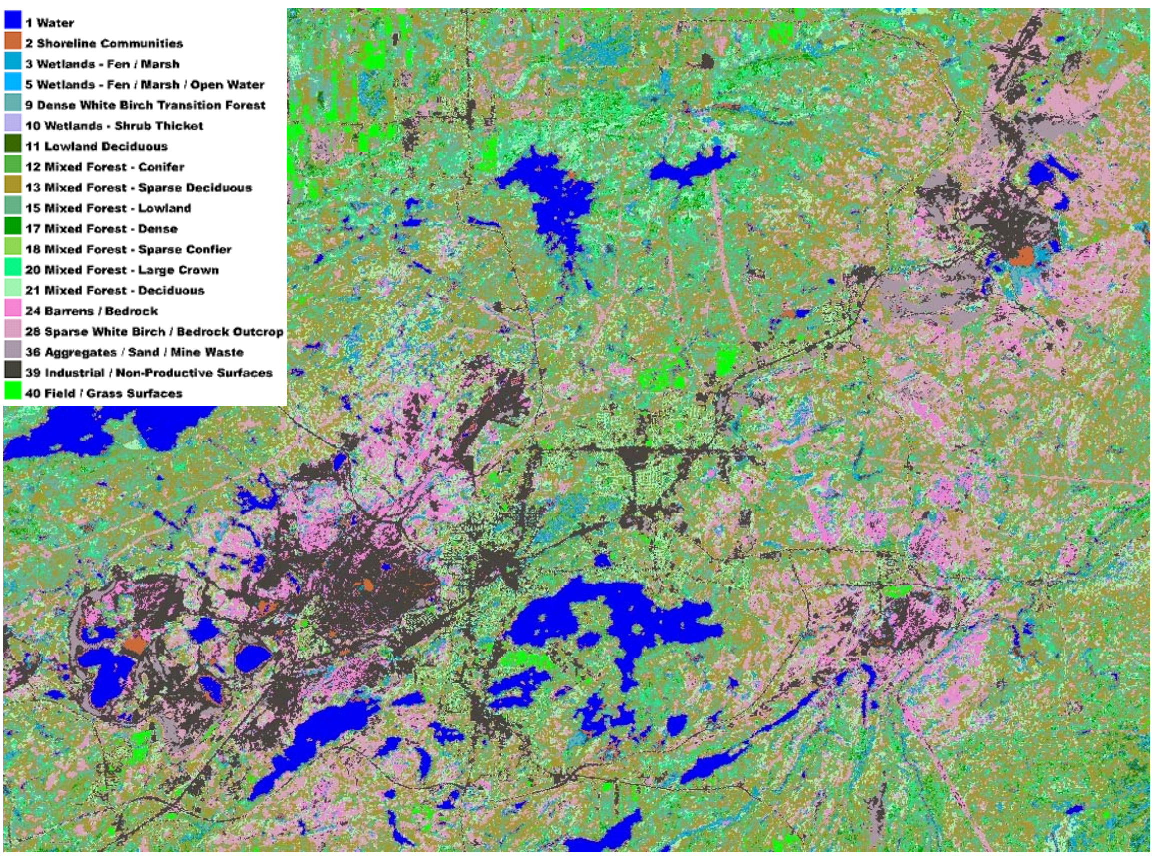


Figure 5-7 Generalized Land Cover of the Sudbury Region

ROI were used to conduct a comparison analysis on the USC image to determine the composition of land cover types. The analysis focused on assisted recovery areas, a natural area as a control benchmark, and areas around the smelters (Table 5.3).

Table 5.3 Percentage of Land Cover Type for Assisted Recovery vs. Natural Recovery ROI for USC as Percentage

Class Number	Classes	Assisted Recovery Areas				Natural Area	
		Entire Recovery Area	Rank	Concentrated Recovery Area	Rank	Area	Rank
1	Water	0.27	15	0.06	17	8.58	5
2	Shoreline Communities	0.31	14	0.11	15	1.13	17
3	Wetlands - Fen / Marsh	3.22	8	8.71	4	14.07	1
5	Wetlands - Fen / Marsh / Open Water	0.10	17	0.08	16	1.25	15
9	Dense White Birch Transition Forest	5.94	6	4.21	9	10.09	4
10	Wetlands - Shrub Thickets	0.05	19	0.05	18	2.20	12
11	Lowland Deciduous	0.06	18	0.05	19	4.56	11
12	Mixed Forest - Conifer	3.06	9	7.63	6	11.25	3
13	Mixed Forest - Sparse Deciduous	31.14	1	18.62	2	12.26	2
15	Mixed Forest - Lowland	7.95	4	5.14	8	5.62	8
17	Mixed Forest - Dense	0.52	13	0.66	11	8.37	6
18	Mixed Forest - Sparse Conifer	0.18	16	0.42	13	5.00	9
20	Mixed Forest - Large Crown Deciduous	2.30	10	1.10	10	4.82	10
21	Mixed Forest - Deciduous	13.06	3	19.05	1	6.03	7
24	Barren / Bedrock	7.90	5	18.44	3	0.54	18
28	Sparse White Birch / Bedrock Outcrop	16.17	2	7.92	5	1.27	14
36	Aggregate / Sand / Mine Waste	1.39	11	0.48	12	0.41	19

Table 5.3 Percentage of Land Cover Type for Assisted Recovery vs. Natural Recovery ROI for USC as Percentage

Class Number	Classes	Assisted Recovery Areas				Natural Area	
		Entire Recovery Area	Rank	Concentrated Recovery Area	Rank	Area	Rank
39	Industrial / Non-Productive Surfaces	5.84	7	7.16	7	1.19	16
40	Field / Grass Surfaces	0.53	12	0.11	14	1.36	13

The table contains the rank, percentages, and area of the land cover type for the ROI. In the case of assisted recovery, the ROI for the Concentrated Recovery area were used as a base reference. The most common land cover type for this ROI was Mixed Forest-Sparse Deciduous with ~31% of the area. This land cover type was much less prevalent in the Entire Recovery area, where this classification occupied ~19% of the area. In both cases these results were greater than the natural area where this community only occupied ~12% of the area.

The two conifer classifications, Mixed Forest - Conifer and Mixed Forest-Sparse Conifer, comprised ~8% of the Entire Recovery area, in contrast to the Concentrated Recovery area where only ~3% was occupied by conifer-dominated classifications. In comparison, conifer dominated classifications occupied 16% of the Natural area. The Assisted Recovery areas have surface characteristics that could be considered marginal in terms of their recovery potential due to the predominance of industrial/urban and bedrock surfaces (Classes 24, 28, 36 and 39). These Classes comprise 31% of the Concentrated Recovery area and 34% of the Entire Recovery area in comparison to the Natural area where these classes comprise only 5% of the area.

Table 5.4 shows the percentage for land cover types in the Semi-Barren and Barren ROI. The primary land cover type for the Falconbridge ROI from USC image was Sparse White Birch/Bedrock with ~25% of the area classified as this type. Copper Cliff was dominated by Industrial/Non-Productive Surfaces with ~35% of the ROI, while the primary cover type at Coniston was Mixed Forest-Sparse Deciduous at ~23%. The Semi-Barren area was similar to Coniston, dominated by Mixed Forest-Sparse Deciduous at ~26%. Similar to the observations of the PC images in Figure 5-7, the generalized land cover showed the greatest change in the Coniston ROI.

Table 5.4 Generalized Land Cover for the Semi-Barren and Barren Areas as Percentage%

Class Number	Classes	Falconbridge	Rank	Copper Cliff	Rank	Coniston	Rank	Semi-Barren	Rank
1	Water	1.88	10	5.81	6	0.83	13	4.35	8
2	Shoreline Communities	1.42	11	1.82	8	0.90	12	1.22	14
3	Wetlands - Fen / Marsh	2.65	9	3.75	7	4.53	8	3.85	10
5	Wetlands - Fen / Marsh / Open Water	0.14	15	0.11	15	0.18	16	0.19	18
9	Dense White Birch Transition Forest	2.82	7	1.68	9	4.70	7	6.56	6
10	Wetlands - Shrub Thickets	0.03	18	0.03	19	0.06	19	0.10	19
11	Lowland Deciduous	0.03	18	0.04	18	0.07	18	0.30	17
12	Mixed Forest - Conifer	1.30	12	1.67	10	2.38	9	4.10	9
13	Mixed Forest - Sparse Deciduous	17.75	2	8.98	4	23.21	1	25.74	1
15	Mixed Forest - Lowland	2.70	8	1.49	11	6.38	6	8.61	5
17	Mixed Forest - Dense	0.09	16	0.10	16	0.31	15	1.59	13
18	Mixed Forest - Sparse Conifer	0.04	17	0.05	17	0.12	17	0.71	16
20	Mixed Forest - Large Crown Deciduous	0.45	13	0.31	14	1.68	10	3.64	11
21	Mixed Forest - Deciduous	7.49	5	11.83	3	12.55	4	10.70	2
24	Barren / Bedrock	6.50	6	17.44	2	15.70	3	5.79	7
28	Sparse White Birch / Bedrock Outcrop	24.55	1	7.90	5	16.58	2	10.54	3
36	Aggregate / Sand / Mine Waste	13.34	4	1.38	12	0.94	11	1.96	12
39	Industrial / Non-Productive Surfaces	16.39	3	35.21	1	8.52	5	9.32	4
40	Field / Grass Surfaces	0.43	14	0.41	13	0.34	14	0.73	15

5.4.3 Vegetation Changes

Seasonal Change in Vegetation using NDVI

The spatial distribution of vegetation was mapped by applying Equation 2 to NDVI images for summer and spring images of 2003. The resulting image predominantly corresponds to the seasonal change of vegetation cover and is displayed in Figure 5-8. The image has been classified into groups representing ratios and thresholds. Any negative values (less than 1.6%) and ratios greater than 5% were threshold and were assumed to be pixels that were related to data artifacts from the geocorrection process. The colours in the image represent the density sliced classes based on the interval range of 0.5 ratios.

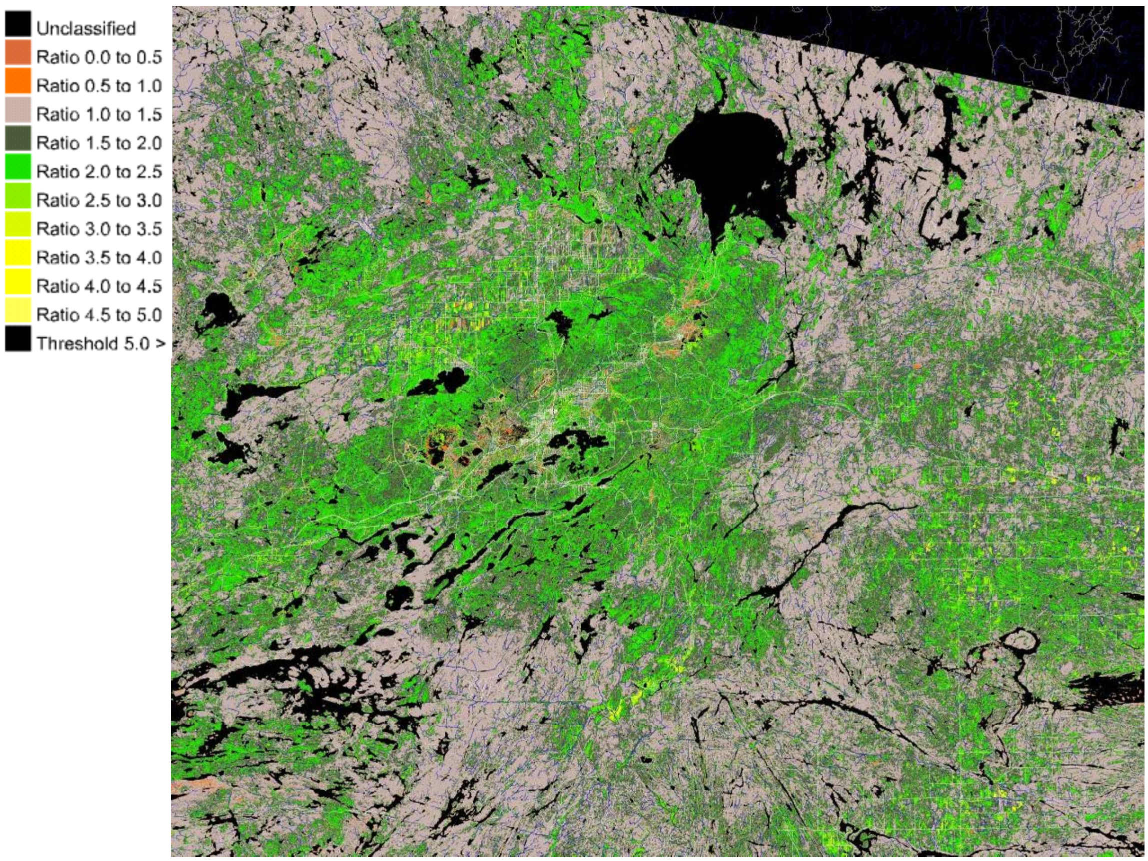


Figure 5-8 Seasonal Change in Vegetation using NDVI for Summer/Spring 2003 Images

Figure 5-8 reveals distinct areas of green to yellow colour, identifying locations where the vegetation, and hence NVDI, increases. The image also shows areas that remained relatively unchanged as gray-silver. Areas that experienced a decrease in NDVI are represented by orange to red colour. The interpretation of Figure 5-8 is that the Semi-Barren area (including Barren areas) experienced an increase in NDVI in comparison to the surroundings. This can be attributed to the significant presence of deciduous growth and herbaceous plants in the semi-barren area. In contrast, the natural area does not show a significant change in NDVI between the spring and summer images. This is likely due to the large proportion of this ROI consisting of mixed forest, coniferous forest, areas of bedrock outcrop, and wetlands, all of which have remained relatively unchanged.

A closer look at the Semi-Barren area in Figure 5-8 shows the increases within the Barren areas have a predominately marginal change in NDVI between seasons and are within the 1.5 - 2.0 ratio class. Areas of urban and mining /aggregate operation show an unchanged or a decrease in NDVI values in Figure 5-9.

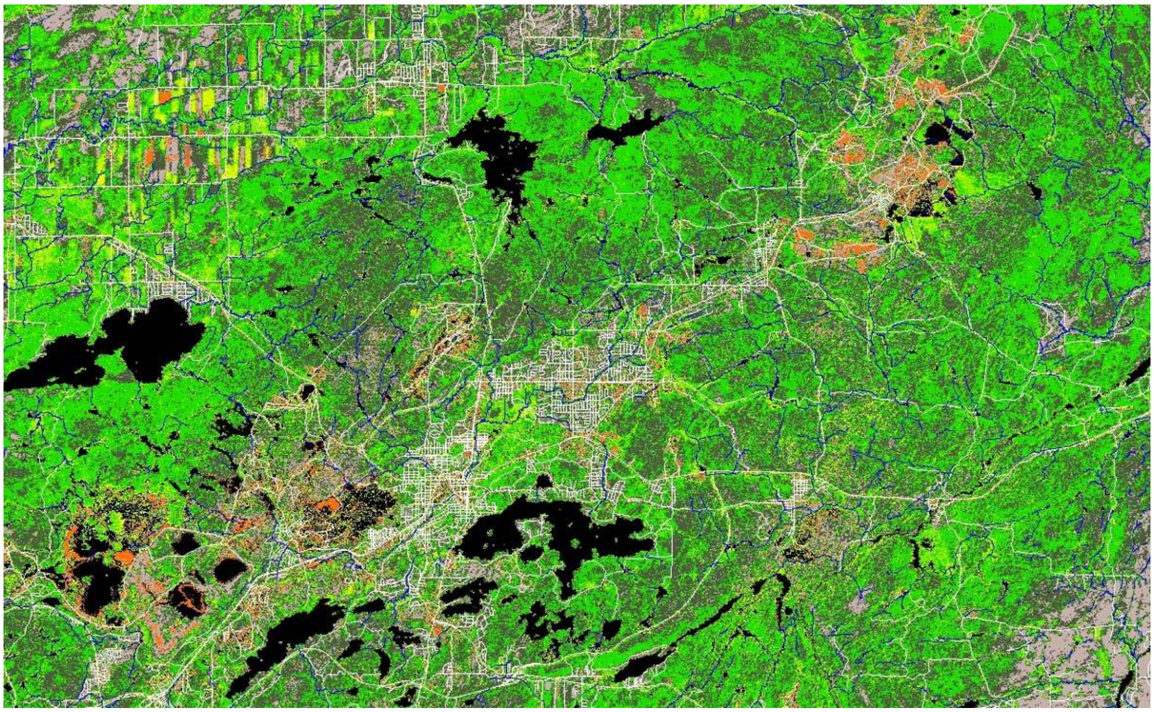


Figure 5-9 Seasonal Change in NDVI values for The Semi-Barren Area

Table 5.5 shows the aerial extent of the seasonal change in vegetation using NDVI. Ratio classes less than 1.00 indicate the percent of the ROI for which NDVI decreased while ratio classes greater than 1.50 indicate the percent of the ROI for which NDVI increased. The ratio class of 1.00 to 1.50 indicates the percent of the ROI for which NDVI did not change. Within the Barren areas the areal extent of NDVI for the Copper Cliff ROI increased by ~75%, Falconbridge increased by 74% , and Coniston showed the most significant positive change with an ~89% increase in NDVI.

Table 5.5 Seasonal Change in Vegetation Cover from NDVI values as a Percentage%

Classification	Falconbridge	Copper Cliff	Coniston	Semi-Barren
Unclassified	3.90	10.44	2.47	6.32
0-0.5	0.88	1.53	0.16	0.40
0.5 -1	5.99	5.19	1.02	1.79
1-1.5	14.15	17.92	9.49	8.76
1.5-2	34.57	34.21	40.72	37.02
2-2.5	27.44	19.04	34.69	36.25
2.5-3	8.01	5.33	7.06	5.73
3-3.5	2.27	2.03	1.92	1.48
3.5-4	0.90	1.03	0.77	0.62
4-4.5	0.43	0.62	0.38	0.34
4.5-5	0.32	0.43	0.25	0.22
Threshold	1.14	2.25	1.07	1.08

Variation in Spring Vegetation Cover

NDVI values were applied to spring images so that they could be related to the presence of conifers such as jack pine, black spruce, *etc*. NDVI values where conifers are present would be larger than the surrounding landscape in the spring. As well, NDVI values should be higher for dense stands and weaker for mixed forest areas or sparse conifer canopy. Figure 5-10 reveals the percent difference between spring 1987 NDVI values and spring 2003 NDVI values, calculated using Equation 3. A range between -25% and 25% was considered unchanged. The observed changes in Figure 5-10 are partially due to the presence of conifers, but could also result from the appearance of early vegetation and alterations to the vegetation from anthropogenic activity.

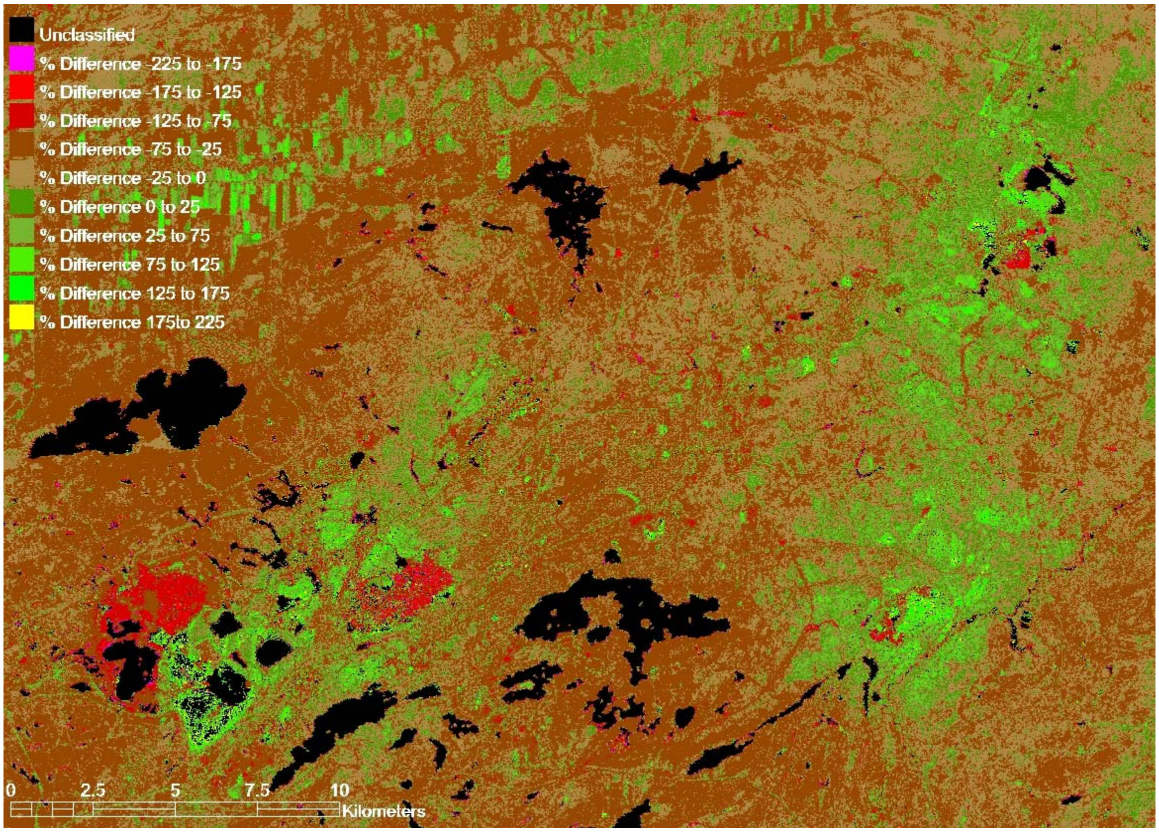


Figure 5-10 Percentage Difference between Spring 2003 and Spring 1987 NDVI values

NDVI difference classes were then evaluated for the Semi-Barren ROI (see Table 5.6) A summary of positive, negative and unchanged was tabulated for the percent difference. For Falconbridge and Coniston, the percent differences show that positive change outweighs negative, while Copper Cliff experienced an overall negative change. An overall decrease in NDVI values was seen in the Semi-Barren area over the 16 year period. This could be attributed to a number of different possibilities, including a decrease in conifers or the presence of other early spring vegetation.

Table 5.6 Vegetation Cover Change Between Spring Images (1987 - 2003)

Classification	Falconbridge	Copper Cliff	Coniston	Semi-Barren
Unclassified	3.34	8.79	2.07	5.61
% Difference -225 to -175	0.27	0.57	0.18	0.28
% Difference -175 to -125	0.63	1.32	0.45	0.52
% Difference -125 to -75	1.32	3.59	1.00	1.73
% Difference -75 to -25	13.36	27.65	18.07	39.97
% Difference -25 to 0	29.04	25.72	32.10	33.31
% Difference 0 to 25	24.34	15.04	21.95	10.61
% Difference 25 to 75	20.17	11.60	17.62	5.68
% Difference 75 to 125	5.42	3.70	4.54	1.48
% Difference 125 to 175	1.55	1.40	1.50	0.55
% Difference 175 to 225	0.59	0.64	0.51	0.26
Positive	27.72	17.33	24.18	7.98
Unchanged	53.37	40.76	54.05	43.92
Negative	18.91	41.92	21.78	48.11

Overall Vegetation Trend Using NDVI and TCT

The change in overall vegetation for the Sudbury area was analyzed using TCT and NDVI as well as a least square regression with a threshold R^2 value >0.66 (Figure 5-11). For TCT, Brightness and Greenness index images were used to create a temporal composite colour image by assigning the 1976 component to red, 1988 component to green and 2003 component to blue. Visual interpretation and the ROI were used over the Semi-Barren/Barren areas to compare the brightness changes and its relationship to vegetation. A white colour indicates that for each of the years the surface brightness is consistent and large relative to other surfaces. High brightness values are usually related to exposed bedrock, aggregate surfaces and soils.

Gray to black colours would indicate the opposite: a consistent but lower brightness value. Gray colours are consistent with land cover such as urban areas and forest cover. Forest and other natural vegetation will lower the brightness, and therefore the majority of changes in surface brightness over non-urban areas can be attributed to vegetation. Where the colour blue is dominant, it represents an increase in brightness for the 2003 image and similarly green for 1998 and red for 1988. Colour mixes such as yellow would be a combination of a gradual decrease from 1976 and 1988 and more rapid decrease in 2003.

The white areas around Falconbridge in Figure 5-11 are consistent over the 27 years and most likely represent the active aggregate area. The Barren area around Coniston shows a mixed yellowish colour suggesting a decrease in brightness, particularly towards 2003. The gray to dark areas surrounding Copper

Cliff indicate a low Brightness value in all years, while the predominately blue area shows a brightness increase in the tailing areas in 2003.

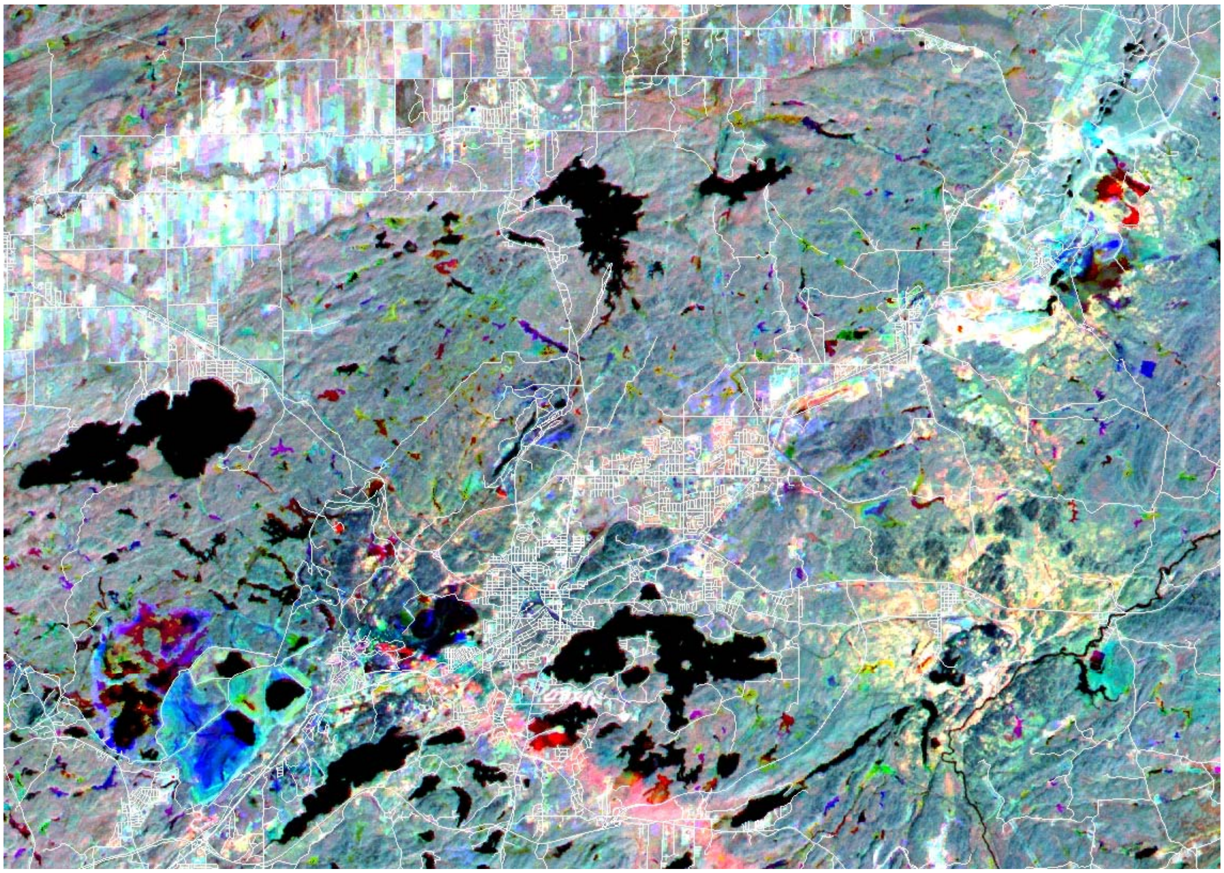
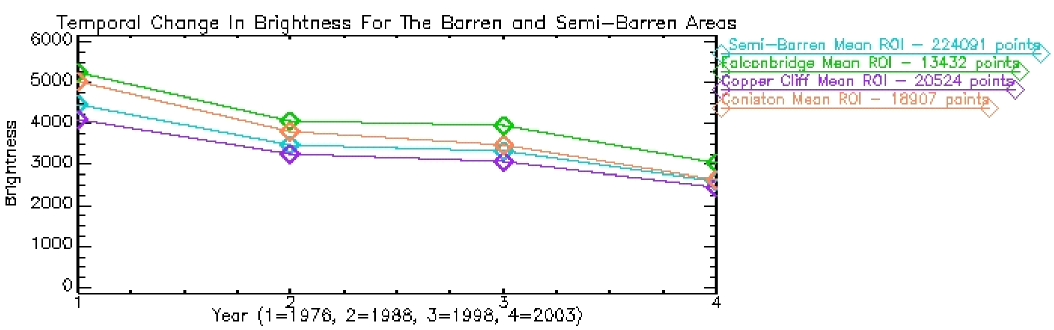


Figure 5-11a Brightness R1976-G1988-B2003 Summer Images

The mean Brightness values for each ROI in the Barren and Semi-Barren areas are plotted (see Plots 1 and 2). These plots show the gradual decrease in Brightness index for ROI in the MSS summer image (1976) and the three summer Landsat TM images (1988, 1998, 2003).



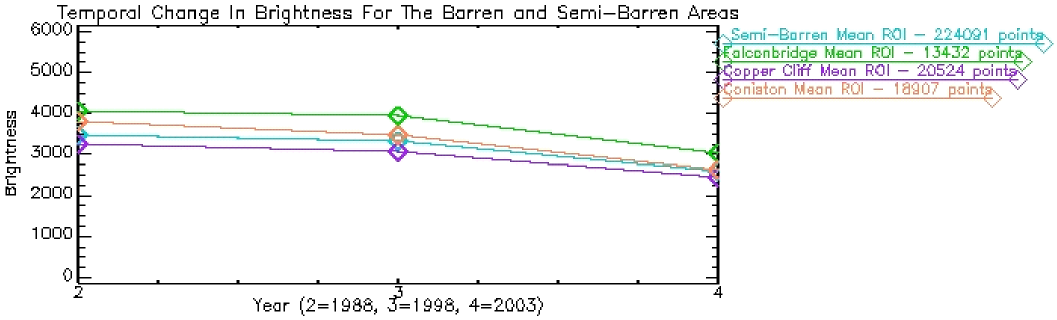


Figure 5-11b Temporal Change In Brightness for the Barren and Semi-Barren Areas (for years 1976, 1988, 1998 and 2003).

TCT greenness uses a combination of spectral bands from invisible to NIR that respond to the presence of vegetation. Like brightness, the colour composite is indicative of the relative influence from a specific time period. For the greenness index composite image, the 1976 image corresponds to the red, 1988 is assigned green and 2003 has a blue colour (Figure 5-12). The most noticeable feature in the image is the darkish areas in the barren areas indicative of low Greenness values. The predominance of blue would suggest that the presence of vegetation is greater in 2003, particularly around Coniston and to a lesser extent the other smelters. This generally corresponds to a decrease in surface brightness with an increase in the presence of vegetation.

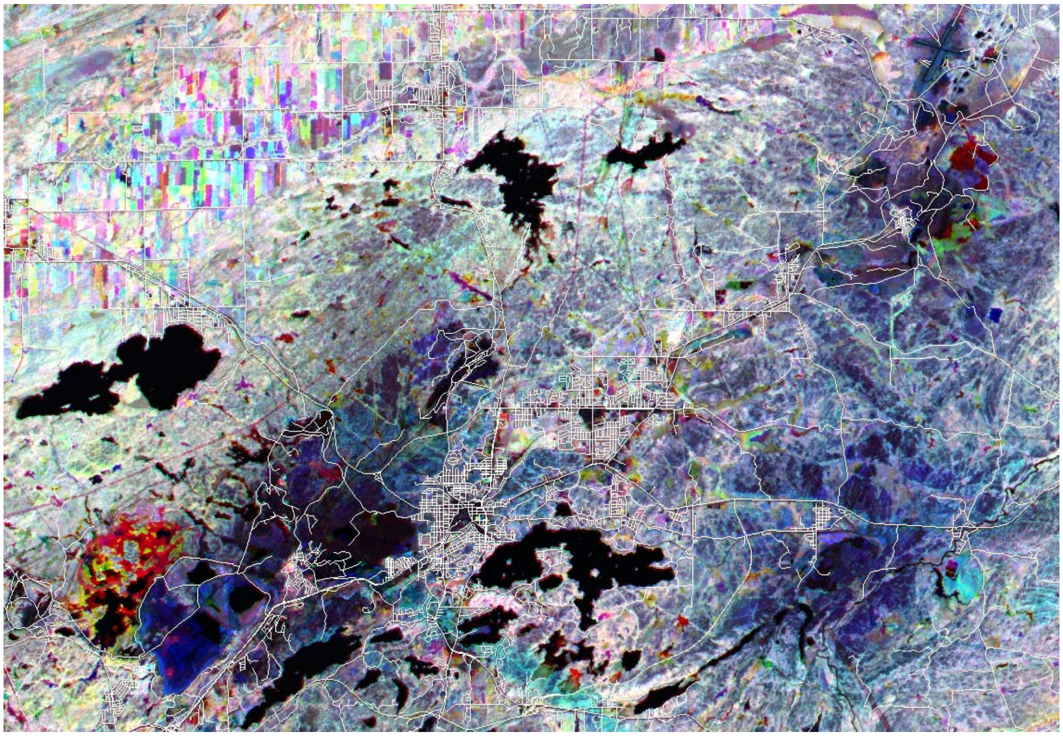
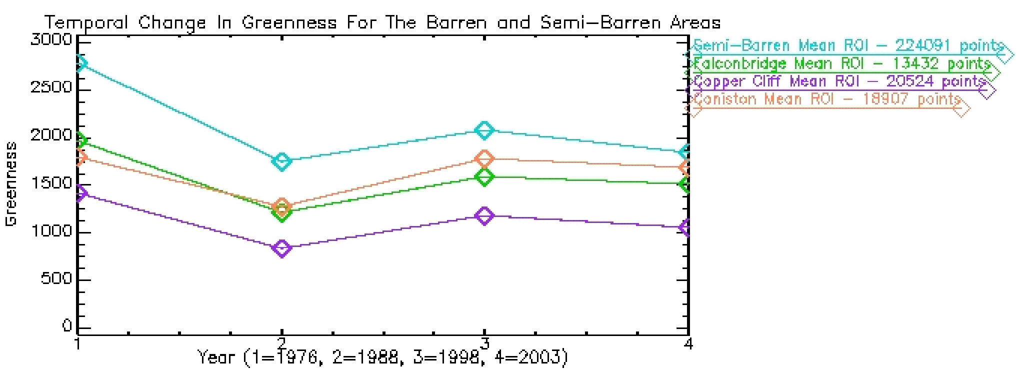


Figure 5-12a Greenness R1976-G1988-B2003



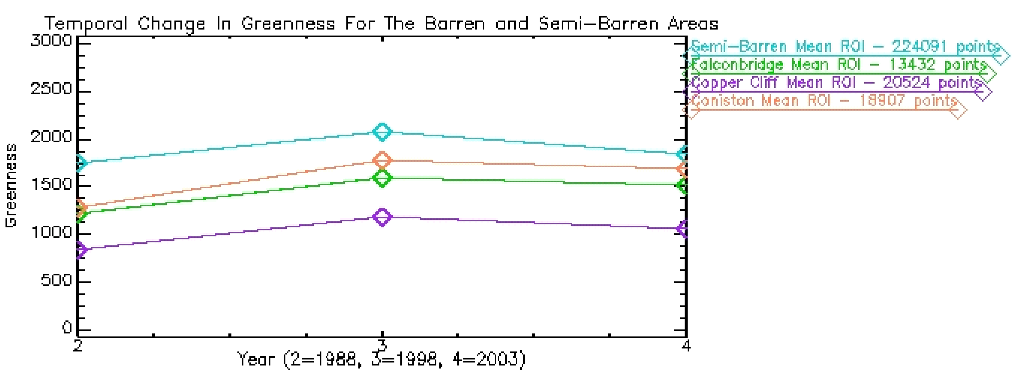


Figure 5-12b Temporal Change in Greenness for the Barren and Semi-Barren Areas (for years 1976, 1988, 1998 and 2003).

The strongest example of vegetation change in the Sudbury area is shown by applying a statistical approach of combining a least square regression and R^2 correlation values to identify pixels that have positive or negative changes and exclude areas that have no clear trend. Figure 5-13 shows the results as a classified image of slope values and identifies areas that were excluded shown as black. The dominant feature in the image is the Barren areas that show a dark to pale green colour indicating a positive trend of increasing NDVI values suggesting an increase in vegetation.

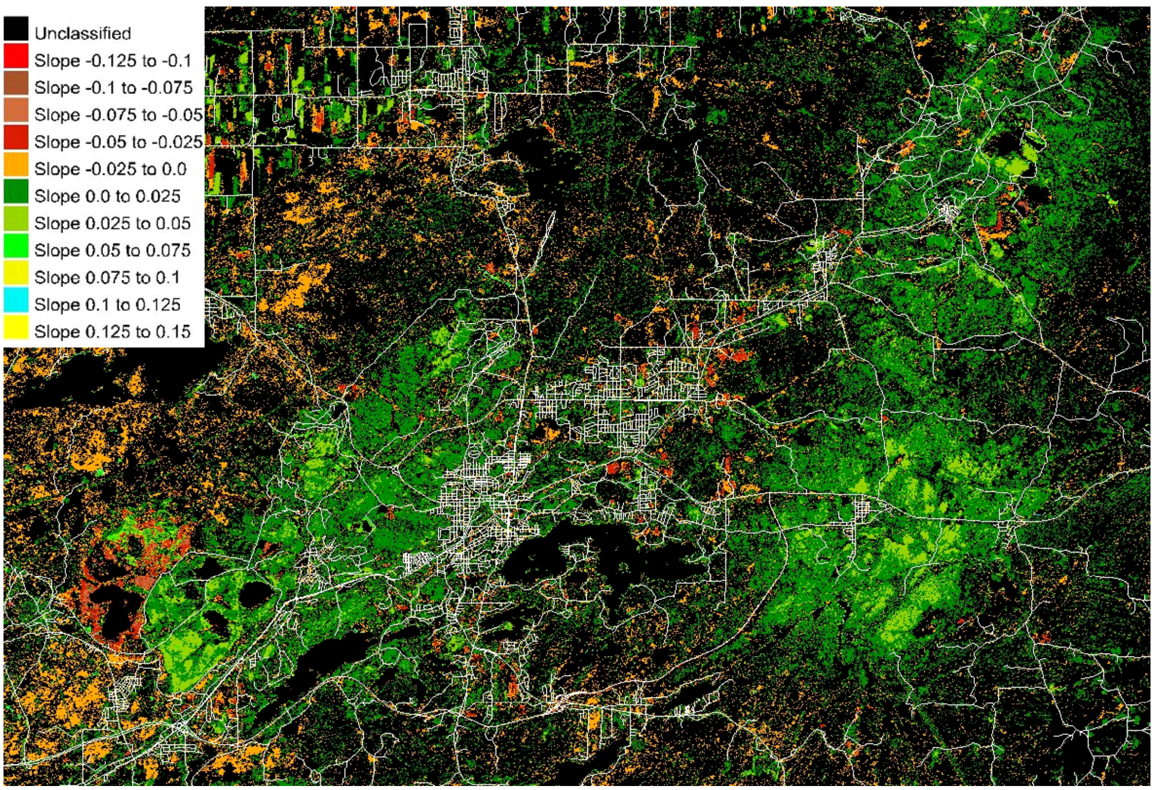


Figure 5-13 Trend in Overall Vegetation Recovery from 1988 - 1998 - 2003

Further examination of the changes in vegetation cover for the Barren areas in comparison with the Semi-Barren and Natural areas was done using ROI to extract pixels for each class and calculate the percentage (Table 5.7). The results indicated that Coniston had the greatest positive change with ~59% of NDVI slope values having a significant positive trend, Copper Cliff with ~53% and Falconbridge with ~41%. In comparison, the natural area change in vegetation was minor with an overall decrease of ~3%.

Table 5.7 Overall Vegetation Trend (1988 - 2003) as a Percentage (%)

Classification	Falconbridge	Copper Cliff	Coniston	Semi-Barren	Natural Area
Unclassified	54.30	41.20	38.66	64.85	88.74
Slope -0.125 to -0.1	0.00	0.00	0.00	0.00	0.00
Slope -0.1 to -0.075	0.02	0.01	0.00	0.01	0.00
Slope -0.075 to -0.05	0.05	0.13	0.01	0.14	0.03
Slope -0.05 to -0.025	0.41	0.68	0.17	0.85	0.26
Slope -0.025 to 0.0	3.96	4.97	2.21	8.74	6.90
Slope 0.0 to 0.025	36.96	43.72	48.04	22.36	3.31
Slope 0.025 to 0.05	4.01	8.75	10.53	2.73	0.41
Slope 0.05 to 0.075	0.16	0.39	0.22	0.19	0.17
Slope 0.075 to 0.1	0.10	0.12	0.08	0.08	0.04
Slope 0.1 to 0.125	0.04	0.03	0.00	0.06	0.10
Slope 0.125 to 0.15	0.00	0.00	0.00	0.06	0.04

5.4.4 Natural Recovery Compared to Assisted Recovery

Seasonal Change in Vegetation Recovery Areas

The Natural area ROI and Assisted Recovery ROI were compared to examine the seasonal change. Table 5.8 lists the seasonal change using the ratio of NDVI as percent of area. The NDVI ratios for the Assisted Recovery ROI show strong positive change, with the Concentrated Recovery area showing ~92% change and the Entire Recovery area showing ~89% change. In comparison, the surrounding Natural area had a change of ~57%.

Table 5.8 Seasonal Change in Vegetation as a Percentage %

Classification	Entire Recovery Area	Concentrated Recovery Area	Natural Area
Unclassified	0.79	0.29	9.94
0-0.5	0.12	0.13	0.04
0.5 -1	0.91	1.06	0.35
1-1.5	6.79	9.23	32.69
1.5-2	47.23	44.15	32.60
2-2.5	37.25	35.63	19.34
2.5-3	4.69	6.47	3.06
3-3.5	1.07	1.56	0.81
3.5-4	0.40	0.54	0.31
4-4.5	0.21	0.33	0.16
4.5-5	0.12	0.15	0.11
Threshold	0.43	0.45	0.60

Variation in Spring Vegetation Cover

Analysis of the percent difference of NDVI values between the spring 2003 and spring 1987 images shows only a small positive change for the Assisted Recovery area, assumed to be related to conifers. However, the difference between the Concentrated Recovery area (~10%) and the Entire Recovery area (~17%) is nearly double the percent difference in NDVI. This is assumed to be related to an increased growth in planted conifers. The Natural area ROI only shows a positive change of ~3% in comparison. It should be noted that there is potential influence on the NDVI values related to early vegetation in the 1987 spring image.

Overall Trend in Vegetation Using NDVI

The recovery of vegetation in the Assisted Recovery area is reflected in Table 5.9. The positive trend as indicated by the slope of the NDVI value is primarily driven by the presence of vegetation. Examining Table 5.9, the Concentrated Recovery area shows that ~31% has a positive trend class while for the Entire Recovery area ~58% was classified with a positive trend. This is significantly larger in comparison to the Natural area ROI which only shows a ~4% positive trend but overall a ~3% decrease. This would suggest the tree planting has the greatest success where the lime has been applied.

Table 5.9 Overall Vegetation Trend (1988 - 2003)

Classification	Entire Recovery Area	Concentrated Recovery Area	Natural Area
Unclassified	60.08	37.99	88.74
Slope -0.125 to -0.1	0.00	0.00	0.00
Slope -0.1 to -0.075	0.00	0.00	0.00
Slope -0.075 to -0.05	0.03	0.01	0.03
Slope -0.05 to -0.025	0.56	0.35	0.26
Slope -0.025 to 0.0	8.02	2.91	6.90
Slope 0.0 to 0.025	27.82	50.74	3.31
Slope 0.025 to 0.05	3.43	7.95	0.41
Slope 0.05 to 0.075	0.04	0.04	0.17
Slope 0.075 to 0.1	0.02	0.00	0.04
Slope 0.1 to 0.125	0.01	0.01	0.10
Slope 0.125 to 0.15	0.00	0.00	0.04

Growth of Trees in the Barren Areas

A Decision Tree analysis (Figure 5-14) was conducted to further refine geographic areas within the Semi-Barren ROI that have experienced positive growth. For this analysis, all class images underwent post classification using a Majority filter of 3 x 3. Seasonal NDVI values where the ratio was greater than 1.5 were again assumed to represent areas of deciduous growth and were selected to continue in the decision process. The next decision examined the overall vegetation trend. Areas where the slope was positive and had an R^2 value 0.66 or greater were selected. The last conditional check used the Unsupervised Classification (USC) image to provide information on the land cover type. The USC image was post classified into six common generalized classes (water, shoreline community, wetlands, forest, barren/industrial, and fields). A majority filter was applied to minimize localized pixels. For the decision tree the Forest class was used to identify areas that represent tree growth in the Barren areas.

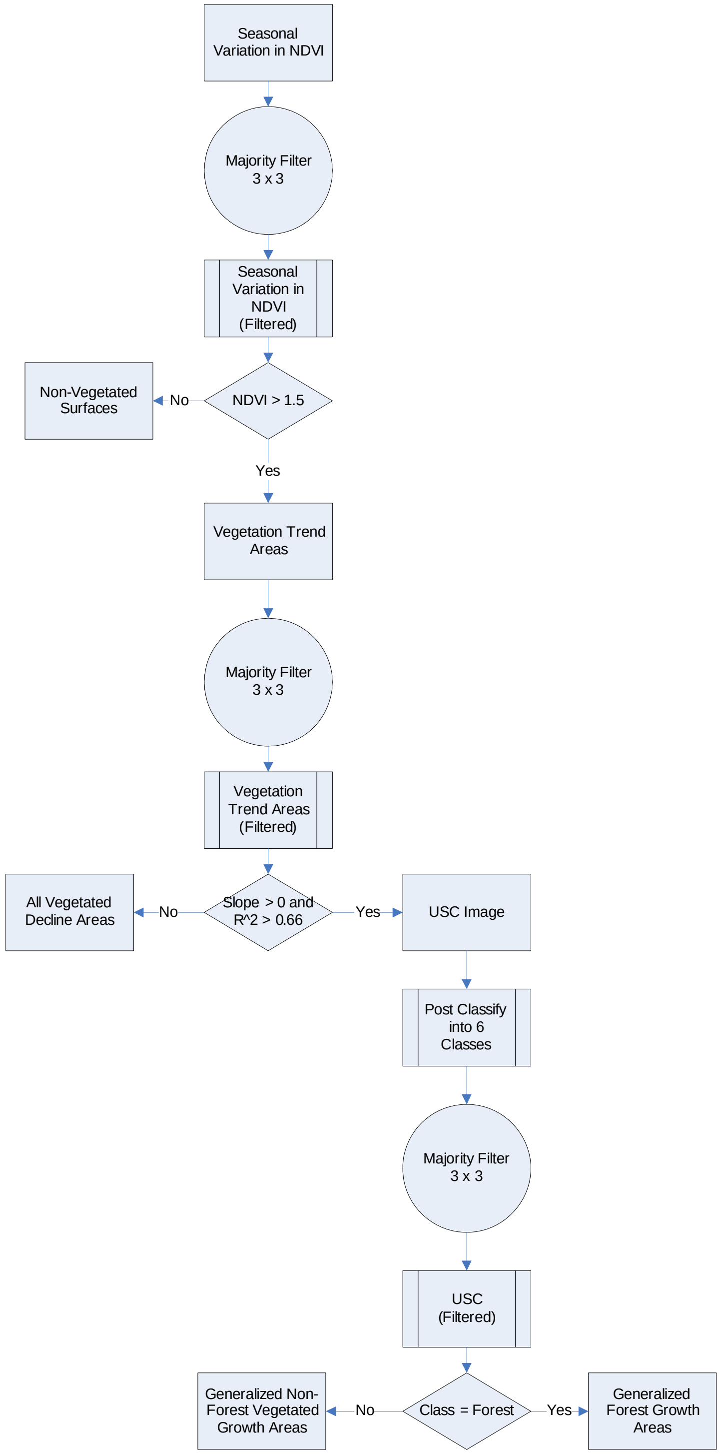


Figure 5-14 Decision Tree

The resulting classified image is shown in Figure 5-15. The dark green represents areas where the vegetation consists of forests with a positive growth trend. The cyan colour shows the Entire Recovery area and the brown vector lines represent the Concentrated Recovery area. The results of the image show that forest growth in the assisted recovery area is limited and there is no clear pattern to the growth without further examination of other factors. Details are further discussed in the summary section.

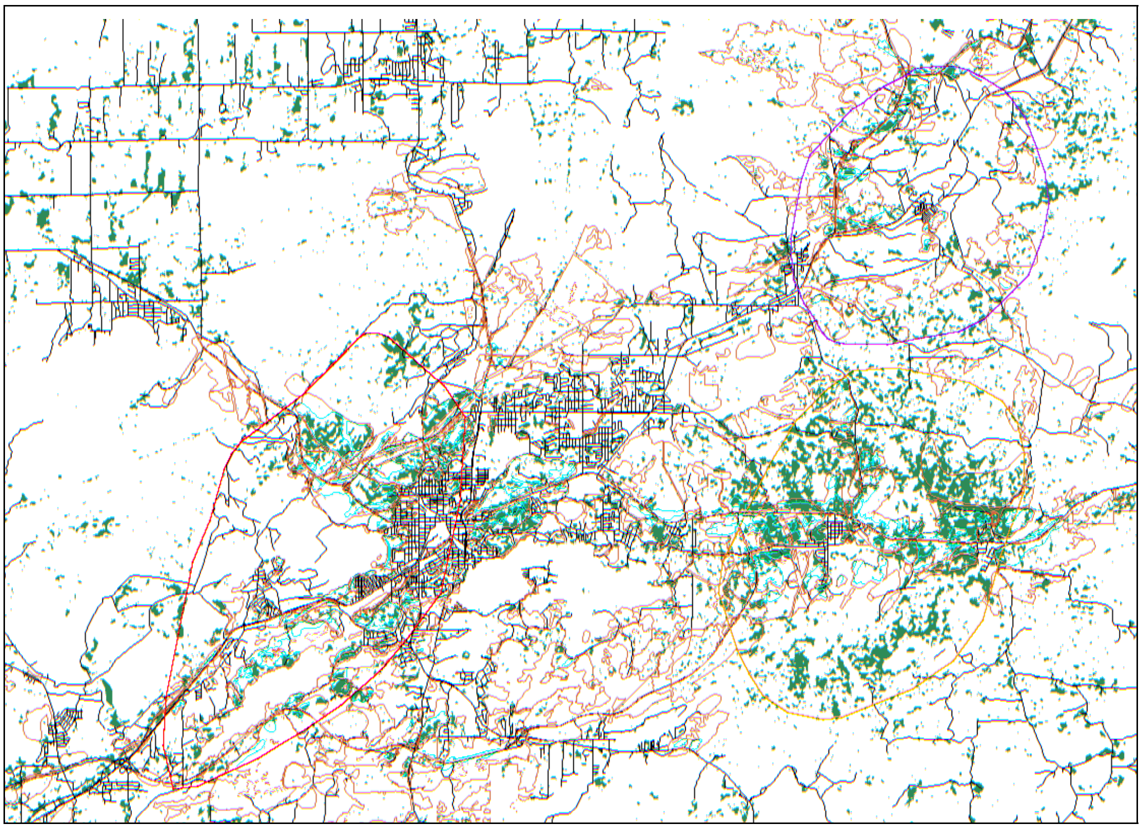


Figure 5-15 Growth of Trees in the Barren Area

5.5 Summary of Analysis

Multi-temporal remote sensing analysis of the Sudbury area has revealed a number of observations related to changes in vegetation cover. The analysis was conducted by using Regions of Interest (ROI) to compare different geographic areas and examining the spatial variability in vegetation change. The ROI were grouped by degree of historic impact on vegetation (the Barren and Semi-Barren areas) and by method of restoration (Assisted Recovery areas). A natural area was used to compare and provide a benchmark for vegetation change (the area outside the Semi-Barren region represents the Natural area). The Assisted Recovery area included two regions: Entire Recovery area and Concentrated Recovery area. The Entire Recovery area was defined as the areas where lime was applied, or where trees were planted, between 1978-2001. The Concentrated Recovery area was defined as the area that had been limed and tree-planted during the same time period. The objectives of the remote sensing analysis were as follows:

- To determine where the seasonal change in overall vegetation cover occurs in relationship to the Sudbury area and the ROI;
- To determine if the changes in conifer vegetation are visible from 1987 to 2003 within the ROI using spring images; and,
- To identify where the positive and negative trends occurred in vegetation cover over the 27-year period (1978-2003) and the 16-year period (1987-2003).

Spectral techniques in this project used indices, transformations, and statistical clustering to relate a radiometric property (*i.e.*, surface reflectance) with a biophysical property (*i.e*,. the presence of vegetation without ground truthing). Ancillary data such as orthophotographs, Forest Resource Inventory data, and ground-truthing descriptions were also examined as part of the analysis. The spatial resolution (*i.e.*, the ground area observed by one image pixel of the satellite) for the 1976 image was 60 m x 60 m and for the other five images was 30 m x 30 m. At this resolution, only generalized vegetation coverage can be referred to. Areas where vegetation change occurred over an area less than a pixel in size would have the spectral signature mixed in and diluted with all the other surfaces in the vicinity.

The remote sensing analysis found that the Barren areas underwent a significant change in seasonal variation in vegetation in 2003 as measured and interpreted from the ratio of NDVI values between spring and summer images. For the Entire Recovery area there was a 92% increase in vegetation cover and for the Concentrated area an 89% increase, as defined by NDVI greater than and/or equal to a ratio of 1.5. The Natural area only experienced a 57% increase in the ratio between spring and summer. This would suggest that most of the surfaces in the Barren area are dominated by vegetation species that seasonally change such as deciduous trees and shrubs. It also suggests that conifer species may not be a large component of the vegetation communities in the Barren areas, or that planted conifers are not yet large enough to be represented in this analysis.

Analysis of vegetation trends relating to conifer species was conducted using two spring images (1987 and 2003). This comparison was conducted using the areas delineated by ROI polygons for the Barren areas and Assisted Recovery areas. To quantify the vegetation change, a percentage difference of NDVI values between the 1987 and 2003 spring images was calculated. This approach was based on the fact that the NDVI response to the presence of vegetation in these images would mainly be driven by conifer species. However, it was believed that there may have been an early spring in the 1987 image, which might have had a slight influence in the percentage difference calculation, possibility underestimating the value. The results of this analysis suggest that coniferous vegetation in the Concentrated Recovery area affected almost double the area as the Entire Recovery area. The Concentrated Recovery area had 17% of the pixels in the polygons, with NDVI percentage differences greater than 25%. The Entire Recovery area showed that only 10% of the area had a NDVI class with a similar positive percentage difference change. This compares to the Natural area, which experienced an increase in NDVI class values over only 3% of the area. This would suggest that conifer trees are maintaining their presence and growing slowly and more progressively in limited selective areas, in particular where liming and tree planting has occurred together. However, this growth does not represent the dominant recovery of vegetation in the study area.

More selective vegetation analysis using a decision tree process revealed the location of areas that are likely forest cover and are experiencing a positive change in vegetation. In addition, it was observed that these areas did not significantly coincide with areas representing the tree planting regions (Entire Recovery area and Concentrated Recovery area). Visual interpretation of the image in Section 5.4.3 shows there are only a few locations within the Assisted Recovery ROI that have undergone sufficient growth between 1987 and 2003 to be classified as forest. It was also observed that areas of forest growth have no distinct pattern as related to the Assisted Recovery area. From the decision tree image, a number of observations were made as follows:

- Some growth of conifers was observed in areas where assisted recovery had taken place between 1987 and 2003;
- There has been a significant number of areas in the Assisted Recovery ROI where no tree growth has occurred; and,
- Tree growth recovery appears to be progressing at a slow pace possibly due to environmental and social factors.

The overall vegetation in the Sudbury area within the Semi-Barren area is recovering. The image in Section 5.4.3 distinctly reveals the spatial significance of the change, as it is concentrated within the Barren areas. The analysis of the vegetation trend used the slope and R^2 of the NDVI values between 1988-1998-2003 as a measure of the change in vegetation. The results show that a positive trend appears to be most significant for Coniston where 59% of the area had pixels with a positive trend; Copper Cliff had a positive trend with ~54% and Falconbridge ~46%. In comparison, the surrounding Natural area shows a negative trend with a decrease in about 3% of the pixels.

Qualitative PCA of the images support the vegetation trend observations. Decline or growth in vegetation will alter surface reflectance values and allow the comparison between images for two different temporal periods. PCA revealed changes in eigenvalues as displayed in colour composite images for summer 1988 and 2003. The change in variance in the image scenes is interpreted with respect to the presence of vegetation and how it alters the land cover reflectance. This is particularly noticeable around the Coniston area that has experienced the greatest regreening between 1988 and 2003.

To further evaluate this trend, Brightness and Greenness Indexes were applied using TCT (see section 5.4.3). These indexes also revealed positive vegetation changes within the Barren areas. TCT analysis provided a qualitative support for the NDVI trend analysis and PCA. Brightness and Greenness index values were generated for the summer images. A comparison analysis using ROI within the Barren area was used to relate changes in spectral reflectance properties to changes in land cover. In the case of Brightness Index, the index is related to surface brightness. Surfaces such as soils tend to have higher Brightness Index values than vegetated surfaces or urban areas such as buildings or roads. Similarly, the Greenness Index selects spectral bands in combinations that would correspond to vegetation. Analysis shows that from 1976-2003, the Brightness Index over the Barren areas had a decreasing slope. This would support other analyses showing an increase in vegetation over time within the Barren areas. The Greenness Index analysis was not as clear between 1976-2003, as the difference between 1976-1988 is a negative slope and 1988-2003 is a positive slope. The high Greenness Index value in the 1976 image may be related to sensor and calibration issues; 1976 Landsat data comes from a sensor with a different spectral and spatial resolution than the other images used. The positive slope of the 1988-2003 summer images suggests that the increase in Greenness Index may be attributed to an increase in the presence of vegetation within the Barren areas.

In summary, the remote sensing analysis has provided a synoptic and temporal view of the change in vegetation cover over the Sudbury area. The results of the analysis suggest that there is natural recovery taking place in the Barren areas as observed from the remote sensing data. This recovery varies spatially and may be the result of a combination of environmental factors and regreening activities. Analysis also suggests that areas where conifer tree planting has occurred show positive changes are taking place, but at a slow pace. Future analysis could further assess the trends, particularly associated with the tree planting, and provide on-going, long-term monitoring in the Assisted Recovery area.

5.6 References

Alberti, M., Weeks, R., and Coe, S. 2004. Urban Land-Cover Change Analysis in Central Puget Sound. Photogrammetric Engineering and Remote Sensing, Vol. 70, No. 9, pp. 343-352.

Ashutosh, S. 2002. Principal component-based algorithm on multispectral remote sensing data for spectral discrimination of tree cover from other vegetation type. Current Science Vol. 82 No 1.

Champagne, C. 2004. Personal Communication.

Crist, E.P., and Richard C.C. 1984. Application of the Tasseled Cap concept to simulated Thematic Mapper data. Photogrammetric Engineering and Remote Sensing, Vol. 50, No. 3, pp. 343-352.

Franklin, S. and Dickson, E. 2001. Approaches for Monitoring Landscape Composition and Pattern Using Remote Sensing.

Franklin, S.E. 2001. Remote Sensing for Sustainable Forest Management, Lewis Publishers.

Freedman, B., and Hutchinson, T.C. 1980. Long-term effects of smelter pollution at Sudbury, Ontario on forest community composition, Can J. Bot. Vol 58.

Gunn, J., Keller, W., Negusanti, J., Potvin, R., Beckett, P. and Winterhalder, K. 1995. Ecosystem recovery after emission reduction in Sudbury, Canada. Water, Air and Soil Pollution 85: 1783-1788.

Hutchinson, T.C., and Gunderman, D. 1998. The Contamination and Recovery of Natural Ecosystems by Smelting and Mining Activities at Sudbury, Ontario.

Lees, D. 2000. Green Rebirth. Canadian Geographic – Annual Environmental Issue Edition, pp. 61-70.

McCall, J., Gunn, J., and Struik, H. 1995. Photo interpretive study of recovery of damaged lands near the metal smelters of Sudbury, Canada. Water, Air and Soil Pollution 85: 847-852.

Monet, S. 2004. Coordinator of Environmental Initiatives, City of Greater Sudbury. Personal communication and data exchange.

Peterson, D., and Running, S. 1989. Application in Forest Science and Management. In Theory and Application of Optical Remote Sensing. A. Ghassem (Ed.) John Wiley & Sons.

Schott, J., Salvaggio, C., and Volchok, W. 1988. Radiometric scene normalization using pseudoinvariant features. Remote Sensing of Environment, 26:1-16.

Struik, H. 1973. Photo interpretive study to assess and evaluate the vegetation and physical state of the Sudbury area subject to industrial emissions. In Sudbury Environmental Enhancement Program Summary Report 1969-1973. Ontario. Department of Lands and Forests, Sudbury, Ontario. Pp. 6-11.

Ustin, S.L., Jacquemoud, S., and Govaerts, Y. 2001. Simulation of photon transport in a three-dimensional leaf: implications for photosynthesis, Plant, Cell and Environment, 24: 1095-1103.

Winterhalder, K. 2002. The effects of the mining and smeltering industry on Sudbury's landscape. In The Physical Environment of the City of Greater Sudbury. D. H. Rousell and K. J. Jansons (Eds). Ontario Geological Survey, Special Volume 6. 145-173.

Winterhalder, K. 1996. Environmental degradation and rehabilitation of the landscape around Sudbury, a major mining and smeltering area. Environ. Rev. 4: 185-224.