Forest Structure, Health and Regeneration Assessment Using Airborne Digital Camera Imagery

Douglas J. King
Dept. of Geography and Environmental Studies
Carleton University, 1125 Colonel By Drive,
Ottawa, Ontario
Canada
K1S 5B6
(613) 520-2600 (ext. 8439)
doug_king@carleton.ca
www.carleton.ca/~dking

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ABSTRACT

Integrated spectral and spatial analysis of high-resolution multispectral imagery provides a means to assess forest structural condition in a variety of applications. This paper describes a research program to develop methods for characterizing forest structural condition in assessment of damage due to anthropogenic and natural factors and in regeneration assessment. Three applications are presented: 1. development of a multivariate structural condition index representing windfall, and mortality due to acid mine contamination, 2. modelling forest canopy structural damage from a severe ice storm, and 3. automated measurement of conifer crop trees and competing vegetation in regeneration assessment. These applications integrate airborne digital camera image spectral information with spatial measures of texture, semivariance, image fractions, and spatial analysis of image fractions extracted from imagery of 0.25m – 1.0m pixels. Image spatial information is generally complementary to spectral information in derived models, improving their quality significantly over models using spectral information alone. Ice storm damage mapping at regional scales using Landsat data is also described. Regeneration assessment includes automated tree crown detection, delineation and measurement algorithms, as well as modelling of competition cover using digital camera imagery of 2.5cm – 10cm pixels. Initial tests in a research experiment where tree spacing and competition species were controlled resulted in tree detection omission errors of less than 6% and commission errors of less than 10%. Automated crown diameter measurements were within 17% of field-measured diameters taken at the base of the crown. When averaged over the study, this error dropped to 3%. Tests in an operational cutover under a range of competition levels are currently underway. Methods and results to-date of projects in each of these applications are presented.

Keywords and phrases: Forest Structure and Health; Regeneration; Airborne Digital Camera; Spectral and Spatial Analysis.

1.0 INTRODUCTION

Forest ecosystems worldwide are undergoing significant changes from natural and anthropogenic disturbances. Efforts are being made to develop methods for sustainable management of forests to reduce adverse impacts while maintaining adequate productivity for human use. Measurement and monitoring components of these efforts include the system of 'Criteria and Indicators' as stipulated in the Montreal Process (Canadian Council of Forest Ministers, 1995), many of these being suitable for measurement using geo-spatial data and analytical techniques (Goodenough *et al.*, 1998). Franklin (2001) summarizes them within a detailed treatment of the context and methods of remote sensing in sustainable forestry. Monitoring of forest structure and health in stressed environments is a significant aspect of sustainable management and of efforts to improve our knowledge of ecological processes. Robust methods are needed to quantify and map forest change resulting from various disturbance types such as long-term stress, sudden high impact stress, or forest management operations (King, 2000). This paper describes a research program that addresses each of these using spectral and spatial analysis of high-resolution remote sensing. Applications consist of contamination and wind damage adjacent to an abandoned mine, structural damage following a severe ice storm, and forest regeneration assessment.

2.0 MULTIVARIATE MODELLING OF FOREST HEALTH AT AN ABANDONED MINE SITE

Much effort has been made to develop methods for measurement of individual forest structure parameters using remote sensing. In forest management, tree size (height and diameter) and stem density are of primary importance for growth and wood volume information needs. In ecology and climate modelling, leaf area index (LAI), per cent cover and other measures of biomass quantity are used. However, forest structure is an integrated composite of individual tree structure, quantity, and arrangement in the landscape in both the horizontal and vertical dimensions. This study attempts to develop an integrated measure of forest structure as an index comprising several variables that can be measured and monitored using remote sensing. Representation of forest structure as a multivariate composite of various parameters has been presented by Everham (1996) and Ferretti (1997). Both of these studies assessed forest structure in the context of structural health, the former in relation to wind damage, and the latter as an indicator of forest vigour. Extending this concept of a composite structure index to measurement using remote sensing has been attempted, but generally with spectral information only. For example, Franklin (2001) summarises studies relating vegetation indices and the TM wetness index to a few structural indices. Jakubauskas (1996) found that more than half the variance of a coniferous forest canonical variate representing LAI, basal area and stem density could be explained by Landsat TM spectral information. Integration of image spatial information into such modelling has been less frequent. An example is Yuan *et al.* (1991) who defined a tree decline index based on visual photographic interpretation of spectral damage symptoms (e.g., chlorosis, visible dead branches) and crown texture (rougher textures representing more open crowns) and then modelled this index using airborne video spectral and textural information.

2.1 Study Site

This study is part of a long-term research project initiated in 1992 to assess and monitor forest damage at an abandoned (in 1974) copper-zinc mine near Timmins, Ontario in the Canadian boreal forest. Surrounding the mine are three tailings areas covering about 350 ha. The study area is a forest approximately 1.4 km by 800 m downstream and often downwind from one of the tailings (Figure 1). An overstory canopy of mature trembling aspen (*Populus tremuloides*) dominates most of the drier areas, while white birch (*Betula papyrifera*) and black spruce (*Picea mariana*) cover the wetter areas. An understory of balsam fir (*Abies balsamifera*) is also present in some of the more mature areas. Visible signs of forest damage are mostly structural and include: 1. uprooted and snapped trees, resulting from strong winds that develop over the open tailings, 2. dead branches and standing dead trees, 3. undersized crowns, and 4. high crown and canopy openness. Crown thinning is particularly obvious near the tailings, possibly due to contaminant loading by wind (visible tailings dust on trees) and/or drainage.

2.2 Data Acquisition

In various studies at the site, plots of 20 m x 20 m or 50 m x 50 m were installed and forest structure and composition for trees of 2 m height or greater were inventoried. Forest measurements were typically of diameter at breast height (DBH), stem density, tree height, crown diameter, canopy cover, leaf area index (LAI) using a Licor LAI-2000 (Welles and Norman, 1991) and a visual health score from 1 (healthy) to 4 (dead). In some studies DBH and stem density were also measured for standing dead and fallen trees. Forest structure gradients towards a more closed canopy further from the tailings were found (Cosmopoulos and King, 2002 submitted) that followed gradients of soil metal content (Lévesque and King, 1999). Temporal analysis of forest structure between 1997 and 1999 showed that the site is very dynamic. Blown down stem density and basal area, and standing basal area increased significantly ($p \leq 0.05$) as did leaf area index (LAI), canopy cover, and live stem density due to proliferation of ground vegetation in areas of increasingly open overstory. Mortality by contamination or natural causes was not as significant as blow down but is present as a more subtle cause of structural change. Forest change was also much greater closer to the tailings. For example, within 210 m of the tailings blow down basal area, canopy closure and live stem density increased by 33.7%, 20.2% and 21.8%, respectively. In interior plots further from the tailings edge, they increased by only 21.8%, 7.3% and 4.5%, respectively.

Imagery has been acquired primarily with a custom-built multispectral digital sensor (King, 1995) that incorporates a Kodak Megaplus 1.4 black-and-white, 1300x1000 pixel format camera with a rotating filter wheel in front of a 28 mm focal length lens. The total view angle was 18.2 x 14.3 degrees. Data were acquired at 8-bit quantization in up to eight user-selectable spectral bands of $\geq$ 10 nm bandwidth within the range of 450 nm to 900 nm. Imagery of the study area was acquired with 25 cm, 50 cm and 80 cm pixel sizes in August of 1993, 1995, 1997, and 1999. Additionally, archived Ontario Ministry of Natural Resources 1:15,840 black and white aerial photographs scanned to 0.4 m pixel spacing, and Kodak DCS 420 colour infrared (CIR) digital camera imagery of 25 cm pixel spacing have been used some studies.

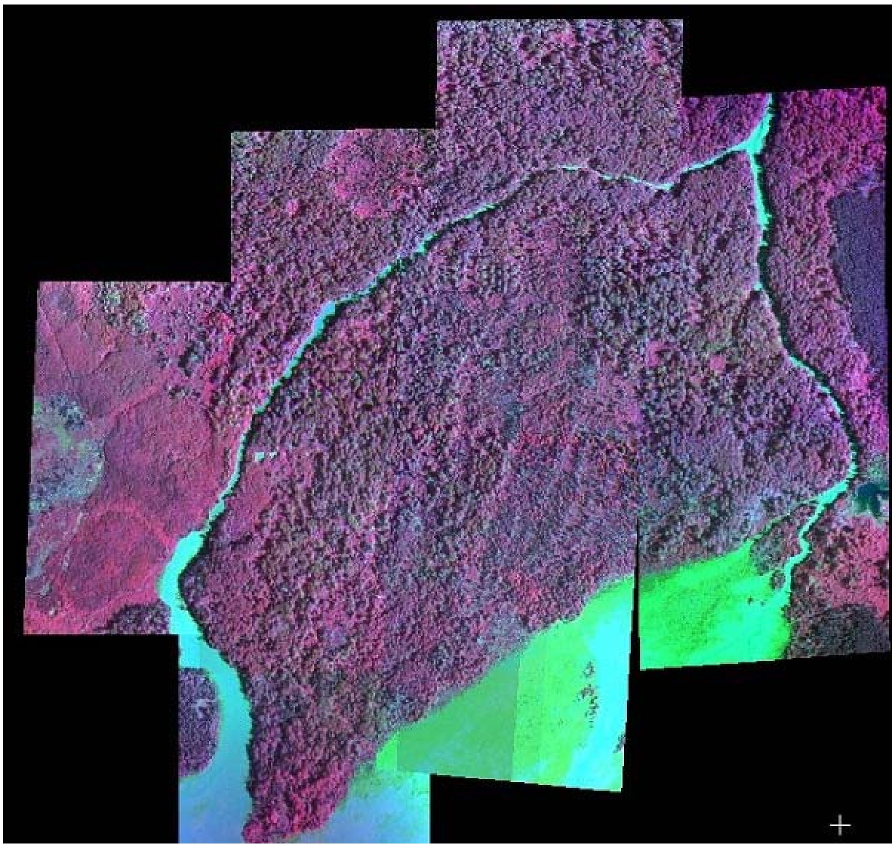

Figure 1. CIR mosaic of the study area in the forest (delineated by the creeks) adjacent to the abandoned mine tailings (at bottom of image). Images were generated with the author's 8-band digital camera sensor using spectral bands: green (545-555 nm), red (665-675 nm), and near infrared (895-905 nm). Pixel size is 50cm.

2.3 Studies Conducted To-date

In previous studies at the site, Walsworth and King (1999) analysed archived aerial photography of four dates from 1961 to 1991 to determine temporal trends in growth and mortality. An automated tree detection and delineation program was used to inventory tree growth and disappearance in each of the three decades of this period. A spatially explicit individual tree based transition model showed that the area within about 200m of the tailings edge exhibited a trend towards continued growth of pioneer, light intolerant species such as aspen, while further from the tailings, succession was towards a more closed canopy which conifers were beginning to infill. Incorporation of neighbourhood species information produced a probability function relating the chance of either conifer or aspen growth into a gap to the number of neighbours of like species. Seed and King (1997) found that LAI in the mixed forest on the western side of the study area could be well predicted using spectral shadow fractions, including deep shadow and transitional shadow on crown edges in 25 cm imagery. However, in a subsequent view angle analysis of these data, Seed and King (2002, submitted), found that significant relations were only achieved in the backscattering and nadir view areas, and not in the forward scattering area. In addition, the shadow fraction was not sensitive to LAI at canopy cover less than about 70% (more open canopy). Instead, shadow brightness was found to be a more robust estimator of LAI ($r^2 > 0.55$) in each scattering direction and across the full cover range of the study (26-95%). Shadow brightness is a better expression of the degree of LAI contribution by understory, which is captured in addition to overstory using optical field based instrumentation such as the LAI-2000. Olthof and King (1997) used the same imagery to show that texture, texture variation and spectral data are complementary in modelling LAI. Lévesque and King (1999) found that semivariogram range in near infrared digital camera imagery (of the author's sensor) was highly correlated with individual crown closure using 25 cm pixels, with crown size using 50 cm pixels, and with forest canopy closure using 1 m pixels. Lévesque and King (2002, submitted) analysed the contributions of raw image semivariogram range and sill, co-occurrence texture, and image fractions of sunlit crown, shadow and exposed wood as well as texture and semivariance analysis of these fractions in stepwise regression models of individual forest parameters and the health score. Spatial transformations (texture, semivariogram range) of either image brightness or image fractions were consistently the most significant and first entered variables in the best models of the forest parameters. Using image samples extracted over the whole canopy (trees and shadows), semivariogram range represented 56% of the variables used in all models and accounted for a large proportion of the models' variance. Texture variables were the most entered when using image samples taken only from tree crowns, but were almost absent from models using image samples taken over the whole canopy (including crown edges and gaps). In particular, texture of the wood fraction was shown to be able to distinguish a condition of poor health, with exposed branches dispersed throughout the canopy, from a condition of better health with only a single dead tree. Each plot had the same wood fraction but its spatial distribution

3.0 MODELLING ICE STORM DAMAGE IN TEMPERATE HARDWOOD FORESTS

Up to 100 mm of freezing rain fell between January 4th and 9th, 1998 in eastern Canada and the north-eastern United States. The area of ice accumulation was approximately 10 million hectares, although forest damage was highly variable and patchy. A storm of such magnitude and spatial extent is estimated to have a return period of at least 500 years (Smith, 1998). In some small areas, all tree trunks had been snapped, while in others, trees were bent in an arc with their crowns frozen at ground level. Due to the magnitude of damage, both ecologically and economically, questions arose whether ice storm damage could be spatially assessed more quickly, objectively and cost-effectively using remote sensing.

3.1 Study 1: Natural Forest Response to the Ice Storm

3.1.1 Study site and objectives

Forests that are not managed for extractive purposes present an opportunity to study and monitor short and long term impacts of a disturbance such as the 1998 ice storm. The study site is the Gatineau Park, a temperate hardwood forest of about 10 km by 50 km northwest of Ottawa. The dominant overstory species in the park is sugar maple (*Acer saccharum* Marsh.), but small patches dominated by American beech (*Fagus grandifolia* Ehrh.), trembling aspen (*Populus tremuloides* Michx.), and red oak (*Quercus rubra* L.) occur. The Gatineau Park was on the northern edge of the ice storm affected area, receiving up to 60 mm of freezing rain. Damage was patchy ranging from non-existent to severe (large gaps left by multiple fallen trees and broken branches) in local areas. As such, it serves as a good site for remote sensing modelling because a wide range of damage is present and undamaged areas provide control measurements of pre-ice storm conditions. Seventy plots of 20 m x 20 m were installed along two north-south transects in areas of damage that ranged from none to severe. Suitable plot size was determined by a semivariance analysis of DBH, crown diameter and tree height using field and remote sensing data of two Quebec Ministry of Natural Resources (QMNR) permanent sample plots where tree position had been mapped (Butson and King, 1999). The objectives to-date have been to: 1. measure and monitor forest damage and structural change over the next 10-20 years, and 2. develop high resolution remote sensing methods for modelling and mapping of damage and structural change.

3.1.2 Data acquisition

Field data included inventory of species, DBH, and the health score for dominant (>1/2 the crown visible to the sensor) and intermediate trees (greater than 1.5 cm DBH). Height, crown diameter, the number of broken stems, and the number of 1st and 2nd order branch wounds were also recorded for dominant trees. Total amount of downed woody debris was measured by counting occurrences using line intercept methods and by calculating total cross-sectional branch area at the intercepts. LAI was measured using hemispherical photography (producing 'effective' LAI, or LAI_e, which assumes random foliage distribution) and the TRAC optical instrument (Chen, 1996). High-resolution imaging was conducted primarily with the Kodak DCS460 CIR digital camera at 57 cm pixel spacing. It produces 3060 x 2036 12-bit format imagery in three spectral bands: 500-600 nm, 570-780 nm, 710-800 nm). CIR 70 mm aerial photography was also acquired and scanned to 4,000 x 4,000 pixels of 25 cm spacing. Figure 2 shows a portion of one of the digital camera images and plot locations on one of the transects. Models of forest structure and health were developed using multiple airborne image variables (Pellikka *et al.*, 2000a). Corrections for image brightness variations due to BRDF (Pellikka *et al.*, 2000b) and camera optical effects formed parts of this study.

3.1.3 Results to-date

Significant stepwise regression models of these forest variables generally included spectral brightness, most often with the NIR band being the primary variable, followed by red band brightness and/or a texture or shadow fraction measure. Downed branch count produced the best model ($R^2_{adj} = 0.71$) followed by the health score ($R^2_{adj} = 0.51$), LAI_e, closure, and basal area (R^2_{adj} = 0.46, 0.50, 0.30, respectively) each with significance, $p \leq 0.01$. Details are given in Pellikka *et al.* (2000a) and King *et al.* (2002, submitted). Significant models were not produced for broken stem and branch wound counts, nor for downed wood area. Currently, research is being conducted to validate LAI measurements using leaf traps and to study vertical forest structure using hemispheric photography acquired at several heights up to 12 m in the canopy. These will be related to the shadow brightness and fraction, which have been shown to be good predictors of LAI_e (Olthof and King, 2000; Seed and King (2002, submitted) in boreal forest. They will also aid in determining contributions of understory to the image signal, whether understory LAI can be predicted from overstory condition, and whether the vertical distribution of LAI can be predicted.

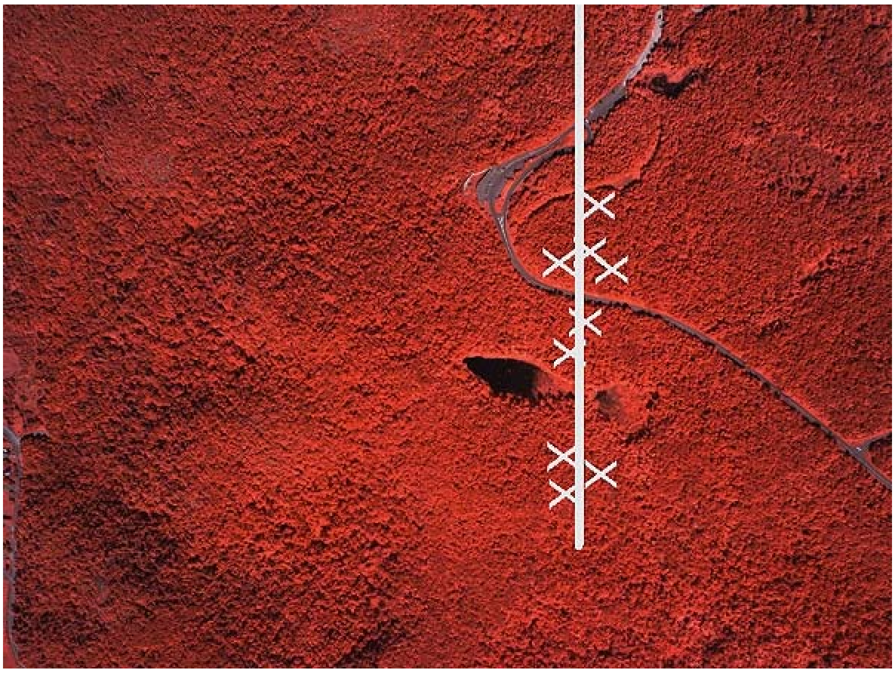

Figure 2. CIR composite image showing some of the plots in a study of temperate hardwood forest damage assessment following a severe ice storm. The image was acquired with a Kodak DCS CIR 460 digital camera. Pixel size is 57 cm.

3.2 Study 2: Managed Forest Response to the Ice Storm

3.2.1 Study site and objectives

The ice storm had significant impact on maple syrup producers as production declined markedly in 1998 (Kidon *et al.* 2001), prompting the Ontario Ministry of Natural Resources (OMNR) to initiate a study of treatment effects on maple health and production (Lautenschlager and Nielsen, 1999). Thirty-eight study blocks were installed in sugar maple forests of varying management and damage conditions in eastern Ontario. The blocks were 100 m x 100 m, consisting of four plots each of 50 m x 50 m. In 35 blocks, each plot had been treated with fertilizer, lime, fertilizer and lime, or nothing (control). In the remaining three blocks, herbicide was applied in three of the plots. The objectives of the remote sensing research component described here were to measure LAI in successive years following the storm and develop models relating LAI and damage estimates to image spectral and spatial information.

3.2.2 Data acquisition

Field data consisted 1999 OMNR visual estimates of per cent crown loss for 6 focus trees per plot and LAI measured in three 50 m transects in each plot with the TRAC in 1999, 2000 and 2001. Kodak DCS460 CIR imagery was acquired in 1999 with 57 cm pixel spacing.

3.2.3 Results to-date

LAI was found to increase significantly (in relation to instrument precision) in many plots between 1999 and 2000 (Olthof *et al.*, 2001) and was analysed for both understory and overstory contributions to this increase through 2001 as well as treatment effects on LAI change (Olthof *et al.*, 2002, submitted). LAI change from 1999 to 2001 was well related to damage sustained ($r^2 = 0.52$, $p < 0.01$), indicating that LAI is a useful variable for monitoring of forest change following such a disturbance. No significant effects of treatments on LAI were found. Modelling using the airborne imagery found that increased crown loss was related to increased shadow fraction, the ratio of red to NIR crown brightness, and decreased canopy NDVI ($R^2_{adj} = 0.42$, $p < 0.01$). Greater LAI was related to decreases in the area-to-perimeter ratio of shadows (shadows less compact in shape) and the green band brightness of tree crowns ($R^2_{adj} = 0.19$, $p < 0.01$), although this relationship did not account for enough variance to be considered as a predictive model. Similarly, canopy gap fraction and plot basal area were modelled significantly but with low amounts of variance accounted for ($R^2_{adj} = 0.22$ and 0.31, respectively; $p < 0.01$ for both). Current research is attempting to improve these relations by applying a correction for brightness non-uniformity to the imagery to reduce BRDF and optical effects. Additional imagery will be acquired to determine if temporal changes in LAI can be detected and if there are any longer term treatment effects that were not evident over the three-year period of the study thus far.

In addition to local modelling, regional modelling of damage using Landsat and other environmental data is being conducted for the purpose of production of large area damage maps that can replace current aerial sketch mapping. Distance to edge (-), in combination with elevation (+) and post storm Landsat Band 7 (+), post storm Band 3 (+), and pre storm Band 1 (-) produced a model predicting damage with $R^2_{adj} = 0.411$, $S_e = 14.9\%$ and $p \leq 0.01$. Damage is greater closer to forest edges and at higher elevations, although the elevation variation across the region was only about 100 m. Landsat Band 7 reflectance (mid infrared) responds mostly to variations in moisture content. It typically increases as moisture decreases, thus the positive relation here shows lower biomass and/or water stress. Band 3 (red) responds to chlorophyll absorption and increases with reduced chlorophyll content. The positive relation with damage in this model confirms this. Band 1 (blue) normally also responds to pigments in foliage and is lower for healthier vegetation. In this model, though, the negative sign indicating increasing blue reflectance with increasing damage is difficult to explain. Currently, non-parametric methods are being tested to allow integration of more variables into the modelling procedure (e.g., slope aspect, other forest resources inventory information such as site quality (an ordinal productivity index), landscape fragmentation indices, etc.).

4.0 FOREST REGENERATION ASSESSMENT

Successful regeneration of coniferous species is critical to forest sustainability in boreal regions. Conifers are the dominant species in this biome, but can be difficult to re-establish after disturbance due to slow growth and sensitivity to competing vegetation. Timely information regarding their stocking levels, health, and competing species abundance is required for effective treatment decisions. Current field survey methods are labour intensive and costly, resulting in low sample coverage and frequency. As a consequence, undesirable forest structures can develop between sampling periods that are difficult to restore to desired conditions. Remote sensing has potential to provide, at lower cost, forest information with greater coverage than is attainable using field sampling. Early work in the development of remote sensing methods for regeneration assessment focused on manual analysis of large-scale photography (LSP). Results have shown that reliable estimates of stocking, species, crown area, health condition, and stratification of key vegetation complexes can be made (e.g., Goba *et al.*, 1982; Hall, 1984; Pitt *et al.*, 2000). However, operational practice of these methods has not been widely undertaken because LSP acquisition and analysis are either highly specialized, time consuming, or subjective, requiring specially trained personnel and equipment (King, 2000). Thus, methods to automate and simplify acquisition and analysis are required for an effective remote sensing based assessment methodology. Two studies have been initiated thus far: 1. empirical modelling of competition cover and classification of conifer crop trees, and 2. automated tree detection and delineation for crown measurement.

4.1 Study Sites and Objectives

The initial study site consisted of an experimental arboretum located outside of Sault Ste. Marie, Ontario, established in 1994 as part of research to identify the effects of various levels of vegetative competition on black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.) Conifers trees were planted at 1 m spacing in 7 x 7 m plots of a given level of competition quantified by the number of competition plants per crop tree. Separate blocks were established with only one competition species in each. The objectives of the first study were to determine if jack pine and black spruce could be classified in low cost CIR digital camera imagery and if cover and LAI of competition could be effectively modelled. In the second study, a tree detection-delineation algorithm was developed and evaluated. It is currently being applied to imagery of a new site that is a re-planted operational cutover with varying amounts of mixed competition. The objective is to develop methods for estimating tree spatial pattern, abundance, crown size, and canopy structure as lower cost and more objective alternatives to field-based or aerial assessment.

4.2 Data Acquisition

Field data at the arboretum that were used in these studies consisted of OMNR measurements of competition cover (visually in 10 per cent intervals), LAI using leaf interception counts and a pin pushed vertically through the canopy, base of crown diameter measured in the N-S and E-W directions, and conifer biomass. Airborne imagery was acquired for the first study in August 1996 using Kodak DCS420 CIR camera and 2.5 cm pixel spacing, and in April 2000 using the Kodak DCS460 CIR camera with 5 cm pixels for the second study. At the operational cutover, a Duncantech Inc. MSC-3100 3-chip CIR camera was used in May 2002 with 6 cm pixels. It produces completely separate spectral bands, unlike the DCS bands, which overlap significantly, reducing the amount of useful spectral information.

4.3 Results To-date

Haddow *et al.* (2000), using 2.5 cm pixel Kodak DCS420 CIR imagery, were able to automatically classify and count conifers at age 2 years in the arboretum site where there was little or no competition (similar to a leaf-off condition) with over 90 % accuracy. It was not possible, however, to spectrally distinguish jack pine from black spruce (Transformed divergence approximately = 1.2). Initial inspection of the most recent Duncantech imagery, with better spectral information, shows the two species to be visually quite distinct, so classification will be re-investigated. Modelling of competition cover and LAI was accomplished with standard errors of 10-20 % using spectral and spatial measures from the DCS imagery.

The tree detection-delineation algorithm (Pouliot *et al.*, 2002) is based on analysis of local transects extending outward from a potential tree apex (identified using a high pass filter). The crown boundary is estimated using the point of maximum rate of change on the transects and a rule base is applied to ensure that the point is contextually suitable. This transect approach is implemented in both the tree detection and crown delineation phases. The tree detection algorithm refines the results of an initial local maximum filter by providing an outline for each detected tree and retaining only one local maximum value within this outline. The crown delineation algorithm is similar to the detection algorithm, but applies a different rule set in creating a more detailed crown outline. Detection accuracy was 89% and higher than all standard local maximum filters of varying window size that were tested (their accuracies typically ranged between 40 and 80%). Both commission errors (3-10% for 5-15 cm pixels) and omission errors (1-6% for 5-15cm pixels) were lower than all local maximum filters tested (1-55% error for the same pixel sizes). Errors of omission and commission were also more balanced, not varying as widely as the fixed window results. Thus, the algorithm provides accurate detection results and removes the difficulty of selecting the most appropriate sample window size for a local maximum filtering operation.

Diameters determined from automated crown delineation had RMS errors of 14.5-17.9% depending on input parameters. Manual delineation RMS error was 11.2%. Decreasing image resolution increased delineation error non-linearly. The difference between the 5 cm and 10 cm pixel crown delineations was not significant (Bonferroni multiple comparison test, p = 1.00), while increasing the pixel spacing to 15 cm resulted in greater overestimation of the crown diameters. At 30 cm pixels, delineation error became extreme. In this study, the optimum average crown size to pixel ratio was found to be 15:1. Ratios below 15:1 (fewer pixels per crown) did not improve results as the within crown variability remained stable, but the crown boundary distinctiveness was reduced, leading to greater error. Ratios larger than 15:1 (more pixels per crown) were heavily influenced by within crown variation, also resulting in substantial error. Aggregating the individual tree results to average error for all trees in the study reduced error to 2.4% as over-estimates and under-estimates balanced each other in the averaging process. In addition, the average error of each of these automated delineations was less than that of the manual delineation. Examination of the individual errors revealed that the automated methods overestimated small and underestimated large crown diameters. Overestimation of the small crown diameters, similar to detection results, was due to the presence of short ground vegetation in close proximity to the crown boundary. In the case of large trees, errors were due to overlapping crowns, causing crown boundaries to be less distinct than the within crown spectral variance.

An important advantage of tree delineation is the potential to model tree structural variables such as tree height, stem diameter and biomass. In this study, preliminary results of delineated crown diameters showed strong relations with tree height (r = 0.86), stem diameter (r = 0.78), and biomass (r = 0.97). As stated above, the method is currently being adapted and evaluated in an operational cutover using only leaf-off imagery to assess both conifers and competition (through texture and shadow analysis). Figure 3 shows an example of this imagery acquired in May, 2002.

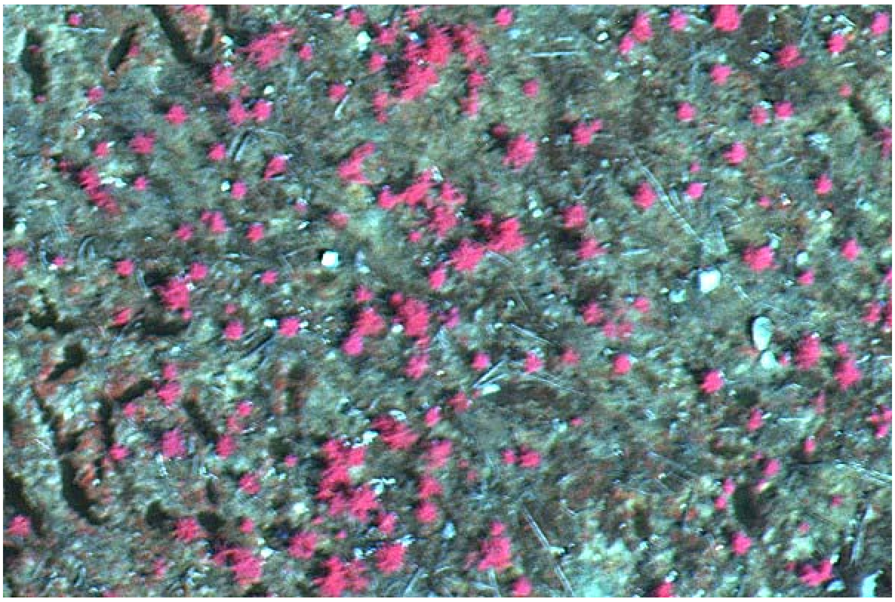

Figure 3. CIR composite image of regenerating forest in an operational cutover. The image was acquired with a Duncantech MCS3100 CIR digital camera. Pixel size is 6 cm.

5.0 SUMMARY

This paper has summarized a research program in high-resolution remote sensing of forest structure and health in disturbed environments. Details on individual projects are given in the cited references. Empirical modelling and classification of forest species groups, structure attributes, and visual tree damage measures as well as object (tree) detection and delineation can be achieved with good to high accuracy using integrated analysis of spectral and spatial image characteristics. Multivariate representation of forest structure using sets of forest variables modelled by multiple image variables serves as a useful means for summarizing and monitoring forest condition in stressed environments.

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