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Extracting Forest Inventory Variables from Landsat Thematic Mapper (TM) Data in the Fort Simpson Region, NWT

by

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Abstract

In this thesis the use of Landsat Thematic Mapper (Landsat TM) satellite imagery in estimation of forest inventory data is analyzed for a study area near Fort Simpson, NWT. Field data were collected from 106 plots to develop empirical models that determine the relationships between stand variables and Landsat TM reflectance, vegetation indices or Tasseled Cap transformations. The general relationship of increasing height, age, crown closure and volume with decreasing reflectance was observed from results generated in this study. These relationships were in part, attributed to the proportion of shadow and reflectance from tree crowns and canopy understory that are observed by the satellite, where overall stand reflectance is decreased due to the influence of shadows cast. Models developed to predict stand variables from remote sensing data were generally stronger for primary successional species, including jack pine and trembling aspen, because the changes in their structure and composition were consistent at each successional stage, over the range of stands sampled. Models were weaker for white spruce, a secondary successional species, and mixed-wood stands since there was greater variability in the structure of these stands due to the different successional pathways they have followed.

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Table of Contents

List of Tables

List of Figures

1.0 Introduction

This chapter provides an introduction to this thesis on determining the extent that forest stand variables could be estimated from Landsat TM data. Included in this chapter is an introduction to the research background that led to the formation of this study; a summary of the thesis organization; a discussion of the information needs presented by Northwest Territories forest managers; and a statement of the research objective and sub-objectives.

1.1 Research Background

In summer 1998 the Government of the Northwest Territories (GNWT) Department of Resources, Wildlife and Economic Development (RWED) presented the opportunity for research into remote sensing and forest inventory (Collaborative Research Agreement (May 11, 1998)). A team of research scientists from the University of Calgary and the Canadian Forest Service (CFS) worked with the Forest Management Division in the Deh Cho Region to acquire information about relevant forestry issues. An information report was prepared that described potential linkages between satellite remote sensing and operational forest inventory data that could be applicable in the Northwest Territories (NWT).

The report entitled "*Remote Sensing and its Application to Forest Management in the Liard Valley, NWT*" (Gerylo *et al.* 1998b) was completed and submitted to RWED in November 1998. The report provided the necessary deliverables from Phase 1 of the GNWT-RWED/CFS Collaborative Research Agreement (CRA). Included in the Phase 1 deliverables were research ideas that were used to formulate Phase 2, "developing a methodology to build a linkage between remote sensing and operational forest inventory techniques". The proposed research involved methodological development, field survey and remote sensing analysis to determine techniques for extracting forestry information from satellite remote sensing data. The approach suggested was to develop empirical relationships between Landsat TM spectral reflectance and forest stand variables of interest for application into NWT forest inventory data collection.

This thesis provides:

- A brief literature review of remote sensing and forest research activities that are applicable to the estimation of forest stand inventory data from satellite remote sensing reflectance data;
- A detailed description of the methodology employed during this research, including an outline of field data collection and processing techniques employed, remote sensing data processing, and discussion of statistical methods applied in model development and validation;
- A summary of the research results;
- Study conclusions and recommendations for future work into forestry remote sensing research in the NWT.

1.2 Thesis Organization

This thesis is organized into 7 chapters. The background for this study, including a description of the GNWT-RWED information needs, is presented in the subsections of this introduction. A literature review of remote sensing and forestry research activities, applicable to estimating forest stand inventory data from remote sensing data, is provided in chapter 2. Chapter 3 describes the study area while chapter 4 outlines the major field data collection and image processing methods applied in this study. Chapter 5 provides a summary of the field data collected and results of the statistical data analysis for modeling stand variables from remote sensing. Chapter 6 provides a discussion of the study results and recommendation for an operational linkage of the derived models. This thesis concludes in chapter 7, with a summary of research conclusions, recommendations for integration into NWT operational forestry practices and additional recommendations for future work.

1.3 Introduction to the Study

Sustainable development and management of the Canadian North's natural resources are among the primary responsibilities of the Department of Renewable Resources, Wildlife and Economic Development (RWED), Government of the Northwest Territories (GNWT) (Forest Development Services 1998b). To manage the forest landscape and ensure that management practices are sustainable, RWED requires detailed forestry information about the location, structure, composition and spatial distribution of forests that span large, remote, regions of the NWT (Personal communication with Steve Gooderham, Regional Forest Manager; Bob Bailey, Director; and Lisa Gallagher, Inventory Forester, RWED, GNWT, July 1998.). A multi-faceted array of information is required by resources managers on each forest stand to make decisions about a range of forest related issues, including determination of the annual allowable cut (AAC) and designation of preferred harvesting regions. In other jurisdictions in Canada and throughout the world this multi-faceted array of information is contained in a digital forest inventory database.

The digital forest inventory database, containing much of the information required by RWED forest managers to contribute to sustainable development and management of natural resources in the Canadian north, includes data on forest stand species composition, crown closure, age, height and volume. Information on the spatial extent and location of various hardwood, softwood and mixed-wood species stands is required to delineate forested land from protected areas, treed bogs and other non-commercial forest types. Crown closure information is needed, as crown closure measurements are good indicators of stand stocking and stand age. Forest managers can determine successional stages and productivity levels of individual forest stands with stand age and height information, while volume information is required for determination of the annual allowable cut (AAC) and for forecasting future growth and yield. A combination of all of this information is used to help determine the amount of potentially merchantable timber that is available within designated harvested regions.

The above-mentioned information may be collected through a forest inventory or volume cruise, however, the amount of land surveyed in the NWT is limited (Figure 1.1), and much of the productive timber is concentrated along the Mackenzie, Slave and Liard river valleys. Inventory and volume information is absent for many regions due to accessibility and the high costs associated with timber cruising. For this reason few forest inventory maps have been produced from detailed air photo interpretation and field site visits, as sampling procedures to acquire this information are logistically difficult and economically impractical.

In regions where forest inventory information is absent, resource managers experience difficulties making decisions that would best contribute to sustainable management of the forested landscape. Therefore, GNWT-RWED has identified the need to develop alternative methods for extracting forest inventory information in the NWT, which would provide forest variable characterizations at relatively low financial costs. Integrating satellite remote sensing with NWT inventory surveys is one approach that could help managers meet these information demands.

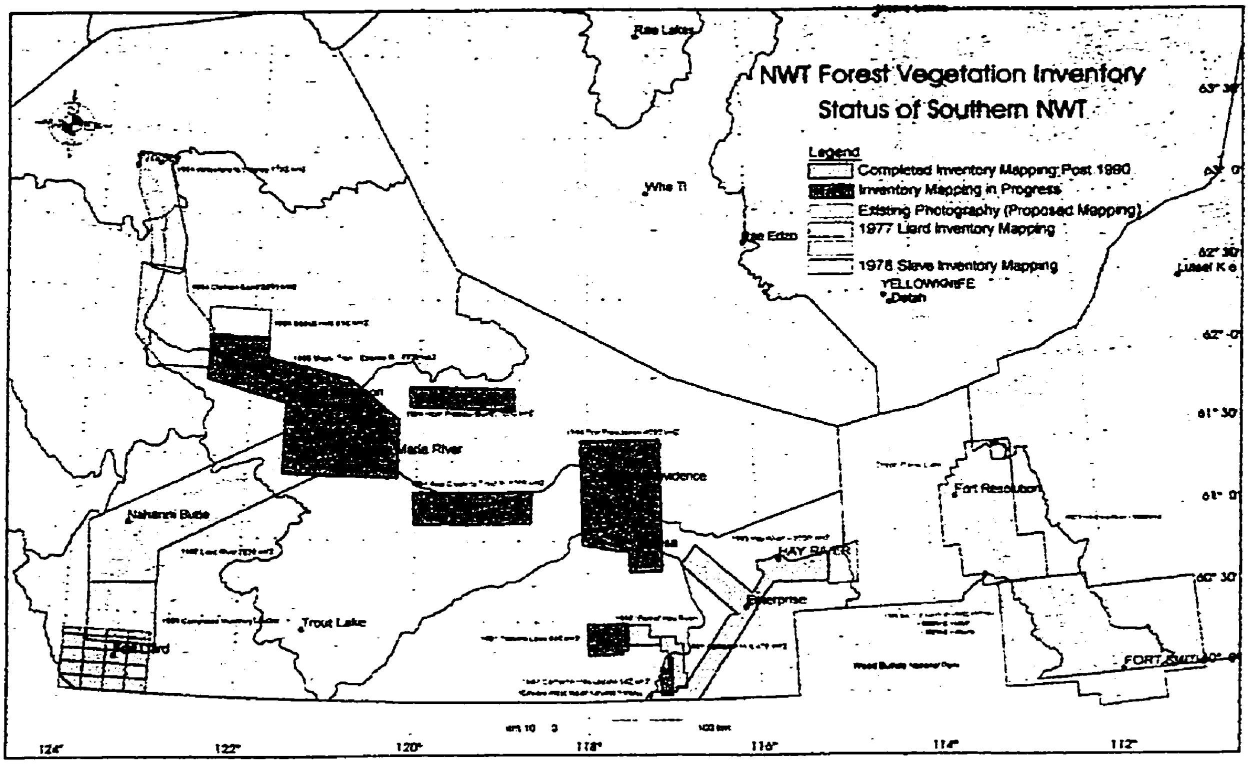

Figure 1.1 Spatial coverage of forest inventory data in the NWT.

Presently, RWED is undertaking a territory-wide cover type mapping project, whereby land cover information, for regions where little forest inventory data exists, is being generated using supervised remote sensing classification techniques with Landsat Thematic Mapper (TM) data. These resulting maps are used to provide information about broad vegetative and non-vegetative covertype classes. While these maps provide information about the broad species composition of forested areas, information about height (m), age (yrs), crown closure (%) and volume (m^3/ha) remains absent.

1.4 Research Objective

Within this context, the objective of this thesis research was to evaluate the use of satellite remote sensing analysis techniques for providing broad estimates of stand variables that could be used to complement existing NWT remote sensing species classifications.

Specifically the primary research objective was to:

- Determine what relationships exist between broad forest stand variables such as height, age, crown closure and stand volume (m^3/ha) and Landsat TM image data that was acquired over the Fort Simpson region, NWT.

The sub-objectives of this research were twofold:

- Establish the empirical factors that either permit or prohibit the generation of models to predict these forest stand variables;

  and,
- Determine whether existing field techniques implemented in the NWT facilitate the integration into geospatial analysis with digital remote sensing.

2.0 Literature Review

The purpose of this chapter is to provide a background on digital remote sensing analysis and the methods that have been used to determine stand variables from remote sensing data. Included in this discussion are an outline of the most commonly applied techniques used to assess the relationship between forest stand variables and remote sensing data, an outline of the kinds of methods used to extract stand information, as well as a summary on the strength or accuracy levels achieved from these analyses.

2.1 Background of Remote Sensing Analysis

Historically the extraction of forest information from remote sensing data has been accomplished using *conventional techniques*, which most commonly involve air photo interpretation (Lillesand and Kiefer 1994). An emphasis has emerged on using more modern methods of digital remote sensing, such as image classification of satellite data (Robinove 1981; Wolter *et al.*1995) and object-oriented analysis of high-spatial resolution airborne sensor imagery (Gougeon 1995, 1997; Gerylo *et al.* 1998a). Along with this shift in analytical paradigm is a transformation in the end products both produced for and desired by forest managers.

In earlier days of forest remote sensing, emphasis was placed on interpreting aerial photographs; by delineating polygons that represented basic stand types. These stand types were defined by a combination of different species compositions, tree heights (estimated through parallax calculations), and crown closures (Avery and Burkhard 1994). Analysis was completed once photo-interpreted data were transferred to hardcopy maps, and given to the end-user for application in planning/decision making (Lillesand and Kiefer 1994).

Aerial photographs remain the primary remote sensing medium used in forest inventory applications, and thus toady are still a primary focuses in remote sensing research (such as Magnussen 1997; Eid and Næsset 1998; and Bolduc *et al.* 1999). However, the need has arisen to develop new approaches that are less expensive than air photo acquisition and interpretation, to obtain forest inventory information. Digital remote sensing data, obtained from earth orbiting satellites and airborne platforms is a potentially lower cost that can be used to supplement traditional methods, while providing additional information on the state of the forest (Leckie 1990). The costs associated with map production from aerial photographs is much higher than that associated with satellite analysis since the cost to acquire and interpret air photos is much larger than that associated with satellite imagery. A more detailed exploration of this topic is provided in Leckie and Gillis (1995), where costs associated with air photo map production are summarized for each Canadian province.

The focus for many recent remote sensing studies has been twofold. The first focus has been on determining the extent that forest inventory variables, such as species composition (Ghitter *et al.* 1995; Gerylo *et al.* 1998a), stand age (Franklin and McDermid 1993; Kimes *et al.* 1999), dominant stand height (Cohen and Spies 1992; Nilsson 1996) and crown closure (Gerylo *et al.* 1998a); Salvador and Pons 1998) can be derived from remote sensing data. The second, yet equally important, focus has been in developing methods that provide further forms of information in addition to forest inventory data. This information is generated to aid decision-making and planning processes for environmental planners such as foresters, ecologists and wildlife experts. Wide ranges of applications have been developed to compliment/supplement traditional air photo interpreted forest inventory information. Examples of remote sensing applications include deriving stand volume from high and low-resolution data (Trotter *et al.* 1997; Hall *et al.*

1998), extracting forest leaf area index (LAI) information to monitor stand productivity (Chen and Cihlar 1996; Franklin *et al.* 1997a,b), applying change detection techniques to monitor and measure change that has occurred throughout the forested landscape over time (Muchoney and Haack 1994; Royle and Lathrop 1997; Cohen *et al.* 1998), and making wildlife habitat mapping/predictions (Blackburn and Milton 1997).

2.2 Digital Remote Sensing

This research involves application of digital remote sensing techniques for estimating forest stand variables from remote sensing data, therefore, it was important to include this sub-section, which gives a brief introduction to the science of remote sensing and a discussion of electromagnetic energy reflectance and its interactions with forest vegetation and canopy structures.

Remote sensing is the science of measuring or acquiring information about some object or phenomena by an electronic recording device that is not in physical contact with the object or phenomena under study (Jensen 1986). Digital remote sensing instruments are designed to measure or record, without direct contact, various environmental characteristics represented by emission or reflectance of electromagnetic energy (Lillesand and Kiefer 1994). Most commonly, remote sensing sensors record reflectance in the visible and infrared portions of the electromagnetic energy spectrum (Figure 2.1). This region of the spectrum is commonly analyzed since land cover features typically exhibit their own unique reflectance characteristics (Figure 2.2). One of the original, and still outstanding, reasons to employ remotely sensed data are that these data are most often applied in monitoring and analyzing large, remote regions, since this is often considered the only feasible method for mapping in such environments.

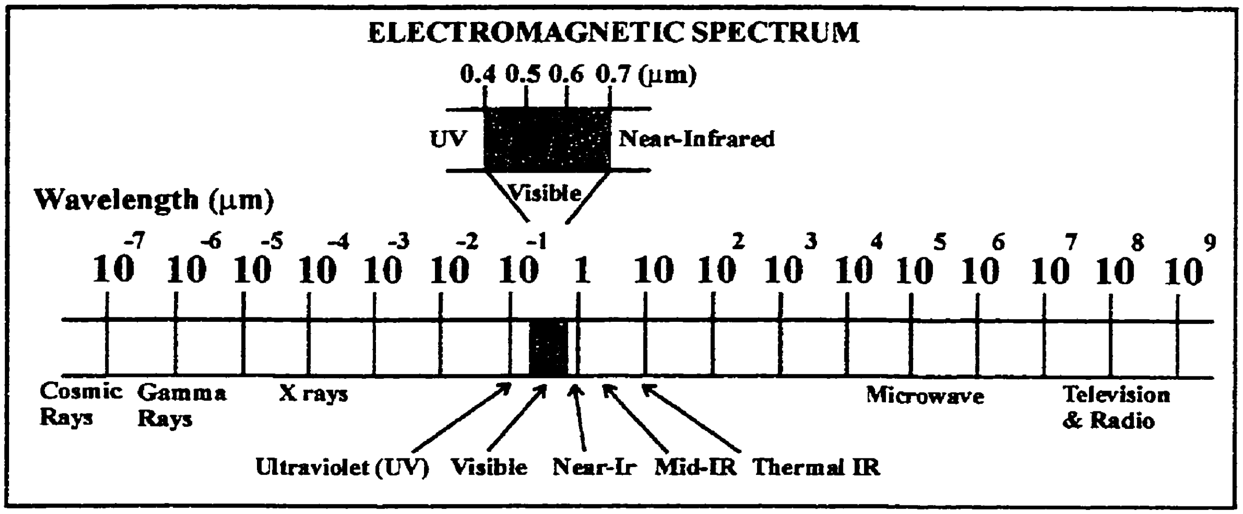

Figure 2.1 The visible and infrared portions of the electromagnetic spectrum are used in satellite remote sensing studies.

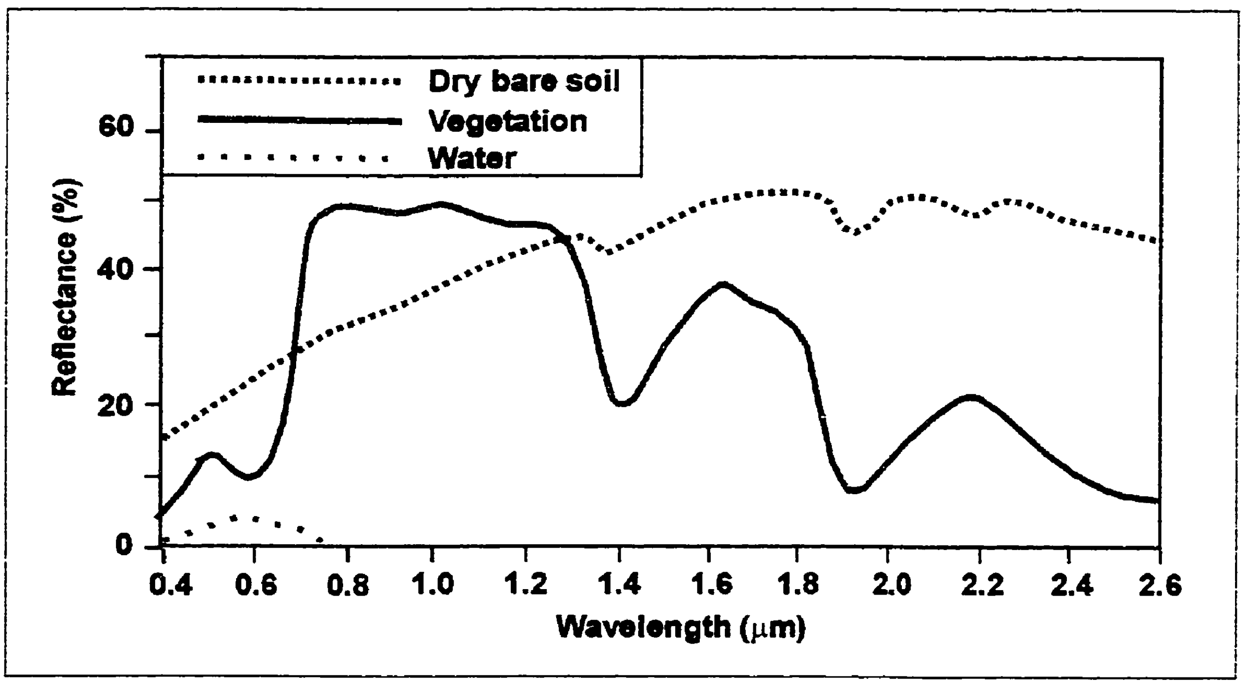

Figure 2.2 Example of spectral curves for vegetation, water and soil.

Optical remote sensing data have been applied to studies of various forms of vegetation since each species of vegetation exhibits its own optical/reflective properties. Vegetation reflects electromagnetic energy differently, based on the chemical bonds and the morphology of leaves or needles and other living or dead structures (branches, cones, etc.). Coniferous and deciduous trees have different reflectance characteristics, primarily based on leaf morphology and composition (i.e. chlorophyll concentrations, size of cells, water absorption characteristics). Along each portion of the visible and infrared spectrum, various vegetation types have their own spectral reflectance patterns that can be measured precisely by sensors at satellite or airborne altitudes.

In the visible portion of the electromagnetic spectrum (0.4 – 0.7 μm, blue, green and red) (Figure 2.2) leaves typically have lower reflectance than in the near infrared. Incident solar radiation is largely absorbed in the blue and red portions of the spectrum by leaf pigments, such a chlorophyll, during the process of photosynthesis. For this reason, leaves have their maximum visible reflectance near 0.55 μm (green region) (Guyot *et al.* 1989).

In the infrared portion of the spectrum (Figure 2.2) leaf absorption is very low since leaf pigment and the cellulose of cell walls are transparent. Absorption is less than 10% and incoming radiation is either reflected or transmitted through the canopy. Leaf structure plays a large role in determining the amount of reflected near-infrared radiation. Typically, deciduous trees reflect more infrared radiation than do coniferous trees (Lillesand and Kiefer 1994). Deciduous stands therefore appear much brighter than conifers do on infrared imagery. Analysis of infrared wavelengths is important to separate coniferous from deciduous species, and most, if not all, existing and planned multispectral satellites measure infrared reflectance.

The morphology or structure of individual vegetation components, such as needles/leaves, branches and cones, play a role in the reflectance of individual trees that are recorded on high-resolution images. On coarser resolution images, spectral response is a result of stand factors that include species composition, stand density, crown closure, height, age, health and ecosite (Gemmell 1995, Guyot *et al.* 1989). Stand reflectance values, measured on remotely sensed imagery, are the result of averaging reflectance values for each landcover class found within the corresponding unit of ground that comprises each pixel. For this reason, vegetation composition as well as stand structure influence the overall reflectance value. Taller trees cast larger shadows that may block the reflectance of understory species more so than shorter trees would (De Wulf *et al.* 1990; Gemmell 1995; Jakubauskas 1996). Changes in crown closure would affect reflectance values for forested stands, since the amount of understory and shadows detected by the sensor would vary with differences in crown closure (Nilsen and Peterson 1994). Finally, vegetation phenology may also influence the reflectance value that is detected since reflectance characteristics of a species would change throughout different phenological stages (Luther and Carroll 1999).

In addition to stand structure, the health and vigor of a forest will influence the spectral response pattern of forest stands (Brockhaus *et al.* 1993; Luther and Carroll 1999). Unhealthy stands may have a lower water absorption capability that may be detected in the middle infrared wavelengths. This change in stand health can be monitored using various change detection techniques (Collins and Woodcock 1996). For example, insect defoliation of stands will alter stand reflectance values as damage could cause needles or leaves to turn different colours and/or fall off. When this occurs the level of defoliation can be detected since reflectance patters would vary based on the degree of defoliation (Franklin and Raske 1994; Luther *et al.* 1997).

Enhanced knowledge of the spectral characteristics of forest stands and desired end-products allows the user to best determine what form of digital remote sensing data to apply to their studies. Remote sensing data are acquired from both airborne and space borne platforms. Platform choice influences the pixel resolution, therefore choice of platform is dependent upon the type of information that is desired by the user, the level of detail required and the scale of desired coverage (Puech and Viné 1999). Airborne data acquisition allows one to obtain the spatial resolution that best suits the level of analysis required, while satellite data are static, with fixed spatial resolutions. Airborne imagery also allows the user to select the time of day and year for data acquisition. User-selected dates for data acquisition are useful for selecting sunny, cloud-free days for optimal data acquisition and for matching critical stages in vegetation growth cycles. This user-selected time window is generally not as flexible with space borne sensors, as most satellite paths are fixed, with specific return dates.

Airborne imagery may appear to be the best choice for image analysis; however, satellite data have benefits of their own. First, medium to low-resolution satellite data, with resolutions that vary from ten metres to over one kilometre, provide a large cost savings, when compared to airborne remote sensing data, which is much more expensive on a cost per hectare basis. For example, in Alberta, a typical airborne image acquisition mission for collecting 2 metre panchromatic *casi* data over an 8 km by 10 km region would cost around $50 000 US for atmospherically and geometrically corrected data (S. Mah, Itres Research Ltd., Calgary, AB 2000, pers. comm.). Conversely, geometrically corrected Landsat-7 satellite imagery could be acquired for a much larger region, spanning 185 km by 172 km, for $970 US (RADARSAT International home page June 2000 – www.rsi.ca/home.htm). Regardless of the data source, it is evident that the high costs of high spatial resolution data often make it prohibitive to obtain a contiguous coverage over large areas (Wilson 1997).

Typically medium to low-resolution satellite images are most effective for providing broad forest covertype maps, generating stand variables models and undertaking change detection studies, especially for remote regions of the globe were landcover information is absent. However, it should be stressed that the information content of satellite classifications would not always provide detailed information that is best suited for all management activities (Leckie 1990).

2.3 Remote Sensing Applications for Collection of Forest Inventory Information

This research involves determining the extent that broad forest stand variables can be estimated from Landsat TM remote sensing data. This research theme has been common to many recent remote sensing studies, since optimal techniques are required to estimate stand variables that are important for assisting in forest management decision making. Image analysis techniques have been developed to predict stand biophysical variables from remotely sensed imagery, including stand height and age, percent crown closure and timber volume (m^3/ha).

2.3.1 Analysis Techniques

Recent reviews on forestry remote sensing (Andersen 1998; Holmgren and Thuresson 1998; Wulder 1998) have noted that most forest variable estimations have been determined on a continuous scale, rather than through discrete classification, since the desired mapping result is often an estimation of a variable over the landscape. These continuous variable estimation techniques are most often applied due to the simplicity of their analysis (Wulder 1998), which is a result of the continuous nature of remote sensing imagery. Most applications involve analyzing empirical relationships between remote sensing spectral information and stand variables using a variety of linear and non-linear correlation and regression techniques, which are then used to assign continuous variables values to each pixel in the remotely sensed imagery (Poso *et al.* 1984; De Wulf *et al.* 1990; Trotter *et al.* 1997; Salvador and Pons 1998).

Gemmell (1995: p. 296) provided a summary of the logic underlying the empirical estimation of forest stand data from reflectance in his study of BC forests using Landsat imagery: "...stand reflectance is primarily dependent on the density, size, and arrangement of crowns and the reflectance's of illuminated and shadowed components in the stand, and indirectly on other attributes (site quality, species composition, age) through their effects on these former characteristics." In other words, when the estimate of forest variables, such as crown closure or age, is desired from an image, the relationship between the amount of reflectance and shadowed areas in the canopy and the crown closure or age is the effective empirical relation that must be estimated.

The second most common approach applied in estimating forest biophysical variables from remotely sensed data has been multispectral image classification. Image classification is used to produce thematic maps of discrete classes, generally using statistical classifiers, which determine the probability that a given pixel belongs to a specific class (Lillesand and Kiefer 1994). Most commonly supervised classification approaches, which require prior knowledge of the desired mapping result, have been used to estimate discrete forest variable classes from remote sensing data (Congalton *et al.* 1993; Fiorella and Ripple 1993; Cohen *et al.* 1995; Jakubauskas 1996). The utility of alternative classification approaches for estimating stand variables have also been tested, including unsupervised image segmentation (Gemmell 1995), *n* dimensional *k*-nearest neighbour (*k*NN) classification (Fazakas and Nilsson 1996; Trotter *et al.* 1997; Reese and Nilsson 1999) and neural network classification (Kimes *et al.* 1996, 1999; Peddle *et al.* 1999).

2.3.2 Stand Height

Research related to deriving stand height from digital remote sensing data has been conducted on a variety of image formats and spatial resolutions. Earlier research was focused on determining spectral relationships between stand height and image reflectance and other DN values (ratios and transformations) from medium resolution satellite data, such as the Landsat TM (Cohen and Spies 1992; Gemmell 1995) and SPOT (De Wulf *et al.* 1990; Cohen and Spies 1992; Franklin and McDermid 1993) and high-resolution airborne spectral data (Franklin and McDermid 1993). More recently, research has been focused on extracting stand height information from airborne lidar (*li*ght *d*etection *a*nd *r*anging) systems (Nilsson 1996; Lefsky *et al.* 1999), profiling radar (Hyyppä and Hallikainen 1996) and laser profilers (Næsset 1997; Magnussen and Boudewyn 1998).

An expected relationship between stand height and reflectance would be that reflectance is an inverse function of height. For example, as trees grow taller the amount of foliage would increase (thereby covering the brighter understory and soils of the forest floor) and shadows cast by them on other crowns and the understory would increase. Typically, correlation coefficients derived from low-resolution satellite data have confirmed that there is a negative relationship between stand height and satellite spectral response. In British Columbia Gemmell (1995) observed this trend when correlating the mean spectral response and height of trees associated with four different spectral classes. A strong negative correlation coefficient of –0.88 was observed between TM band 5 (mid-infrared) and mean tree height, since an increase in tree heights would lead to an increase in the amount of shadows that occur within the stand. This shadowing influence has been identified as a physical link to the negative relationship between reflectance and tree height. In an earlier European study De Wulf *et al.* (1990) observed that the height has a physical link with the radiance measured by the sensor, since height controls the shadowing patterns within and beneath the forest canopy.

Past literature has demonstrated that stand height predictions from remote sensing data often provide variable results, which occur due to the variable nature of the forest stands being studied. This flows from a general weakness of the empirical methods compared to the canopy reflectance modeling approach favoured in more experimental studies (e.g. Li and Strahler 1985, Woodcock *et al.*1997). Most empirical studies used to relate forest variables from remote sensing data present results which are optimal to the day the imagery was acquired, the forest species of interest, the local study area and the methods applied. For example, Franklin and McDermid (1993) found a moderate and negative relationship between Lodgepole pine and SPOT satellite visible reflectance, where R values varied from –0.45 to –0.56. When these variables were input to a regression model to predict stand height, a weak R-square value of 0.32 was achieved.

Another study by Cohen and Spies (1992) in Oregon reported on the relationship between height and image reflectance/transformed values for an old-growth Douglas fir and Western hemlock forest. They demonstrated overall stronger relationships, especially when incorporating the Landsat TM tasseled cap transformation for wetness. This transformation used information from TM bands 5 and 7, not available in the SPOT satellite data set used by Franklin and McDermid (1993). In Oregon a strong relationship was observed between forest stand height and wetness, with an r-square value of 0.72. The variability in results provided by these studies demonstrate the need for the image analyst and the user of remote sensing information to keep the interpretation of results, and the application of any derived model functions, empirical to the local study area with the same imagery used to generate the relationships.

2.3.3 Stand Age

Stand age has been predicted from remote sensing data using both continuous variable estimation techniques and spectral classification approaches, on low-resolution satellite and high-resolution airborne data. Similar trends in results have been observed when applying either analytical technique to estimate relative stand age, however the strength of results has been variable. Age is not a structural variable of a forest, rather it is a descriptor that can be highly related to structural variables such as height or crown closure. Therefore, the expected relationships between age and reflectance might be more complex than those associated with height; for example the relationship might be primarily a function of how much of the forest soil is covered by leaves as the forest ages.

In other areas, the relationship might include decreased visible reflectance and increased infrared reflectance with increasing age. The physical condition responsible for this relationship would be increased canopy foliage. As the amount of leaves increases, the visible reflectance would be expected to decrease (especially in the red band because of increased absorption by chlorophyll). The amount of near-infrared reflectance caused by the water and cellular structure of the leaves would increase with increased foliage (Curran 1980). Therefore, on satellite imagery, older stands would appear darker in the visible bands and brighter in the infrared bands. A large number of factors can reduce the amount of absorption in the visible bands and scattering in the near infrared (Guyot *et al.*1989). For example, the topographic effect has been shown to significantly alter reflectance as a complex function of slope (Gu and Gillespie 1998); similarly, the amount of shadowing might confound these expected relationships (Dansen and Curran 1983).

In some studies an inverse relationship between stand age and both visible and near infrared spectral reflectance has been observed, where spectral reflectance values in all bands decrease as stands mature (De Wulf 1990; Cohen and Spies 1992; Jensen *et al. 1999*), while relationship strength varies depending upon the type of imagery used and forest environment studied. For example, Franklin and Luther (1995) observed weak, but significant linear correlations between stand age and Landsat TM values (i.e. band 4, R = -0.33) in balsam fir stands with mean stand age ranging between 32 and 108 years. Significantly stronger relationships were reported by Jakubauskas (1996) when characterizing lodgepole pine seral stages in Lodgepole pine/sub-alpine fir stands, when age ranged between 5 to 350 years (i.e. TM band 1, R = -0.65).

Most often linear correlation analysis is used to relate stand reflectance values with stand age. While this linear technique has been successful for forest stands with low age ranges, the relationship for stands with a large range of age classes, including very young stand (<20 years), is often non-linear (Nilson and Peterson 1994; Jensen *et al.* 1999). For example, Nilson and Peterson (1994) demonstrated this non-linear relationship using airborne spectrometer data. They observed that reflectance values decreased rapidly during the first 20 to 40 years, then saturated thereafter. This non-linear relationship has also been observed Jakubauskas (1996), when studying the reflectance patterns of lodgepole pine stands, where the largest change in spectral response was found to occur during the first 20 to 30 years of lodgepole pine growth. When a base-10 logarithmic transformation was applied to stand age all overall correlation values improved in strength, for example the relationship between Landsat TM band 1 and age improved from –0.65 to -0.78.

The relationship between spectral response and stand age has been interpreted by most authors as being largely attributable to changes in stand structure. Crown closure, LAI, stand species composition and height characteristics change as stands mature, which would influence the overall canopy and understory reflectance value detected. Typically, shadow components increase with stand maturity, since tree height increases with age and more shadows are cast by taller trees, thereby decreasing the overall stand reflectance (Nilson and Peterson 1994; Cohen *et al.* 1995; Jakubauskas 1996). It should be noted that this relationship will begin to saturate once stands reach a given age, since very little changes occur within the structural complexity of a forest at older ages. For example, in their study of Oregon forests using Landsat TM Cohen *et al.* (1995) stated that "there was little predictability in the spectral response of conifer forests beyond about 200 years of age, or once old growth characteristics are attained…forest stand conditions continue to evolve, but spectral changes appear uncorrelated with that development."

Additional studies have been undertaken to predict stand age from spectral reflectance data by assigning broad age categories, rather than continuous age values, to each pixel on the imagery. Gemmell (1995) used unsupervised image segmentation techniques to group Landsat TM data into four homogenous spectral classes. Mean spectral values were obtained for each spectral class, for each band, and were correlated against the average stand age. A negative relationship was observed, which is consistent with other continuous variable studies, and strong correlation coefficients were achieved (i.e. TM band 5, R = -0.88). More traditional classification approaches have been undertaken that apply supervised image classification and discriminant analysis techniques to determine successional stages or age classes of forest stands. Jakubauskas (1996) applied classification techniques that combine spectral data with GIS elevation data to identify five successional stages for lodgepole pine stands. Discriminant analysis was used to determine the probability that each pixel belonged to one of the age classes, yielding an overall accuracy of 84%.

Similar results were observed by Fiorella and Ripple (1993), who distinguished between five successional stages of temperate coniferous forests using two consecutive classification models, yielding an overall classification accuracy of 78%. In the first model class separability was high among the first three successional classes, but was weak between mature and old growth forest stands. Therefore, to best distinguish between these older forest stands and increase the overall classification accuracy, a secondary analysis model was applied that made use of the structural index (SI) (Landsat TM band ratio 4/5) and Landsat TM tasseled cap wetness transformation. This second model improved the overall classification accuracy, thereby allowing all five successional classes to be mapped with acceptable precision.

Complex classification techniques, such as the k nearest neighbour (kNN) classifier or neural network analysis, have been employed in extraction of stand age from satellite imagery, however, they have yet to demonstrate successful operational utility. Reese and Nilsson (1999) applied the kNN approach to estimate age of Swedish forest stands from Landsat TM data. The root mean square error (RMSE) varied from 34 to 47 years in two separate studies areas, indicating that further research would be required before applying the kNN approach into operational applications. Kimes *et al.* (1996) demonstrated a much lower RMSE (~ 5 years), however, the dynamic range of the input data (< 50 years) prohibited extrapolation of these results to typical forest stands, whose age range far exceeds 50 years.

2.3.4 Crown Closure

Techniques to extract percent crown closure (percentage of land area covered by the vertical projection of tree crowns) have not been explored as frequently as other stand variables have been in recent literature. However, in recent years more research has emerged applying either low-resolution (Butera 1986; Salvador and Pons 1998; Deuling *et al.* 2000) or high-resolution spectral imagery (Baulies and Pons 1995; Gougeon 1995, 1997; Gerylo *et al.* 1998a) to predict or calculate stand crown closure.

Typically, low-resolution approaches have involved application of continuous variable estimation techniques to predict crown closure. For example, Salvador and Pons (1998) used Landsat TM spectral bands and 25 spectral ratios to predict stand canopy coverage (crown closure). They observed that models that incorporated all six spectral bands were significant but weak (R^2 = 0.34) and that incorporation of additional independent variables from spectral ratios improved the strength of models ($r^2 \sim 0.6$). These models, however, proved non-robust since a low number of field plots and high numbers of independent variables were used to build the models. With a large number of independent variables high collinearity among variables would likely occur and create an inconsistency between predicted and observed values. Therefore, the authors suggested that the analyst use caution when applying multiple variables to a model, since remote sensing data are often highly correlated, which would thereby increase the collinearity within the data set.

Deuling *et al.* (2000) studied the empirical relationships between the Landsat TM tasseled cap transformation for wetness and crown closure (%) in cedar/hemlock, Engelmann spruce and subalpine fir stands in the southwestern portion of British Columbia. A goal of their study was to determine what relationship exists between crown closure and the Landsat data. Results varied, depending on how the forest stands were stratified for analysis. In climax forest stands, a strong positive relationship was observed between crown closure and wetness values ($R = 0.86$), as well, a strong regression model was built to predict crown closure, with an adjusted r-square value of 0.73 and a standard error of estimate near 10%. These results suggest that an increase in crown closure would allow a greater proportion of the stands canopy to become visible, and thus increase the reflectance values measured by the TM sensor. Wetness values increased since wetness has been interpreted to be sensitive to the amount of moisture held within tree leaves (Cohen and Spies 1992), therefore wetness values increased as more canopy foliage was viewed by the sensor. When studying younger, seral stands, a weaker relationship was observed between percent crown closure and Landsat wetness values ($R = 0.47$), and only a weak regression model could be built to predict crown closure (adjusted r-square = 0.14 and standard error of estimate ≈ 22%) for wetness values. Deuling *et al.* (2000) interpreted that these weaker results were obtained in seral stands since the stands species composition was heterogeneous, with a wide range of species compositions that often contained hardwood vegetation components. This mixed-wood composition would give more variable reflectance values that would lead to variable wetness index values. The large differences in correlation and model strengths achieved in this study help reiterate that studies to predict stand variables from Landsat data are empirical to the local study region and forest stands surveyed, and that relationships in a single study region can vary according to each individual stand.

While techniques to predict crown closure from satellite data have involved continuous variable estimations that may be used to provide broad estimates, techniques applied to high-resolution largely differ. High-resolution analysis techniques have often focused on identifying groups of pixels that represent discrete stand "objects", such as individual tree crowns. Therefore, crown closure could be calculated by determining the percent area occupied by these objects. A variety of image processing techniques, with varying degrees of complexity, have been developed to delineate individual trees crowns on high-resolution images, thereby separating the trees crowns from the shaded background (Gougeon 1995; Meyer *et al.* 1996; Gerylo *et al.* 1998a). Following identification of tree crowns, techniques have been developed that group individual tree crowns into discrete stands (Gougeon 1997), or to calculate percent stand crown closure, with accuracy rates that may exceed 90% (Gerylo *et al.* 1998a)

2.3.5 Stand Volume

Empirical relationships between remote sensing data and volume have been determined using correlation and regression techniques on a wide variety of satellite data, including very low resolution Special Sensor Microwave/Imager (SSM/I) (Grandell *et al.* 1998) and AVHRR data (Fazakas and Nilsson 1996); lower resolution Landsat MSS imagery (Poso *et al.* 1984); and medium resolution Landsat TM (Gemmell 1995; Reese and Nilsson 1999) and SPOT data (De Wulf 1990; Ripple *et al.* 1991). Additional studies have focused on applications that use high-resolution airborne data, including spectral casi (Franklin and McDermid 1993; Baulies and Pons 1995) and MSV data (Hall *et al.* 1998); or airborne lidar (Nilsson 1996), radar (Hyyppä and Hallikainen 1996) and laser (Nelson 1997) data. Each study to predict volume is empirical to the local study region, as local variations in stand structure and environment (landscape and climate) will influence the observed relationship.

Ripple *et al.* (1991) tested the utility of Landsat TM and SPOT data for estimating stand volume. A significant correlation existed between softwood volume and reflectance data, allowing strong predictions of stand volume. Other studies, however, have not been as successful. For example, Trotter *et al.* (1997) experienced high RMS errors when estimating stand volume in New Zealand pine plantations, where the smallest achieved error was 80 m^3 ha^{-1}. The main reason cited was the homogeneous canopy conditions; as in all remote sensing studies, when the crown is completely closed the sensor detects reflectance only from the top of the canopy. In Finland conifer forests Hyyppä *et al.* (1998) predicted stand volume with similar results, where relations between stand volume and SPOT and Landsat TM spectral response were poorly correlated (R^2 0.25 and 0.27, respectively) with high standard errors (near 90 m^3/ha). In more variable areas, such as the interior BC study area of Gemmell (1995), it has been reported that relationships between volume and spectral response have low sensitivity to high stand volumes. Regression models could successfully predict lower stand volume, however, the models were less accurate for predicting volumes that exceeded 400 m^3 ha^{-1}.

As with the stand height, age and crown closure models, the derived relationships to predict volume are largely dependent upon the bulk stand reflectance response. Gemmell (1995) identified that timber volume was related to this bulk stand reflectance, which was created through differences in height, age, species composition, slope and aspect. The strength of the model may also be dependent upon the range of reflectance DN values used to create the model. If a low range of reflectance DN values is used for model development, the derived model strengths may be weak, due to the low variability in the input image variables (De Wulf *et al.* 1990; Franklin and Luther 1995; Gemmell 1995).

Therefore, when building future stand volume models it would be best to input image variables that have a large dynamic range of reflectance DN values.

3.0 Study Area

This chapter describes the study area where this research took place. A physical description of the environment; including landscape geology, soils and climate, and forest biophysical information; including species type, stand composition, structure and succession, are provided in the sections following this introduction. The overall purpose of this chapter is to provide the reader with a familiarity of the study region and to help build a better understanding on the types forest stands present in the southern NWT that remote sensing models will be built for.

3.1 Landscape and Locational Description

The study area for this research is located within the Boreal forest zone, a broad northern circumpolar belt that is found in many region along the northern hemisphere. The North American portion of the belt stretches from Alaska to the Rocky Mountains and eastwards towards the Atlantic Ocean. The boreal forest is an important North American forest since it occupies more than 60% of the total forested land found within Canada and Alaska, while maintaining relatively low species diversity (Johnson 1996).

More specifically, the study area is located within the Taiga Plains ecozone, an ecozone that covers over 64.7 million hectares of Canadian land. Within this ecozone over 50 million hectares of land is covered by forest, of which over 17.1 million hectares is considered to be productive (Canadian Council of Forest Ministers 1997). The specific region of interest for this study is centered around the village of Fort Simpson. This village is located within the Deh Cho Forest Management region of the NWT, in the southwestern portion of the NWT (Figure 3.1).

The Fort Simpson region, located at an average elevation of 450 m, is characterized by poorly drained, gently rolling forested plains (Forest Management Division 1997). Much of this region is composed of major Devonian and Cretaceous-aged basement rocks, including sandstone and shale, which are covered by soils developed from glacial till, lake and river deposits (Day 1968).

The average annual temperature for the Fort Simpson region is –3.9°C, with a large scope of daily average temperatures, ranging between –26.9°C in January to 16.7°C in July. Within this range of temperatures there is also a large spread of maximum daily temperatures, which range from -50°C to 36°C. In the summer months, Fort Simpson receives an average rainfall of 205 cm, which is one of the primary factors in the development of the regions varying forest stands (Forest Management Division 1997).

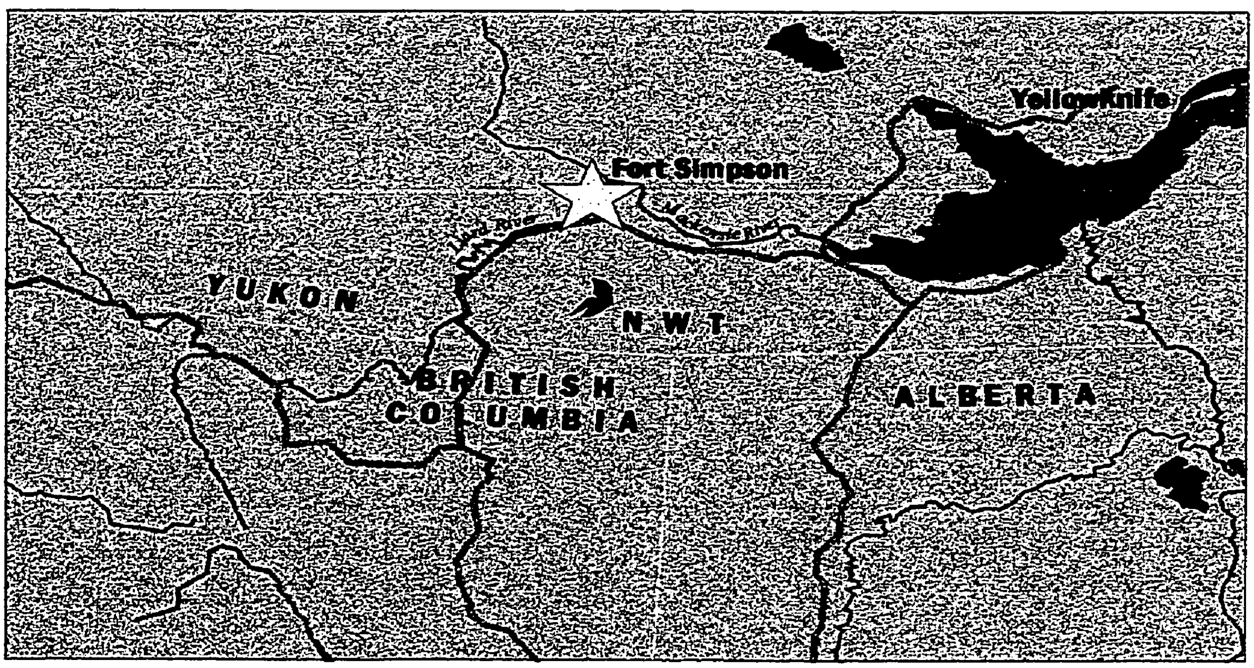

Figure 3.1 Location of the study area in Fort Simpson, NWT.

3.2 Regional Species Composition

The Fort Simpson region is situated within the Upper Mackenzie (B.23a) forested region characterized by Rowe (1972) and the Ecological Stratification Working Group (1995). Dominant tree species in this region are typical North Boreal species, which are shown in Figure 3.2 and described herein. White spruce (*Picea glauca* (Moench) Voss), balsam poplar (*Populus balsamifera* L.) and trembling aspen (*Populus tremuloides* Michx.) are dominant species along the alluvial flats that border the region's many rivers, while benches above the flood plains exhibit much different forest patterns. Jack pine (*Pinus banksiana* Lamb.) and trembling aspen are found in drier, sandy positions. Sites with higher moisture content, such as muskegs and depressions, are populated by black spruce (*Picea mariana* (Mill) B.B.P.), tamarack (*Larix laricina* (Du Roi) K. Kock) and white birch (*Betula papyrifera* March) species (Day 1968; Rowe 1972).

Micro-topographical effects and fire are the two key factors that generally influence the composition and structure of the forest stands in this boreal region. Micro-topographical effects, as briefly described in the above section, help determine which species will dominate a given site. For example, drier sites, such as the sandy benches found above the river valley, would be dominated by moisture intolerant species, such as jack pine or trembling aspen, while moister, nutrient rich sites would be inhabited by species that require higher amounts of nutrients and moisture, such as white spruce and balsam poplar. Finally, poorly drained depressions are populated by moisture tolerant species, such as black spruce and larch. While this micro-topographical influence helps determine what the forest composition will be at a large scale, another factor affects the composition and structure of forest stands at a broader scale.

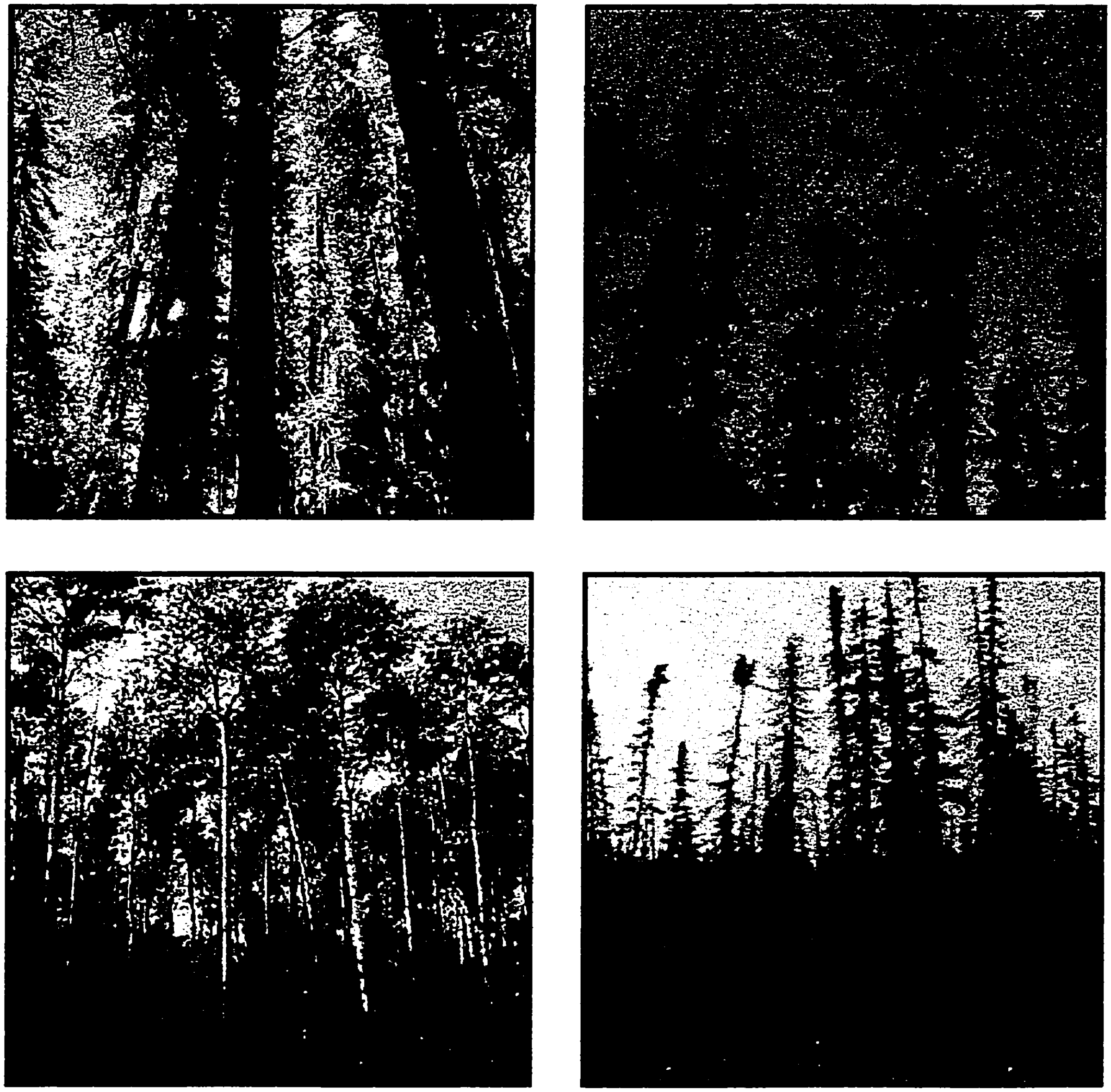

Figure 3.2 Dominant tree species of the Fort Simpson region, NWT are shown, clockwise, from top-left corner; white spruce, jack pine, black spruce/tamarack, and trembling aspen.

Fire is the other key factor that influences the composition and structure of forest stands in the boreal region. Fire is the most important natural disturbance to forest stands in the boreal region, where any given area will burn every 50 to 150 years (Johnson 1996). Since fire is such a common disturbance in the boreal forest, many boreal trees have adapted to surviving the effects of fire. These are the *pioneer* species that will re-vegetate and dominate a given region following fire. Jack pine and black spruce have adapted to fire by producing serotinous cones. These cones are sealed in a hard coating that prevents premature seed release. The cone remains preserved for many years until stricken by fire, at the time the extreme heat of the fire breaks through the resinous bonding of the cone and releases the seeds. These seeds germinate rapidly since the fire often burns through the duff and surface organic matter and exposes the mineral soil, which thereby servers as a bed for the released seeds (Burns and Honkala 1990a). Another pioneer species that occupies a site following a fire disturbance is trembling aspen. The regeneration techniques of aspen differ from pine, since aspen do not have cones that release seeds following a fire. Rather, once an aspen stand is disturbed it will quickly start to form suckers from its roots. These suckers rapidly allow the entire aspen community to regenerate before other species are given the opportunity to compete with their growth (Burns and Honkala 1990b).

As the boreal forest matures, it passes through a series of characteristic developmental stages. Typically, white spruce, a shade tolerant species, will slowly begin to grow beneath the canopy of the fast growing, shade intolerant pine and aspen. Growth is often restricted for the spruce, as it is impeded by the dominant overstory species. Therefore, the overall light intensity the spruce receives will affect its overall growth (both in height and shoots/roots) (Burns and Honkala 1990a). Over time the dominant species canopy will begin to die out as they mature or are affected by natural disturbance factors. Once they die, they create large gaps in the forest canopy that the spruce rapidly take advantage of. Spruce will release (fast growth) rapidly beneath a canopy gap, allowing the spruce to meet and rapidly exceed the height of the dominant canopy species. If this understory spruce community is left undisturbed by fire or pest damage, the spruce will eventually dominate the forest, filling in canopy gaps as pioneer species decline in number. This developmental characteristic lends to great variation in the relationship between stand height and crown closure for stands that share similar years of origin. This relationship is weakened further by spruce recruitment factors.

Typically, white spruce grows beneath the shade of pioneer species; however, in many circumstances white spruce may establish itself in open regions (Burns and Honkala 1990a). This could occur following a fire or other disturbance and seed sources for jack pine are absent or root structures for aspen are missing or damaged. In these circumstances white spruce may become the dominant species since its seeds are often transported through the wind, collected by shrub species to slowly allow root development. If this form of spruce recruitment occurs the relationship between height and crown closure again will largely differ for any given year of origin since the spruce growth pattern will differ for each individual stand type and recruitment form.

The secondary successional stage, where spruce dominates the forest stand, is most often halted by fire. At this time the regeneration process undertaken by pioneer species would (most commonly) occur, and the successional development process would repeat itself until halted by another disturbance agent. It is very rare to find a forest stand in the NWT that has developed into a climax community, the final succession stage, since fire halts the development of the climax species, balsam fir (Johnson 1996).

Since succession and competition play large roles in the development of forest stands in the NWT mature forest stands are typically characterized by a wide range of tree sizes that grow in open, patchy stands. The openness of these stands permits new tree species to establish themselves, leading to a multi-structured forest canopy, with different species dominating different canopy layers (Kimmins 1997: chapter 15). This openness also permits large growth of understory species, such as alder or rose, which have been observed to often cover over 50% over the understory area.

4.0 Methods

This chapter presents details of the methods applied throughout this research for estimating stand variables from Landsat TM data. Included in this chapter are discussions on the methods employed in field data collection, data preprocessing, image analysis and statistical analysis.

4.1 Digital Spatial Data

The digital spatial data utilized in this study included Landsat 5 Thematic Mapper (TM) satellite data and air photo interpreted forest inventory data that resided in a geographic information system (GIS) database. Concise descriptions of these two sources of data are provided in the following subsections.

4.1.1 Landsat Thematic Mapper (TM) Data

Landsat 5 TM data was acquired over the Fort Simpson region August 16, 1993 and an example sub-set of the image is shown in Figure 4.1. This image was acquired at the Track/Frame position 51/17 at 18:45. The Landsat-5 TM is a spaceborne sensor that collects data in seven wavelength bands over large spatial regions that span 185 km by 185 km. The wavelength range and location of the TM bands were designed to improve the spectral differentiation of vegetation and earth surface features. Image data for TM bands 1 to 5 and 7 are collected at a spatial resolution of 30 meters, with each picture element (pixel) representing a 30 m by 30 m area over the earth's surface. The spatial resolution of TM band 6 is much coarser than the other bands (120 m by 120 m), which was designed to collect data in the thermal region of the electromagnetic spectrum (Lillesand and Kiefer 1994), and was therefore not used in this study.

This image was chosen for analysis, even though its vintage was old, and was acquired late in the summer months when sun angle are low, since it is the most recent cloud and smoke free image available for the study region. The difference of six years between image acquisition and field data collection could affect the strength or interpretation of the derived models, since the forest stands may have changed over the time period due to a variety of factors. These factors may include, but are not limited to, disease and pest damage that could slow the growth and development of individual trees, additions or reductions in stand cone crops that would affect individual stand reflectance values, and human thinning of stands that would increase the shadow content of a stand. Additionally, the low sun angle found in the NWT in mid-August (due to its northern latitude) may make it difficult to understand the differences in spectral response of the forest (Helmer *et al.* 2000), since a low sun angle would create larger shadows and possibly reduce the amount of vegetation understory detected by the Landsat sensor. Despite these possible sources of error, it was decided that this image remained suitable for the analysis tasks set forth by this research.

4.1.2 Geographic Information System (GIS) Data

Digital land information, in the form of a Geographic Information System (GIS) database, was provided by the Forest Management Division of RWED in August 1999. This information was obtained from 1:20,000 black and white photos, which were acquired over the study area during the summer of 1995 and interpreted during 1996 and 1997. Additional GIS data was obtained from preexisting 1:50,000 National Topographic Survey (NTS) map sheets, which displayed the spatial coverage of basic road systems, vegetation cutlines, lakes, rivers and steams.

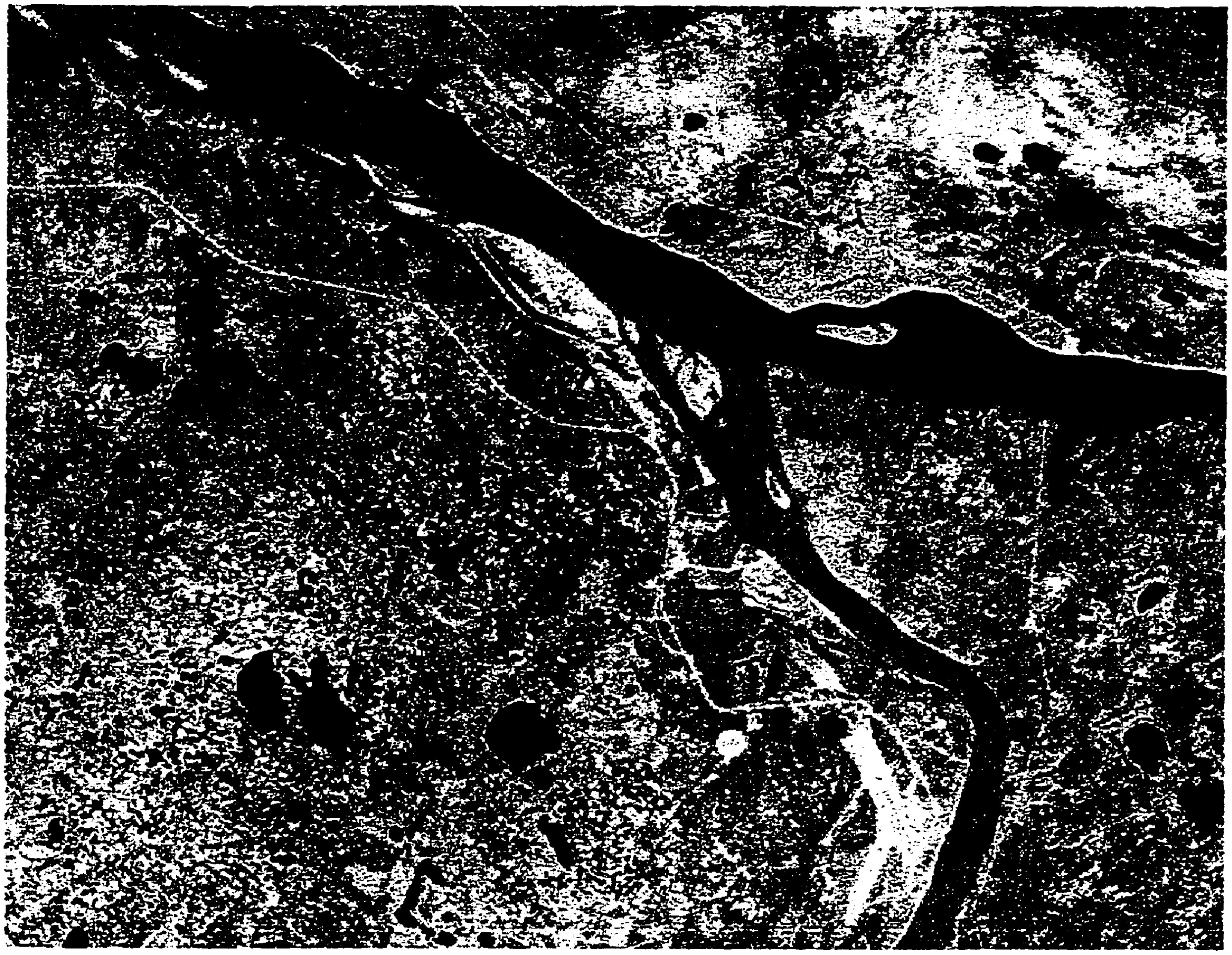

Figure 4.1 Example Landsat-5 Thematic Mapper (TM) data showing a sub-set of bands 5, 4, and 3 as a false colour composite over the Fort Simpson region, NWT.

The forest inventory polygon data contained in this database were interpreted from the aerial photographs by applying NWT air photo interpretation and GIS and spatial database standards, which are outlined in full detail in Forest Development Services (1998a, b). Polygon information included estimates of dominant stand height (estimated to the nearest metre), stand origin year (in ten year intervals), species composition (in 10% classes) and crown closure (in 10% classes) for each identified forest stand. Additional polygon information was provided for larger water bodies, such as large rivers, lakes and bogs. The line data contained in this database included delineations of major roadways, forest clearings, seismic lines, vegetation cut lines and small rivers or streams.

Additional GIS data was created to allow accurate representation of field plot locations, and is discussed further in Section 4.2.2 (*Field Plot Positioning*). The point data obtained from digitized field plot locations were used to extract air photo interpreted forest inventory information from the GIS database, which would be used for future comparison of air photo interpreted and remote sensing modeled forest variables. To obtain the forest inventory polygon attribute data, point-in-polygon analysis was undertaken, using Arc Info software, to transfer all polygon attribute data to the point locations that fell within each polygon. The point-in-polygon analysis was useful for reducing the size of the GIS database, since the final point information was the only data that was required for export into, and analysis in, the PCIWORKS database.

4.2 Field Collection of Forest Variables

Two separate collections of field data were considered for analysis in this project. The first collection was comprised of data collected by Forest Development Services field crews in July 1998, while the second collection comprised field data obtained by the research team during July and August 1999. This section describes the methods employed for measuring field plots and precisely locating them on the digital imagery.

4.2.1 Field Data Collection and Plot Positioning

In the summer of 1998 Forest Development Services field crews collected data in variable radius field plots that were located in pure white spruce, jack pine and trembling aspen stands. Comparable stands were surveyed in 1999 by the research team using polygon sampling strategies and field measurement techniques that were similar to those that were employed in 1998. Consistency in methods was necessary to ensure that field data measurements collected each year were consistent with one another.

Each field plot location was determined by applying a stratified sampling strategy that was designed to ensure that the plots chosen reflected the general characteristics of the forest region. A stratified, hierarchical system, as shown in Figure 4.2, was implemented to identify suitable plot locations. At the first hierarchical sampling level forest inventory polygons from the GIS database were stratified into pure species (greater than or equal to 80% of one species) and mixed-wood stands (less than 80% of one species).

At the next sample level two crown closure classes (Figure 4.2), based on the full range of photo-interpreted

classes, were identified. The full range of crown closure measurements was divided into two groups, which were based on the range and midpoint of crown classes. Inventory polygons in the lower half of the range (lower crown closures) were assigned to the open canopy class, while polygons in the upper range were considered closed canopy.

The final hierarchical sampling step was implemented to stratify forest inventory polygons into three height classes (Figure 4.2). The sample technique employed was similar to the crown closure stratification where the full range of interpreted heights was determined from inventory polygons and divided into three height classes. Height class 1 included the shortest stands, height class 2 grouped stands with intermediate heights, and height class 3 included the tallest stands.

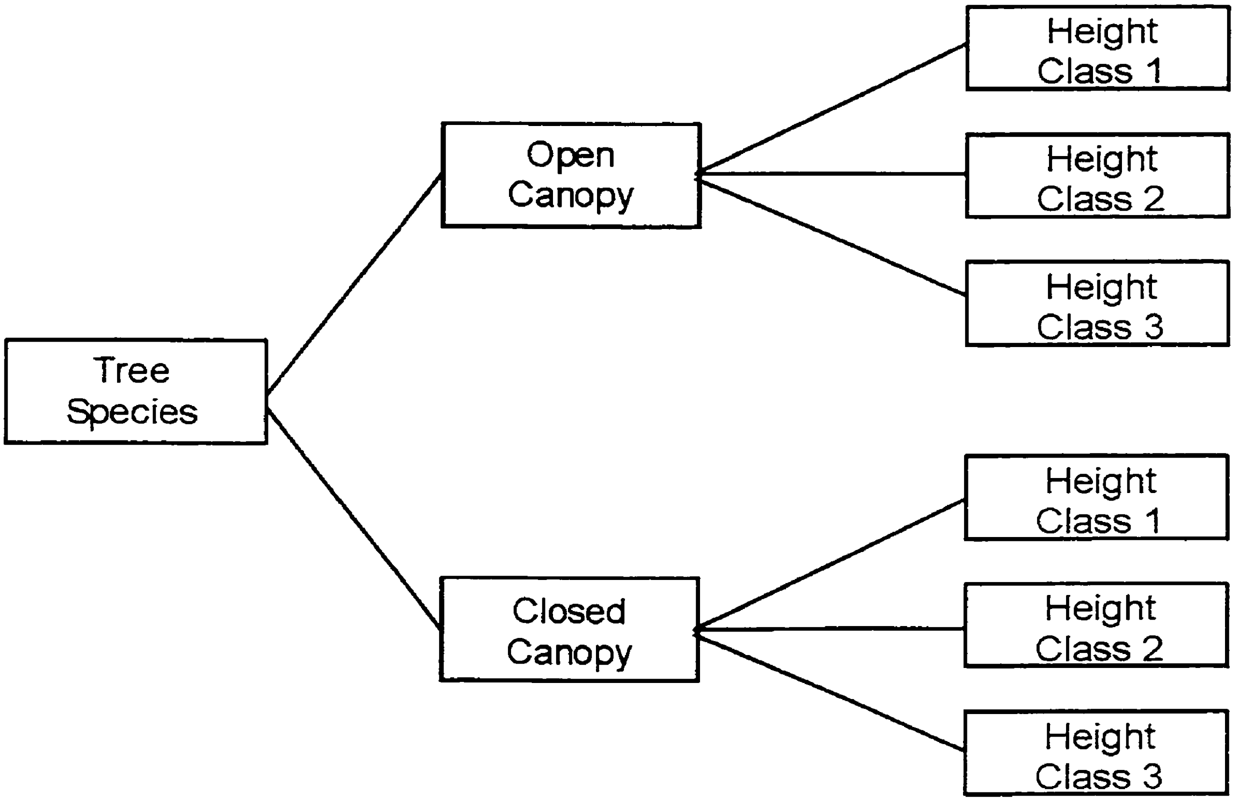

Figure 4.2 Hierarchical sampling strategy employed in this research.

Inventory maps were examined visually to locate the positions for each stratified sample class. Inventory polygons were examined to determine regions where three or more sample classes could be found, within a close geographic proximity to each other, therefore allowing three samples (inventory polygons) to be sampled each day. Prior to the availability of GIS data, air photos were interpreted and road surveys were implemented to determine suitable locations for field samples. It would have been preferable to stratify the GIS data and perform random samples to locate field plots, however GIS data were not made available until the first week of August, five weeks after field sampling began. The final decision factor taken into account when designating sample locations was the availability of field control points. Inventory polygons were only chosen for sampling when at least one control point could be identified in the field and on the air photo, which would thereby permit high accuracy when identifying the sample and plot locations on the air photos.

Three field plots were located within each polygon sample, as demonstrated in Figure 4.3; to ensure that the variability inherent in photo interpreted forest stands was captured. The placement of each field plot was determined by placing a straight transect line through the middle of each forest inventory polygon. These transect lines, which measured 100 metres in length, were split into three even sections to allow a consistent spacing between each field plot location. The first plot was located, at minimum, 60 metres from the stand boundary to eliminate edge effects from neighbouring stands and to ensure that the pixel response was pure to the stand being sampled. The second and third plots were located 50 metres apart from each other to ensure that each plot location fell within a different TM pixel.

Variable radius plot cruising techniques were used to collect field data in both the 1998 and 1999 samples. This cruising technique, which is the most commonly implemented practice in the NWT, was used for collecting the 1998 data. Therefore, it was determined that field plots surveyed by the research team in 1999 would also implement the variable radius plot technique to ensure data samples were collected in a consistent manner.

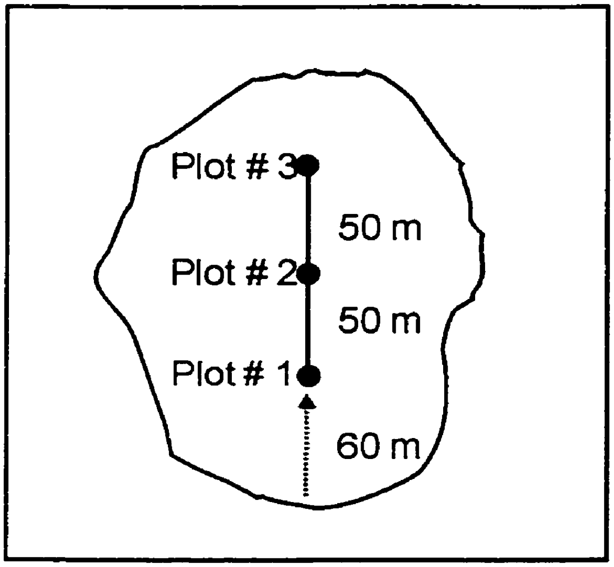

Figure 4.3 Placement technique for locating the field transect and plot locations within each sample forest inventory polygon.

Variable radius plots are often preferable to fixed area plots because they are simpler to construct and save substantial plot measurement and computation times, without sacrificing accuracy. Furthermore, they often give a "better balanced sample of the various diameter classes within the forest stand" (Dilworth and Bell 1975: page 1). This is achieved since plot size is be dependent on the size of the trees within the plot. Most commonly, prisms are used to determine which tree stems to measure within the plot. A prism is a wedge-shaped piece of glass that bends light rays to establish a critical angle-gauge projection. The ratio of the projection angle and tree diameter is used to determine which tree stems to measure.

The radius of each plot was determined by holding the prism directly over the centre of each plot. The prism was held up to the eye of the cruiser, and the visual appearance of each tree stem viewed in the prism was deflected to the side, as indicated in Figure 4.4. If the amount of displacement was smaller than the diameter of the tree, the tree was be considered "in" and would be measured; if larger, the tree was "out" and would not be measured. When the amount of displacement was equal to the tree diameter the tree was considered "borderline" and would be counted as a half tree. Rather than identify the tree as a half, every second half-tree was counted as a full tree.

In some situations trees within the plot were hidden from the cruiser. In this case, the observation point was moved to a more advantageous position, while taking care to ensure that the exact distance from the plot point to tree was maintained. In other circumstances, trees were leaning within the plot, therefore the prism was rotated until the displacement formed a right angle with the tree stem.

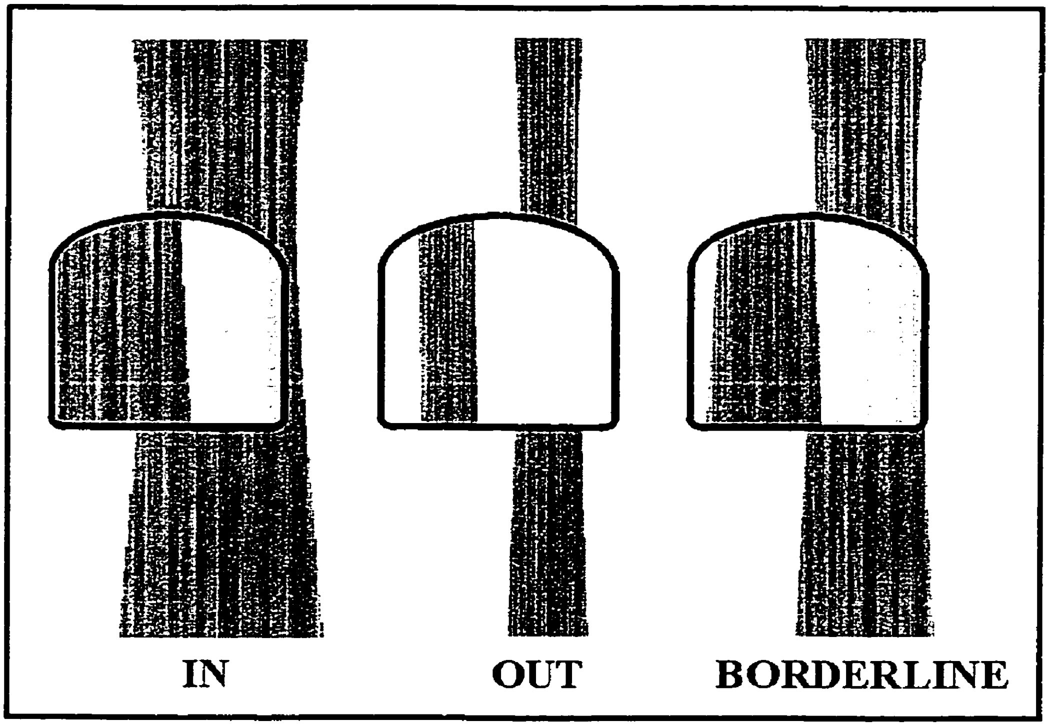

Figure 4.4 Procedure for determining if tree stems are "in", "out", or "borderline".

The basal area factor (BAF) of the prism would affect the size of the angle-gauge projection, thus influencing the number of tree stems measured. Prisms with a smaller BAF would be used to measure trees with both large and small tree diameters, while a larger BAF would only be useful for counting tree stems with large diameters. When collecting data in the NWT, Forest Development Services prefers that a minimum of 8 trees, with DBH's greater than 9.1 cm be measured in each plot (Forest Development Services 1998b). These minimum values are set to ensure that the full range of stand conditions are observed and measured. A BAF of 2 was used in this study to ensure that wide ranges of tree diameters were surveyed.

Variable radius techniques were used to identify and number each stem that fell within the plot boundary. Each tree was assigned a stem number by painting the number on the stem or by placing numbered flagging tape on each tree. Field tally sheets were completed for each plot, which were to be later input into the digital database. The species of each tree was identified and diameter at breast height (1.3 m above the ground) was recorded. When irregularities in the stem shape or form were encountered alternative measuring strategies that account for deformities were implemented, as demonstrated in Figure 4.5

Tree height was measured with a Suunto clinometer from the ground to the leader of the tree. Tree height was obtained for a sub-sample of the stems surveyed in 1998, where height was measured for one tree, for each species, at each height class (dominant/co-dominant/intermediate). The field techniques employed in 1999 differed from those used in 1998 since tree height was measured for every tree stem found within the plot boundary.

Dendrochronological analysis was performed on a sub-sample of tree stems within each plot. Stand age was determined by counting the tree rings for the leading tree species found in the dominant canopy layer. A tree core was obtained from the stem that best represented the average diameter-height relationship for the leading tree species. This core was measured and counted in the field during the 1998 field season. The 1999 field crew collected the cores and analyzed them in the lab at a later time. The age count was adjusted using age adjustment factors listed in Table 4.1, which take into account the lack of rings visible from the first few years of tree growth (Forest Development Services 1998b).

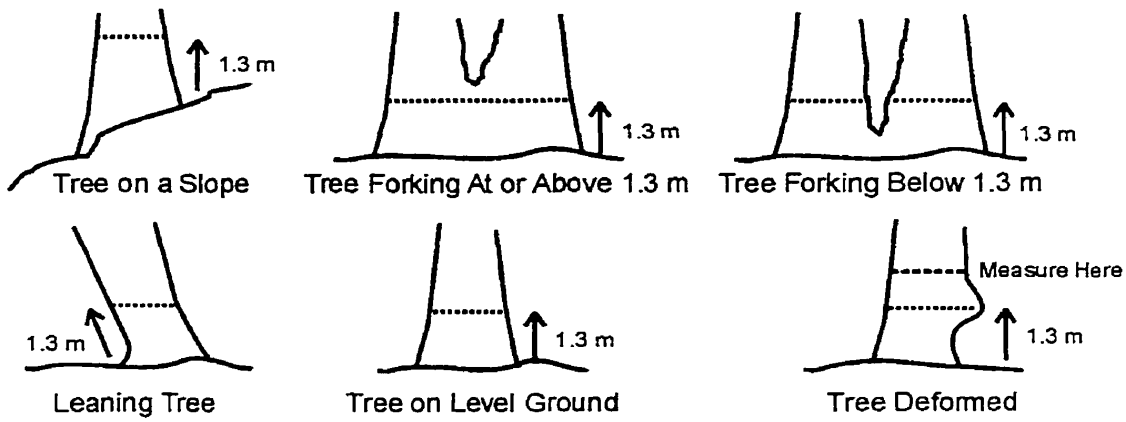

Figure 4.5 How to measure DBH on trees with irregularities in stem structure.

Table 4.1 Age adjustment factors for common NWT forest species.

Species	*Adjustment*
Deciduous (Aspen, poplar, birch)	5 years
Jack pine	10 years
White spruce	15 years
Black spruce	20 years

Methods to measure percent crown closure differed for each year. During the 1998 field season, crown closure guides were used to visually estimate crown closure into 10 percent intervals. While this qualitative method may be deemed appropriate for a typical inventory/volume cruise, this method would not provide quantitatively consistent results, since estimates will vary depending upon the individual cruiser's experience. To ensure that crown closure measurements were quantitative and consistent a different measurement method was implemented in the 1999 field survey. During the 1999 field season, crown closure was determined with the aid of a spherical densiometer. The densiometer is a concave mirror with an etched grid pattern that is used to count the percentage of land area covered by tree crowns. With this instrument, percent crown closure was measured to the nearest percentage by averaging four separate measurements that were taken at 90° intervals at the plot centre.

Stand structural information that would help describe the trees within the stand were identified, using stand definitions presently utilized by the Forest Management Division of RWED (Forest Development Services 1998b). A stand was considered to be single layered if there was minimal variation in the tree heights for all of the dominant and co-dominant species (variation in heights must have been plus or minus 3.0 metres), and there was only one distinct canopy layer (i.e. no intermediate tree species). Stands would be considered multistoried when more than one recognizable height layer (at least a 3.0 m difference) existed. Each story would consist of either different tree species or the offspring of the dominant canopy layer. It was important to distinguish between each canopy layer since only the dominant/co-dominant canopy layer was to be used in determination of each stand descriptive summary, such as average dominant/co-dominant height or diameter, total volume (m^3/ha) and stems/ha.

4.2.2 Field Plot Positioning

In order to build models that predict stand variables from remote sensing data, field plot locations needed to be accurately located on the satellite data. It was important to ensure that accuracy was high when locating the field plot vector coordinates, to allow proper querying of stand variables from the GIS data and to extract image reflectance and transformed values from the satellite data.

Typically, field plot coordinates are accurately determined using differential correction techniques and a global positioning system (GPS) receiver. GPS measurements are obtained from the center of each study plot, and directly transferred to the digital database. Application of this technology would allow one to gain positional accuracy of each plot location with less than 1 metre error. Unfortunately, differential GPS was unavailable for this research, therefore, traditional surveying techniques were implemented to determine precise plot coordinates, as demonstrated in Figure 4.6.

Field plots locations were precisely located by applying the following steps:

- Begin orientation at known ground control points (GCP's), which could be found on the air photo and in the field;
- Traversing to field plot locations using compass bearings and accurate distance measurements;
- Pinpricking each plot location on aerial photographs;
- Applying line transformation techniques to transfer pinprick locations to the hardcopy forest inventory maps by measuring the distance from the tie-in start location to the beginning of each plot transect and measuring the distance and bearing along the transect to each field;
- Digitizing field plot locations from inventory maps;
- Transferring digital (vector) coordinates to the raster satellite imagery.

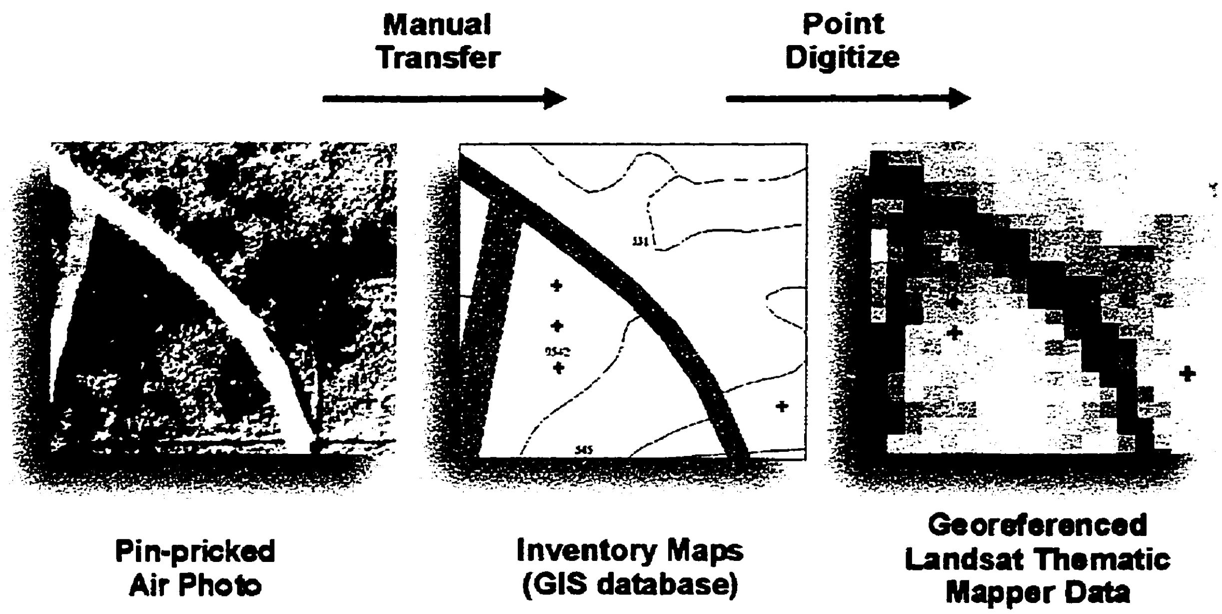

Figure 4.6 Overview of the technique used to locate field plots on the remote sensing data.

4.2.3 Tree-Height Diameter Models

Tree height was only measured for a select number of trees within each study plot during the 1998 field survey. This was problematic since tree height information was required for every stem in each plot, to calculate average height and total volume for each stand. In order to facilitate these calculations tree height-diameter models were built to predict total height for white spruce, jack pine, and combined aspen/poplar species.

All tree heights and diameters measured in 1998 and 1999 were put into one database that consisted of 2229 trees. Descriptive statistics, scatterplots, histograms and correlation coefficients were analyzed, prior to model development, to determine if extreme outliers existed in the database. It was assumed that outliers would exist, since growth conditions of trees may be altered by any combination of natural effects, such as fire, lightning or wind-throw. Furthermore, additional outliers may have resulted from measurement or recording errors. Of the original 2229 trees measured, 36 trees were identified as extreme outliers, which left 2193 stems for generating the tree height-diameter models.

Development and validation of the tree height-diameter models was undertaken using two separate data samples. It was decided that, at a minimum, at least 50% of the trees surveyed would be used in model development, while the remaining cases would be used for model validation. To ensure that at least 50% of the sample was used, it was determined that each model would be based upon a 400 tree sample. Random values were assigned to each case and sorted in ascending order. The first 400 samples were extracted for model development, while the remaining cases were reserved for validation (Table 4.2).

Table 4.2 Sample size distribution for height-diameter model development and validation.

Tree Species	*n*	% Sample for model (400 trees)	% Sample for validation (# trees)
Aspen / Poplar	795	50.3 % (400)	49.7 % (395)
Jack Pine	615	65 % (400)	35 % (215)
White Spruce	783	50.1 % (400)	49.9 % (383)

Scatter plots indicated that the relationship between tree height and diameter, for each species, did not follow a linear trend. Rather, the relationship exhibited a curvilinear "S" shape distribution. For this reason, simple linear regression models would not have been able to provide strong best-fit models. Instead, a Sigmoidal, Chapman Four Function Model, which is the recommended function for building height-diameter (Huang *et al.* 1994b), was used to build and test the relationship. The base function for this model is shown in Equation 1:

$$y = yo + a\left(1 - e^{-bx}\right)^{c} \qquad [1]$$

where y is the dependent variable, x is the independent variable, yo, a, b, and c are variables that are to be estimated, and e is the base of the natural logarithm (~ 2.71828).

To best build the tree-height diameter function Huang *et al.* (1994b) have recommended that the equation be modified by inserting a constant value for *yo*. This new function, named the "Chapman-Richards", was the function chosen for analysis in the research and is shown in Equation 2:

$$H = 1.3 + a\left(1 - e^{-bD}\right)^{c} \qquad [2]$$

where *H* is the tree height (m) to be predicted, *D* is the diameter at breast height (cm) and the variable *yo* was replaced by the value 1.3, which was used to ensure that when *D* was equal to 0, *H* would be equal to 1.3.

The strength of each derived model was assessed using the coefficient of determination (adjusted R^2) and the standard error of the estimate (SEOE). A validation sample consisting of field data not used for generation of model coefficients was used to compare predicted tree height with field-measured tree height. Descriptive statistics, Pearson's correlation coefficients and paired sample t-tests were conducted using the validation sample for each tree species.

4.2.4 Volume Calculations

The Fort Simpson region falls within the Trout Forest Management Unit (FMU) of the NWT, where volume tables have been previously developed for the dominant species used in this research. These models were developed using a limited sample size (ranging from 10 – 154 samples per species), for only large diameter tree species, therefore tree volume may not have been obtained with high accuracy for the large range of tree sizes surveyed in this study. Instead, volume equations developed for ecologically similar regions in Alberta (#3 Wetland Mixed-wood, #4 Sub-Arctic), based on a larger sample size over a large range of tree sizes, were used to calculate individual stem volume. These model forms and the techniques applied to derive them are fully described in Huang *et al.* (1994a).

4.2.5 Database Calculations and Summaries

Individual tree height, DBH and volume data were used to create plot summaries for each plot measured in this study using equations presently used by RWED Forest Development Services in their FORINV program (CSROBINS Information Technology 1998). Since variable radius plots were used in this study, equations that take into account the prism basal area factor were implemented because a prism BAF will influence the basal area of trees surveyed, thus influencing the overall circular size of each plot.

Stand basal area was calculated using all trees stems located in the dominant and co-dominant canopy layer using Equation 3:

$$BA = \sum t \times BAF \qquad [3]$$

where the total basal area (*BA*) for each plot was determined by multiplying the prism basal area factor (*BAF*) by the sum of all tree stems (*t*) surveyed. Next, stems per hectare (stems/ha) for all trees in the dominant and co-dominant layers was determined for each study plot using Equation 4:

$$st = \sum \frac{BAF}{\left(\frac{dbh}{200}\right)^2 \times pi} \qquad [4]$$

where *st* is stems/ha, *DBH* is diameter at breast height and pi is a constant for the ratio of the circumference of a circle to its diameter, with a constant value ~ 3.14. Mean height (*MH*) was calculated for each study plot by using the individual tree height data (*HT*) obtained from dominant and co-dominant species surveyed in each plot, using Equation 5:

$$MH = \frac{\sum \left(HT \times \frac{BAF}{\left(\frac{DBH}{200}\right)^2 \times pi} \right)}{stems/ha} \qquad [5]$$

The equation to develop mean diameter at breast height (*MD*) for dominant and co-dominant species was similar that for height, as shown in Equation 6:

$$MD = \frac{\sum \left(DBH \times \frac{BAF}{\left(\frac{DBH}{200}\right)^2 \times pi} \right)}{stems/ha} \qquad [6]$$

Total stand volume (*v*) (volume/ha) (m^3/ha), based on individual tree stem volume (*vol*) was determined using equation 7:

$$v = \sum \frac{(vol \times BAF)}{\left(\frac{dbh}{200}\right)^2 \times pi} \qquad [7]$$

Percent species composition was determined using the percent basal area for each species as a representative of that species total stand composition using Equation 8:

$$SC_s = 100 \times \frac{\sum t_s \times BAF}{BA} \qquad [8]$$

where percent species composition (*SC*), for species *s*, is determined by dividing the basal area for species *s*, by the total stand basal area. Finally, stand age was assigned to each plot by measuring the age of the leading tree species that was found in the dominant canopy layer. Tree age was determined by counting the number of tree rings on cores obtained at breast height from each tree. Adjustments to these age counts were taken to reflect the number of years between point of germination and 1.3 above ground (Table 4.1).

4.2.6 Field Data Selection

Prior to model development, a qualitative assessment was used to determine if the field data collected in 1998 was comparable in quality to the 1999 data. Ideally, a sub-sample of field plots measured in 1998 could have been re-surveyed in 1999 to establish if there was a significant difference between field measurements. Unfortunately, data consistency concerns were not deemed necessary until close inspection of the data flagged many 1998 data points as suspect.

Many field plots measured in 1998 were deemed suspect, due a larger variance in crown closure classes, which did not exist in the 1999 data., for example crown closure measurements obtained in the 1998 data sample were near 80%, which was never observed in 1999. Furthermore, a lower level of precision was employed when identifying the 1998 field plot locations on the aerial photographs, which thereby resulted in lower accuracy for plot placements. Based on these discrepancies only the field data collected in 1999 was used for all subsequent analyses and model development in this research.

4.3 Digital Image Processing

Preprocessing of the digital Landsat Thematic Mapper (TM) data was undertaken to prepare the database for image analysis. This subsection describes the preprocessing tasks employed in preparing the digital database.

4.3.1 Landsat TM Preprocesing

Pre-processing of the satellite remote sensing data is necessary to ensure that the data is atmospherically and geometrically correct prior to analysis. Atmospheric corrections were applied to the Landsat TM data to reduce the effect of atmospheric scattering, which were most obvious in the visible bands (blue, green and red) and convert the original radiance data, which includes energy that is emitted and reflected from the atmosphere and earth surface, to reflectance information, which is only the energy emitted and reflected from the earth's surface.

The atmospheric correction package available in PCIWORKS was used to correct the Landsat imagery. The algorithm applied used a series of correction functions that were compiled for specific atmospheres, aerosol types, zenith angles and attitudes. The algorithm applied in this correction took into account the aerosol conditions that one would find in a rural continental setting, when not influenced by urban and industrial aerosol sources. Typical ground reflectance values were compared to actual radiance values to calibrate the algorithm correction equations for each Landsat TM band. Dark lakes were used to train the correction model, since clear and dark lakes should exhibit a similar reflection pattern of low reflectance values in the visible bands (reflectance values ranging around 3 – 5 %) and almost no reflection in the infrared (values should be near 1 %). Once the training was completed the PCI algorithm determined the appropriate correction equation to apply to each band and performed a correction on each image channel. The correction process worked well in most regions of the imagery, removing much of the image haze. Some regions of the imagery, however, were covered in a thicker layer of haze that could not be completed corrected for. Observations of this remaining haze were most obvious in the visible bands, which are affected most often by various atmospheric effects.

It was necessary to covert the image radiance values to reflectance information, to allow for accurate interpretation of vegetation spectral patterns and precise calculation of vegetation indices, which is demonstrated in Figure 4.7. The pattern evident in the raw spectral curve did not accurately represent the true response pattern of vegetation. Blue reflectance (TM band 1) was misrepresented, as it was much higher than reflectance in either green or red bands. Image corrections reduced the effects of haze, thereby blue reflectance was reduced, and the green band (TM band 2) became higher than the both blue and red (TM 3) bands. Green reflectance was higher, since chlorophyll contained in healthy leaves absorbed more blue and red energy, while reflecting more green energy, thus causing vegetation to appear green to the human viewer. Conversion of the raw data to percent reflectance also permitted the infrared wavelength data (TM bands 4, 5, and 6) data to best fit the typical reflectance curve for vegetation.

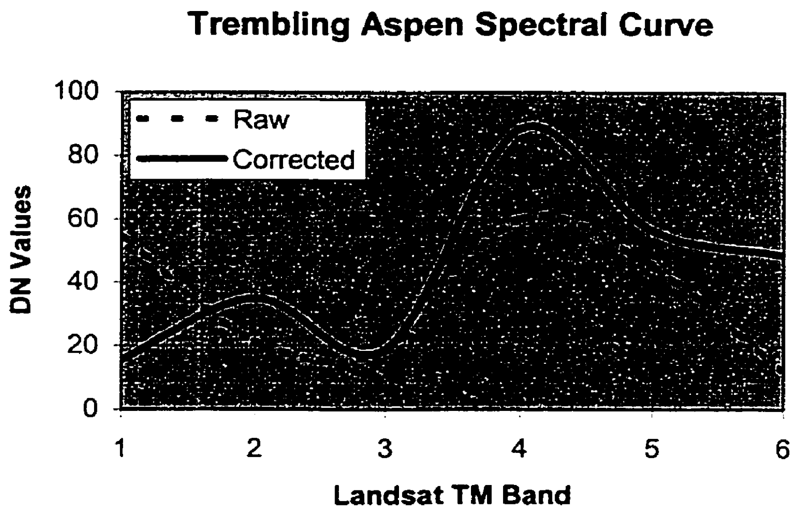

Figure 4.7 Spectral reflectance pattern of trembling aspen prior to and following atmospheric correction and conversion to absolute reflectance.

Landsat data was geometrically corrected using PCI software. Over 60 ground control points (GCP's) were identified from the GIS data in various locations scattered throughout the study region. GCP's were selected from road, seismic line and water line features and forest inventory polygons. Road and seismic line data were the preferred data source for choosing GCP's, since these features are static and easy to identify on the imagery. In the sparsely populated NWT, however, these types of features were difficult to locate, due to the lack of identifiable controls points that could be identified throughout the study area. For this reason water line features and forest inventory polygons were used to determine additional GCP's.

Difficulties were encountered when geometrically correcting the northwest portion of the study region since the basemaps for this region, were created in the early 1970's. Therefore, many of the human made features, such as the Wrigley highway, had not been constructed yet, and were therefore not mapped. This would have led to difficulties when identifying precise control points when geometrically fitting the GIS inventory data. Therefore, the northwest region of the GIS database was slightly skewed, thereby leading to a misrepresentation of GIS polygons, and thus decreasing the potential precision for the Landsat TM geometric correction. Elimination of this problem will not be possible until basemaps have been updated, using more precise geometric control points and land features. This problem may also be eliminated by collecting GCP's using wide area GPS, since the precision of GPS points should be strong now that the US government has turned off the selective ability feature for collecting GPS point locations.

A first order polynomial transformation model was used assign geographic and UTM coordinates to the Landsat data. A first order model was chosen to geometrically rectify the data since this model form is simple, which thereby permits efficient computation time when correcting the imagery, and reduces the chance of image distortion in regions where GCP's could not be identified. During image rectification a resampling algorithm is used to extract and interpolate the DN values from the original, uncorrected image to the new, corrected image. The algorithm chosen for resampling for was the nearest neighbour (NN) interpolator. NN interpolation determines the grey level form the closest pixel to the specified input coordinates, assigning that value to the output coordinate. This method was chosen for its efficiency in computation time, since it does not alter the grey level values through any mathematical operations. The NN technique is the preferred resampling method when image classifications or image models will be derived following image rectification, even though this process introduces small error in the registered image, since pixels may be offset from the rotation change giving the image a blocky or jagged appearance.

The average residual error resulting from the first order polygon transformation was less than 1 pixel (30 m) in size, despite the overall difficulties in locating accurate control points.

4.3.2 Vegetation Indices and Landsat TM Tasseled Cap Transformation

Ancillary digital information may be used to increase the amount and variety of data supplied to classifiers, or to regression models to increase the overall accuracy of image classifications and level of accuracy that may be achieved by regression models (Hutchinson 1982; Stehman 1996). Mathematical and statistical operations performed on the remote sensing imagery may be used to derive new ancillary variables from the original spectral values, such as the creation of vegetation indices and band transformations.

Vegetation indices and band transformations are often utilized as ancillary data sources because Landsat TM bands alone do not always provide strong levels of distinctive information. This lack of distinction occurs when the variance between bands is low, which occurs since many of the visible or infrared wavelengths are often highly correlated with each other, or when bands exhibit weak ranges of reflectance DN values. When this occurs the data may not be sufficient for distinguishing among various landcover classes. Vegetation indices and spectral transformations may be used to increase the information content provided by the remote sensing data and improve the distinction between landcover classes. Three vegetation indices and three band transformations were utilized in this study to determine if they would help build stronger models to predict the various forest mensurational variables.

4.3.2.1 Vegetation Indices

Vegetation indices were tested since they are commonly used to provide additional information on the spectral properties of vegetation communities. Band transformations were also tested, since they are used to compress a large portion of the variance among bands into one channel of data.

The first vegetation index applied, which is also the most commonly used ratio in remote sensing analysis, was the Normalized Difference Vegetation Index (NDVI) (Rouse *et al.* 1974, as cited in Chen 1996). This index is computed using Equation 9:

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad [9]$$

where *NIR* is the near infrared band (Landsat TM band 4) and *RED* is the red band (Landsat TM band 3). The range of NDVI values will vary from –1 to 1, where high (positive) values would indicate dense vegetation; a high infrared reflectance and low red reflectance (due to absorption of red light by chlorophyll pigments). Low (negative) NDVI values could indicate sparse vegetation or non-vegetated land surfaces (high red and infrared reflectance, such as bare soil, or low red and infrared reflectance by water).

The next two vegetation indices applied in this research were infrared indices. These indices were chosen since various vegetation studies have demonstrated that infrared bands contain a larger range of spectral information than visible bands do when studying vegetation components, which thereby allows greater information to be provided to the subsequent models (De Wulf *et al.* 1990; Franklin and McDermid 1993). This first infrared model analyzed was the Structural Index (SI), which was first termed by Fiorella and Ripple (1993). The formula used to compute this index is shown in Equation 10:

$$SI = \frac{NIR}{MIR} \qquad [10]$$

where *MIR* is the middle infrared band (Landsat TM 5). The authors discovered that this ratio was an excellent predictor of stand age in Douglas-fir forests, and was highly affected by changes in stand structure. The second infrared index was computed using Equation 11:

$$\text{IR indices} = \frac{NIR}{FIR} \qquad [11]$$

where *FIR* is the far infrared band (Landsat TM 7), which has also been shown to be highly correlated with stand variables.

4.3.2.2 Landsat TM Tasseled Cap Transformation

The band transformations used in this study were the Landsat TM tasseled cap transformations for *brightness*, *wetness*, and *greenness*. These transformations are used to compress the data available from the 6 primary TM bands of analysis into 3 new channels of data. This compression of data is useful since the dimensionality of the TM data is quite often less than the total number of bands (Crist and Cicone 1984).

Brightness (BR) was determined by multiplying each TM band by a positive constant value, and adding a vector additive term, which is used to keep the derived values consistent with those that would be obtained using the Landsat-4 TM sensor, as shown in Equation 12:

$$\begin{aligned} BR = {} & 10.3695 + (0.2909 \times TM1) + (0.2493 \times TM2) + (0.4806 \times TM3) + \\ & (0.5568 \times TM4) + (0.4438 \times TM5) + (0.1706 \times TM7) \end{aligned} \qquad \text{(Crist } et\ al. \text{ 1986)} \qquad [\,12\,]$$

where *TM1* is TM band 1 (green), *TM2* is TM band 2 (blue), *TM3* is TM band 3 (red), *TM4* is TM band 4 (infrared), *TM5* is TM band 5 (mid-infrared) and *TM7* is TM band 7 (far-infrared). As demonstrated by Equation 12, brightness is the weighted sum of all six TM reflectance bands. Greenness (GR) is a different measure, which shows how much contrast there is between the near-infrared and the three visible brands, as shown by Equation 13:

$$\begin{aligned} GR = {} & -0.7310 + (-0.2728 \times TM1) + (-0.2174 \times TM2) + (-0.5508 \times TM3) + \\ & (0.7221 \times TM4) + (0.0733 \times TM5) + (-0.1648 \times TM7) \end{aligned} \qquad \text{(Crist } et\ al. \text{ 1986)} \qquad [\,13\,]$$

The last transformation is wetness (WET), which is the contrast between the mid-infrared and other four bands, is described in Equation 14:

$$\begin{aligned} WET = {} & -3.3828 + (0.1446 \times TM1) + (0.1761 \times TM2) + (0.3322 \times TM3) + \\ & (0.3396 \times TM4) + (-0.6210 \times TM5) + (-0.4186 \times TM7) \end{aligned} \qquad \text{(Crist } et\ al. \text{ 1986)} \qquad [\,14\,]$$

In a forestry context, Crist *et al.* (1986) have found the wetness transformation to be related to stand structure, as wetness values increase when structural complexity and shadowing effects increase. This occurs since shadowed areas will receive more illumination in the visible and near-infrared bands than in the mid-infrared, which would result in higher wetness values.

Tasseled Cap transformations were applied in this research, since past work has demonstrated the ability to relate various forest mensurational variables to tasseled cap transformations (Cohen and Spies 1992; Cohen *et al.* 1995; Deuling *et al.* 2000). For example, Cohen and Spies (1992) found that wetness values were highly related to the height and age of closed-canopy Douglas fir and western hemlock stands, with correlation coefficients varying from –0.85 to –0.9. Opposite relationships were observed by Deuling (2000) when investigating the relationship between wetness values and stand variables. Positive relationships were generally observed, in open canopy forest stands, between wetness values and stand variables, such as age or height (R values of 0.77 and 0.63, respectively). These studies are strong examples that support the use of Tasseled cap transformations in prediction of stand variables, while highlighting the emphasis on the empirical nature of stand modeling studies, since study results are always empirical to the local forest type, for the season and data the imagery was acquired.

4.3.3 Reflectance / Transformation DN Value Extraction

Once the entire image database preprocessing steps were completed, reflectance/transformed DN values were extracted for each study plot. The PCIWORKS XPACE task *vsample* was used to extract the values for each vector point, which represented individual study plots, by writing the reflectance/transformed value for each pixel, that fell under the vector points, into a text file. The text file was imported into Microsoft Excel and was sorted by the GIS photo-interpreted species composition for each field plot, to facilitate future analyses by each individual species group (pure pine, spruce, aspen and mixed-wood stands).

4.4 Statistical Analysis

White spruce, jack pine, and combined aspen/poplar stands differ from one another for many reasons, such as growth patterns and structure. For this reason it was important to perform separate analyses and build separate models for each species type. This section describes the steps taken to build continuous variable models for each species type.

4.4.1 Descriptive Statistics

Prior to model development, descriptive statistics were calculated for the pure white spruce, jack pine and trembling aspen/balsam poplar stands. Statistics applied included mean, minimum, maximum, and range, and where determined for each stand variable, including average height, percent crown closure, dominant age and total volume (m^3/ha). This basic statistical analysis is required for determining if any extreme outliers exist in the database and to verify that a sufficient range of forest variables were surveyed that would ensure that strong statistical models could be created.

4.4.2 Establishing Relationships

Prior to model development it was important to further explore all of the datasets, to better understand how stand variables are related to image reflectance and transformed values. Therefore, Pearson's product moment correlation analysis was used to determine what relationships existed between:

a. **Stand variables**: including stand height, age, crown closure, volume, stems/ha and basal area;
b. **Image extracted values**: including all 6 Landsat TM bands, vegetation indices and Landsat TM Tasseled Cap transformations; and
c. **Stand variables and image extracted variables:** which included the stand variables stand height, age, crown closure and volume, and image

extracted values from all 6 Landsat TM band, 3 vegetation indices and Tasseled Cap transformations.

All correlation values that were significant at the 95% confidence interval ($p < 0.05$) were flagged with an asterisk (*). Scatterplots were generated to further visualize the most significant relationships, which helped determine if the relationship between the two variables were linear and provide a further understanding on the variability inherent in each relationship.

4.4.3 Model Development

Multiple linear regression analysis, using a backwards-variable selection procedure, was employed to predict stand variables from image reflectance and transformed values. All significantly correlated variables, at the 95% confidence interval, were initially input to the regression model. The backwards-variable selection procedure was used to sequentially remove variables that did not meet selection criteria. The variable that demonstrated the smallest partial correlation with the dependent variable was considered first for removal. If it met the elimination criteria, it was removed. Then the next variable remaining in the equation with the smallest partial correlation was considered next. This procedure continued until there were no variables left in the equation that satisfied removal criteria. The criterion used was the probability of the F-ratio. If the probability value exceeded 0.10, the variable was removed. This probability value was chosen, as it is the default value, and thus the most commonly applied value in backwards regression model (SPSS Base 9.0 Applications Guide 1990)

Model strength was determined through the adjusted r-square, shown in Equation 15:

$$r^2_{ADJ} = 1 - \frac{(n-1)(1-r^2)}{n-p} \qquad [\ 15\ ]$$

where n is the number of observations, p is the number of terms of the created model (with $p - 1$ independent variables) and r^2 is the determination coefficient. The root mean square error was also calculated with each model, to aid in further interpretation of the model strength and assessment of its potential significance in operational applications. Further, overall model significance and residuals plots were used in assessing the strength and performance of each regression model.

5.0 Results and Analysis

The results obtained through processing of the field data, data exploration and statistical analysis to build and validate forest variables models are presented and briefly analyzed in this chapter. A detailed discussion of the results and analysis follows, which feed into the final conclusions and recommendations, presented in the final chapter.

5.1 Data Preprocessing

Results obtained from the pre-processing and summarizing of field data are provided in this subsection, followed by a summary of the statistical characteristics, by species, of the resulting field database.

5.1.1 Tree Height-Diameter Measurements

Height-diameter models for all species were statistically significant with adjusted R^2 values that ranged from 0.76 for jack pine to 0.81 for white spruce (Table 5.1). The range of standard error varied from 1.92 m to 2.49 m among the species, where the smallest standard error was in jack pine stands and the largest overall standard error was in trembling aspen stands.

Table 5.2 presents the derived model coefficients for each species height-diameter model. The model coefficients for a, b, and c were statistically significant for each species, indicating that the coefficients may be reasonable for predicting stand height.

Table 5.1 Height-Diameter model development summary statistics.

Species	Model Development Sample	
	Adjusted R^2	*Standard Error*
Jack Pine	0.759*	1.92 m
White Spruce	0.81*	2.39 m
Trembling Aspen	0.796*	2.49 m

*** Statistically significant at p=0.05**

Scatter plots for each tree species and their associated line of best fit are shown in Figures 5.1 through 5.3. The slope of the curve is indicative of the rate of growth as young trees grow faster and this is illustrated by a steeper slope. The shapes of the curve are also curvilinear since the growth rate for all species will decrease with age as trees mature. There was increasing scatter with increasing tree height and DBH. As trees mature, growth appears to be more variable that may be explained, in part, by the many factors that influence growth such as tree health, site moisture, soil nutrients, competition, and micro-topography. Therefore, it may be inferred that the strength of each predicted height would weaken as the DBH increases.

Table 5.2 Model coefficients determined from height-diameter models.

Species	*n*		*Coefficient*	*Std. Error*	*t*	*P*
Jack Pine	400	a	19.4694*	0.4531	42.9713	0.0001
	400	b	0.1059*	0.0121	8.7368	0.0001
	400	c	1.4087*	0.1732	8.1323	0.0001
White Spruce	400	a	27.1242*	1.6116	16.8311	0.0001
	400	b	0.0551*	0.0087	6.3286	0.0001
	400	c	1.3788*	0.1458	9.4542	0.0001
Aspen	400	a	27.8865*	2.0352	13.7022	0.0001
	400	b	0.0515*	0.0109	4.7279	0.0001
	400	c	0.9905*	0.1057	9.3753	0.0001

*** Statistically significant at p=0.05**

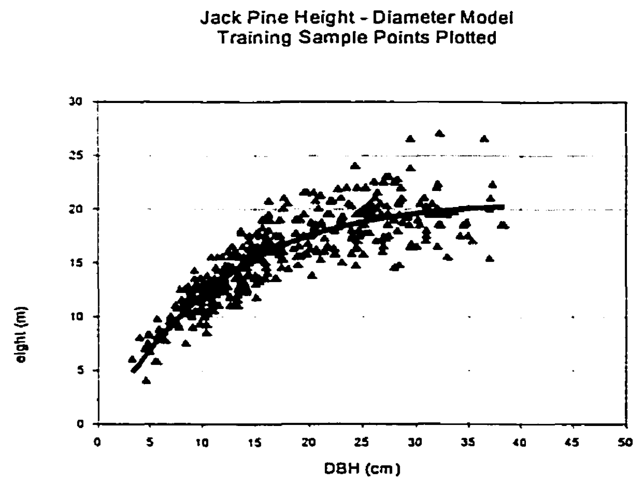

Figure 5.1 Jack pine height-diameter scatterplot and line of best fit.

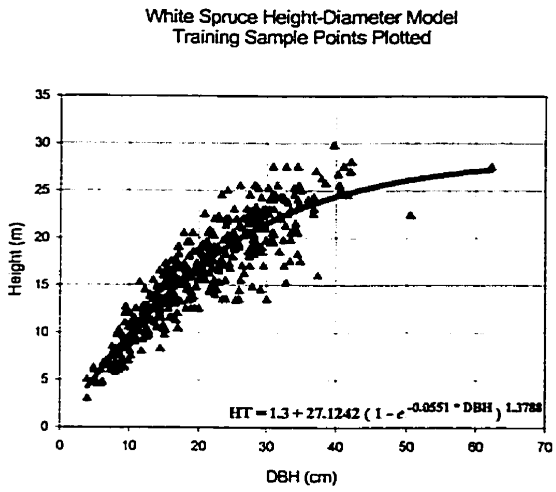

Figure 5.2 White spruce height-diameter scatterplot and line of best fit.

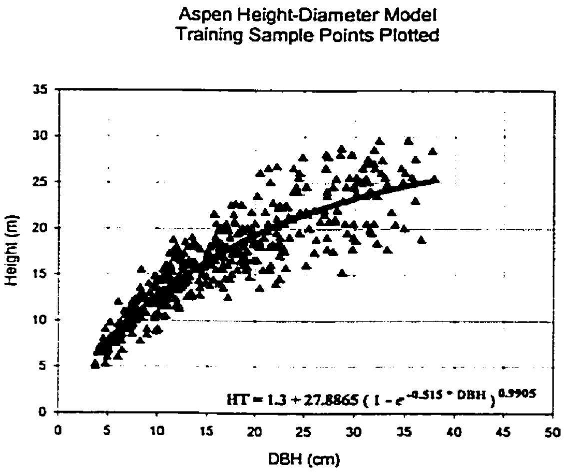

Figure 5.3 Trembling aspen height-diameter scatterplot and line of best fit.

Validation of height-diameter models for each species was accomplished by comparing the predicted heights with actual field heights in the validation sample. Average field-measured and predicted heights were very similar for each species, and predicted values were less variable (Table 5.3).

Table 5.3 Descriptive statistics from validation sample field measured and model predicted height.

Species	*Height Source*	*Mean*	*N*	*Std. Deviation*	*Std. Error Mean*
Pine	Field Height (m)	16.22	215	3.95	0.27
	Predicted Height (m)	16.1	215	3.34	0.23
Spruce	Field Height (m)	16.36	383	5.73	0.29
	Predicted Height (m)	16.24	383	5.03	0.26
Aspen	Field Height (m)	16.22	395	5.12	0.26
	Predicted Height (m)	16.15	395	4.45	0.22

Field measured and model predicted heights were highly correlated and similar for all tree species. The highest correlation coefficient was with white spruce ($R = 0.89$, $p = 0.0001$), and both jack pine and trembling aspen were identical ($R = 0.88$, $p = 0.0001$).

The differences in mean tree heights were small and ranged from 0.07 m for trembling aspen, to 0.12 m, for white spruce and jack pine (Table 5.4). The standard error of the mean suggests the variability of tree height estimation was similar across all species using the developed height-diameter models. Finally, the two-tailed significance results demonstrated that there were no statistical differences between field-measured and predicted tree heights across all species.

Table 5.4 Results provided by paired sample t-tests to determine is a significant difference exists between mean field measured and model calculated tree height.

	N	*Mean*	*Std. Deviation*	*Std. Error Mean*	*Sig. (2-tailed)*
Spruce	215	0.12	2.56	0.13	0.368
Pine	383	0.12	1.90	0.13	0.343
Aspen	395	0.07	2.46	0.12	0.549

5.1.2 Database Calculations and Summaries

Field plot summaries determined for white spruce, jack pine, trembling aspen and mixed-wood stands are shown in Appendix A in the form of four separate tables, organized by species group. Field plot identification codes beginning with the letter ***G*** represent plots that were collected by the 1999 field team, while plots beginning with the letter ***H*** represent data collected by the 1998 field crews from the Hay River Forest Development Office. Note that the 1998 data are included for reference and were not used for the development of any stand variable models.

All spectral reflectance, vegetation index and Tasseled Cap transformation values, as well as photo interpreted GIS data for crown closure, age and height, were extracted from the digital image database and are presented in Appendix B. Four tables are provided, summarizing all of the image data for jack pine, white spruce, trembling aspen and mixed-wood stands.

5.2 Statistical Data Analysis

Prior to model development and validation, relationships between stand variables and image spectral response were determined for each individual species group.

5.2.1 Exploring Field Data

Descriptive statistics were calculated for each stand variable, and species grouping to describe the sample of trees that were surveyed. In jack pine stands, the range of mean height measured varied from 9 m to 20 m, while an overall mean height of 14.7 m was surveyed (Table 5.5). A large range of age groups was sampled, varying from 21 to 169 years old. Within this sample a small range of percent crown closure and total stand volume (m^3/ha) were surveyed, with a total crown closure range of 32% and volume series of 163 m^3/ha.

Table 5.5 Jack pine descriptive statistics for 1999 field plots.

	N	*Range*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
VOL (m^3/ha)	25	163.2	94.0	257.2	161.6	43.3
CC (%)	25	31.9	21.1	53.0	35.4	8.1
HT (m)	25	11.3	8.9	20.2	14.7	3.4
AGE (yrs)	25	148.0	21.0	169.0	66.9	37.0
DBH (cm)	25	19.6	7.2	26.9	14.6	5.6
STEMS (#/ha)	25	5677.0	340.0	6017.0	2187.2	1651.0
BA (m^2/ha)	25	28.0	12.0	40.0	24.7	5.8

The range of forest conditions surveyed in the white spruce stands varied from jack pine, since minimum and maximum values were, generally, much higher (Table 5.6). Mean stand height varied from 10 m to 24.3 m. The range of stand age was similar to jack pine (149 years old), however the maximum stand age of 198 indicated that more mature spruce stands were surveyed, which could be expected since white spruce, being a secondary species, generally outlives the pioneer jack pine species. A large group of crown closure classes were surveyed, representing a large range of stand conditions, with closures varying between 12% and 52%. The wide range of total stand volume surveyed (283 m^3/ha) and the high standard deviation (65 m^3/ha) associated with this range of volume indicated that a large group of spruce stands, with variable volumes, were surveyed.

Table 5.6 Descriptive statistics from 1999 white spruce field plots.

	N	*Range*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
VOL (m^3/ha)	32	282.9	31.9	314.8	153.0	65.3
CC (%)	32	39.3	12.2	51.5	33.6	10.4
HT (m)	32	14.4	9.9	24.3	18.4	4.4
AGE (yrs)	30	149.0	49.0	198.0	116.0	37.9
DBH (cm)	32	21.3	11.2	32.5	21.8	6.2
STEMS (#/ha)	32	2913.0	187.0	3100.0	691.0	696.5
BA (m^2/ha)	32	26.0	6.0	32.0	19.6	7.3

Descriptive statistics calculated for the 28 trembling aspen stands are shown in Table 5.7. Results presented in this table indicate that the largest range of mean stand height was surveyed in the aspen stands, where mean height varied from 7.8 m to 26.0 m tall. The range of age classes surveyed was slightly lower than the softwood stands, with a decrease in the overall range by 8 to 9 years. The largest maximum crown closure measured in this study was observed in the aspen stands (maximum crown closure of 64%), while the range of crown closure values remained consistent to the ranges presented by pine and spruce stands (near 37 %), indicating that aspen stand canopies were generally more closed than the other species stands. Finally, a large range of total stand volume was surveyed, where volume measures varying from 56 to 262 m^3/ha, which could be expected in stands with large ranges of average heights.

Table 5.7 Trembling aspen 1999 field plot descriptive statistics.

	N	*Range*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
VOL (m^3/ha)	28	205.6	56.4	262.1	134.6	55.7
CC (%)	28	37.2	26.5	63.7	42.5	8.9
HT (m)	28	18.2	7.8	26.0	15.6	5.1
AGE (yrs)	28	140.0	37.0	177.0	90.2	35.3
DBH (cm)	28	24.6	5.6	30.2	14.4	7.3
STEMS (#/ha)	28	7610.0	166.0	7776.0	2117.6	1723.9
BA (m^2/ha)	28	24.0	12.0	36.0	19.8	6.0

Table 5.8 shows the descriptive statistics obtained for mixed-wood stands. Since a wide range of stands, with varying species compositions, was surveyed it would have been expected to find the large range of mean stand height (17.8 to 25.7 m) and age (range of 149 years). The range of percent crown closure and total volume were also large (37% and 205 m^3/ha), but, more noticeably was the high standard deviations for these two groups (10.7% and 71.8 m^3/ha, respectively), which could be interpreted as a result of the mixed species groups and varying successional stages found in the mixed-wood stands

Table 5.8 Mixed-wood 1999 field plot descriptive statistics.

	N	*Range*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
VOL (m^3/ha)	21	232.8	41.1	273.9	154.9	71.8
CC (%)	21	33.5	25.5	59.0	42.8	10.7
HT (m)	21	17.8	8.0	25.7	18.0	4.9
AGE (yrs)	19	149.0	26.0	175.0	101.1	46.0
DBH (cm)	21	24.7	5.4	30.1	21.1	6.9
STEMS (#/ha)	21	8152.0	108.0	8260.0	1113.6	1873.9
BA (m^2/ha)	21	26.0	6.0	32.0	20.0	7.3

Pearson product moment correlation analysis was used to establish the relationship between stand variables in white spruce, jack pine, trembling aspen and mixed-wood stands, and results of these analyses are presented in Tables 5.9 through 5.12

Relationships among jack pine stand variables are shown in Table 5.9. Mean stand height was positively correlated with stand age (0.82, $p = 0.0001$) and mean DBH (0.93, $p = 0.0001$), while negative relationships were observed between height and total stems/ha (-0.88, $p = 0.0001$) and percent crown closure (-0.73, $p = 0.0001$). The relationships demonstrated with stand age were similar to height, where a positive correlation was observed with DBH (0.76, $p = 0.0001$), and negative relationships were found with stems/ha and crown closure (-0.66 and –0.6, and $p = 0.0001$ and 0.002, respectively). The strong interrelationships between jack pine stand variables was not surprising since jack pine is a pioneer species, which exhibits a consistent trend in stand structural changes as the stand matures. The relationship between total stand volume and height was weak, but significant (0.41, $p = 0.042$), and no relationship was found between volume and mean DBH, which was not expected since these two variables were used to calculate total volume. The only strong and significant relationship for jack pine stand volume was with total stand basal area (m^2/ha), with a correlation coefficient of 0.74, $p = 0.0001$. This relationship was expected since total basal area measured in a variable radius plot is partially related to, and can be used to, calculate the total volume of a stand (Dilworth and Bell 1975).

Table 5.9 Correlation coefficients between jack pine stand variables.

	VOL (m^3/ha)		*CC (%)*		*HT (m)*		*AGE (yr)*		*DBH (cm)*		*STEMS/HA*	
	R	Sig	R	Sig	R	Sig	R	Sig	R	Sig	R	Sig
CC (%)	-0.13	0.520										
HT (m)	0.41*	0.042	-0.73*	0.000								
AGE (yr)	0.34	0.100	-0.60*	0.002	0.82*	0.000						
DBH (cm)	0.30	0.148	-0.82*	0.000	0.93*	0.000	0.76*	0.000				
STEMS/HA	-0.15	0.480	0.74*	0.000	-0.88*	0.000	-0.66*	0.000	-0.85*	0.000		
BA (m^2/ha)	0.74*	0.000	0.37	0.069	-0.30	0.148	-0.24	0.245	-0.34	0.099	0.52*	0.008

*** Statistically significant at $p=0.05$**

White spruce correlation coefficients from field data are presented in Table 5.10. The relationship between white spruce stand height and DBH was similar to that observed with jack pine, with a strong positive correlation coefficient of 0.94, $p = 0.0001$. The relationships between spruce height and both DBH and stems/ha exhibited the same relationship directions, when compared to jack pine, but the strength of their relationships were lower with R values of 0.59, $p = 0.001$ and –0.62, $p = 0.0001$, respectively. The relationship between age and stand variables were also weaker for white spruce stands, where a weak positive relationship for age and DBH ($R = 0.62$, $p = 0.0001$) and weak negative relationships were observed between age and both crown closure and stems/ha (R values of -0.38 and –0.52, and p values of 0.04 and 0.003, respectively). The significant, but weak, relationship between age and crown closure was the only significant association observed for crown closure and stand variables. One interpretation of this relationship is that spruce crown closure, unlike pine, is a stand variable that is not highly related to changes in stand maturity (successional development).

A further ecological interpretation of these weaker relationships in white spruce stands may be that the successional paths taken by each stand differ, which would thereby facilitate a unique growth trend characteristic for each spruce stand. The different forms of spruce recruitment and competition that have taken place within each stand would have affected the present growth and stems density patterns. These factors would therefore weaken most relationships between stand variables, since no single direct trend could be observed.

The association between total stand volume and other stand variables differed for white spruce, when compared to jack pine, since there was a strong association observed between volume and both height and basal area (R values of 0.61 and 0.87, with p values of 0.0001 and 0.0001, respectively). Also a significant relationship was observed between volume and DBH (R = 0.48, p = 0.006), which was not observed with the pine stands. This was expected since height and DBH were used to calculate volume and, as mentioned in the jack pine section, basal area is related to volume. There was no relationship between age and volume, however, since tree size appeared to vary greatly among the stands, for any given age class. Again, a plausible explanation may be found in considering the wider range of successional pathways and level of competition experienced by each spruce stand.

Table 5.10 Correlation coefficients between white spruce field variables.

	VOL (m^3/ha)		*CC (%)*		*HT (m)*		*AGE (yr)*		*DBH (cm)*		*STEMS/HA*	
	R	*Sig*	*R*	*Sig*	*R*	*Sig*	*R*	*Sig*	*R*	*Sig*	*R*	*Sig*
CC (%)	-0.07	0.710										
HT (m)	0.61*	0.000	-0.16	0.386								
AGE (yr)	0.33	0.074	-0.38*	0.040	0.59*	0.001						
DBH (cm)	0.48*	0.006	-0.23	0.210	0.94*	0.000	0.62*	0.000				
STEMS/HA	0.06	0.764	0.01	0.939	-0.62*	0.000	-0.52*	0.003	-0.71*	0.000		
BA (m^2/ha)	0.87*	0.000	-0.04	0.825	0.18	0.312	0.05	0.788*	0.05	0.791	0.52*	0.002

*** Statistically significant at p=0.05**

The correlation coefficients determined for aspen stand variables are shown in Table 5.11. As with jack pine, strong positive relationships were observed between mean aspen height and both stand age and mean DBH, where R-values were 0.8 and 0.95, and p values of 0.0001 and 0.0001, respectively, and a strong negative association was established between height and stems/ha, with an R-value of -0.83, p = 0.0001. A strong positive association between stand age and DBH (R = 0.82, p = 0.0001) and a negative relationship with age and stems/ha (R = -0.66, p = 0.0001) was observed, while no relationship was found between age and crown closure. These correlation coefficients indicated that aspen tree diameter increased and stems/ha decreased as stands matured. Crown closure, however, does not change with age, perhaps signifying that the closure of an aspen stand canopy is not directly related to the successional development of aspen stands. In fact, unlike jack pine, there were no observed associations between crown closure and any stand variable, indicating that factors other than those studied would influence the closure of a stand.

Correlation analysis of total volume and aspen stand variables provided differing results from those presented with pine and spruce stands. As with the softwood species, a positive relationship was observed between aspen total volume and both average height and basal area, with correlation coefficients of 0.62 and 0.74 and p values of 0.0001 and 0.0001, respectively. As with the conifer species, this relationship was expected since height is used to calculate stem volume and basal area is related to volume. Another trend that aspen shared with the softwood species was the lack of association between stems/ha and volume, demonstrating that, in this sample of stands, a change in a stands stems/ha (naturally provoked) would not directly affect the total wood volume.

The relationship between aspen volume and age was different from that observed for the softwood species since a positive relationship was observed (R = 0.54, p = 0.003), revealing that stem volume increased with age for aspen. This was expected since the mature aspen stands sampled typically exhibited greater woody bulk than younger stands did. A trend similar to jack pine was observed between total volume and average DBH, where no significant association could be established. As with the pine results, this was surprising since DBH is used to calculate individual stem volume. The explanation for this lack of relationship may lie in better understanding the ecology of the aspen and pine stands, discussed more fully in the following chapter. However, it is important to note that this research is concerned primarily with the remote sensing relationships, and a detailed ecological investigation of stand development and growth is beyond the scope of the present research objectives.

Table 5.11 Correlation coefficients between aspen stand variables.

	VOL (m^3/ha)		*CC (%)*		*HT (m)*		*AGE (yr)*		*DBH (cm)*		*STEMS/HA*	
	R	Sig	R	Sig	R	Sig	R	Sig	R	Sig	R	Sig
CC (%)	0.25	0.209										
HT (m)	0.62*	0.000	0.35	0.069								
AGE (yr)	0.54*	0.003	0.26	0.186	0.80*	0.000						
DBH (cm)	0.45	0.015	0.35	0.064	0.95*	0.000	0.82*	0.000				
STEMS/HA	-0.39	0.039	-0.15	0.452	-0.83*	0.000	-0.66*	0.000	-0.79*	0.000		
BA (m^2/ha)	0.74*	0.000	0.06	0.754	-0.03	0.860	0.06	0.753	-0.17	0.397	0.21	0.279

*** Statistically significant at p=0.05**

The correlation coefficients obtained from mixed-wood stand variables are shown in Table 5.12. Like all other species, a negative relationship was observed between height and stems/ha and strong positive relationships were established between stand height and both age and DBH. The trends evident in the remaining correlations among stand variables are all similar to those observed with aspen stands. No relationship was observed between crown closure and the other stand variables, which could be a result of the mixed species compositions in these stands, thereby confusing the observed relationship. The relationship between stand volume and height, age and basal area were all positive, while the association between volume and stems/ha was negative, which again followed the same trends presented by the aspen stands. It may be interpreted that these relationships were similar to those presented in the aspen stands since aspen contributes a dominant influence to a little over half of the mixed-wood study plots, with aspen composition contributing to at least 50% of the species composition.

Table 5.12 Correlation coefficients between mixed-wood stand variables.

	VOL (m^3/ha)		*CC (%)*		*HT (m)*		*AGE (yr)*		*DBH (cm)*		*STEMS/HA*	
	R	Sig	R	Sig	R	Sig	R	Sig	R	Sig	R	Sig
CC (%)	0.30	0.193										
HT (m)	0.64*	0.002	0.11	0.636								
AGE (yr)	0.67*	0.002	0.16	0.505	0.87*	0.000						
DBH (cm)	0.39	0.079	-0.10	0.676	0.86*	0.000	0.66*	0.002				
STEMS/HA	-0.27	0.239	0.34	0.129	-0.68*	0.001	-0.54*	0.018	-0.78*	0.000		
BA (m^2/ha)	0.86*	0.000	0.29	0.203	0.19	0.412	0.28	0.254	-0.03	0.909	0.09	0.698

*** Statistically significant at p=0.05**

5.2.2 Exploring Image Data

Descriptive statistics were calculated for each image channel for every species group (Jack pine, white spruce, aspen and mixed-wood stands) and are included, for reference, in Appendix C.

The largest range of reflectance DN values was found in the Landsat TM infrared bands, when compared to the visible band (Appendix C). The largest range of values was consistently observed in the near infrared band (NIR) (TM band 4) for all species, with value ranges varying from 50 to 75, which provided the greatest separation among the mean reflectance values for the four species groups (Figure 5.4). Aspen had the highest mean reflectance DN value (113), while mean reflectance decreased incrementally for mixedwood, pine and spruce stands, respectively. The average standard deviations for

NIR reflectance DN's were near 14, therefore, there would have been some overlap in mean reflectance for two species groups: aspen/mixed-wood and pine/spruce; however, distinction would be possible amongst the two groups. Figure 5.4 also reveals that the other two infrared bands (TM 5 and TM 7) demonstrated a greater separation between their mean reflectance DN values than the visible bands (TM bands 1, 2 and 3).

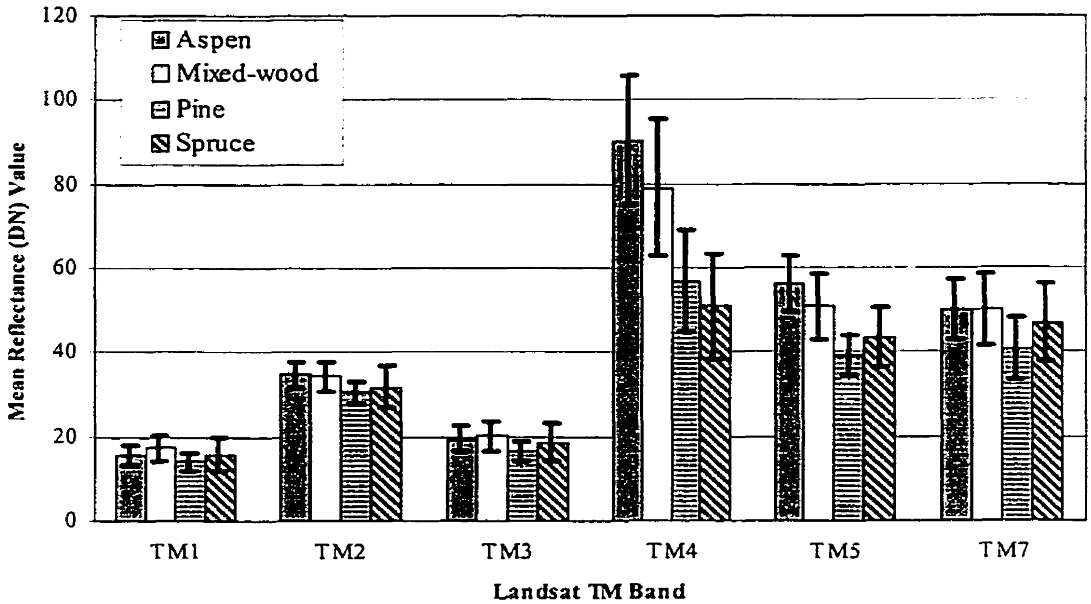

Figure 5.4 Mean Landsat TM DN values for each species class.

Mean transformed DN values were plotted for the three vegetation indices, for each species group, and are shown in Figure 5.5. A trend similar to that discussed in the previous paragraph was observed again, where aspen consistently had the highest mean DN value for each vegetation index, and values decreased incrementally for mixed-wood, pine and spruce stands. This was expected, since aspen reflection is highest in the NIR band (TM 4), because a high concentration of chlorophyll is present in the aspen leaves, which reflect a high amount of energy, while reflectance in the other bands is much lower, yielding higher ratio values for aspen.

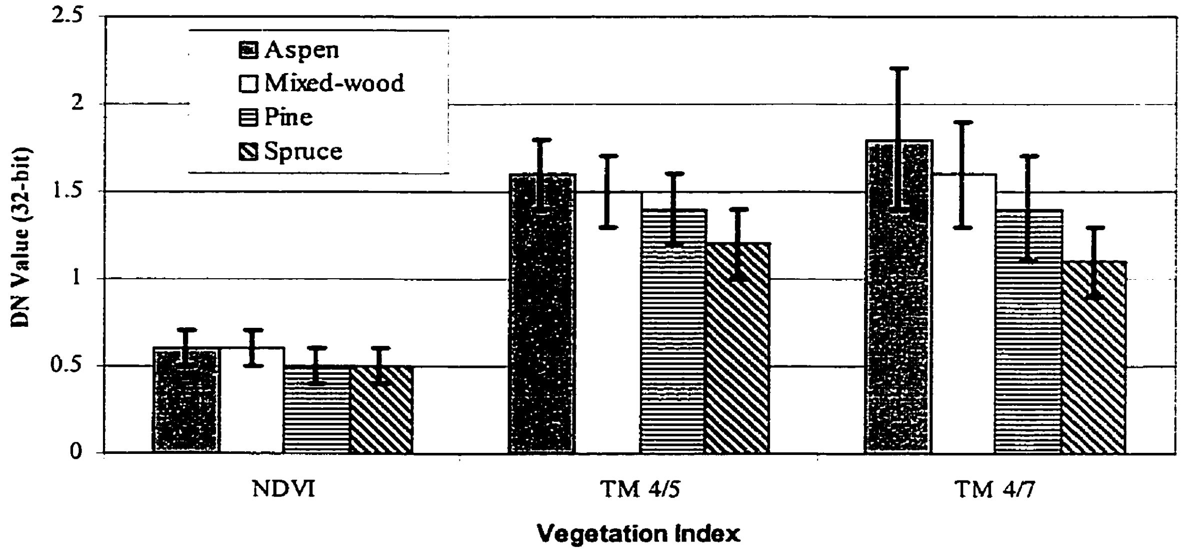

Figure 5.5 Plot of mean DN values from each vegetation index, for each species type (32-bit data source).

Mean Landsat TM Tasseled Cap transformation values, for each species, are shown in Figure 5.6. The highest brightness values were experienced in the aspen stand, with a mean transformed DN value of 86; similarly, greenness was highest for aspen. This makes sense since deciduous aspen would normally appear as the 'brightest' and 'greenest' of the stands in normal colour photography, for example, or by visual assessment. It was expected that aspen stands would be brighter, since healthy aspen stands, generally, absorb more incoming red radiation than softwood stands, and reflect more green radiation, due to the broad-leaf structure of aspen.

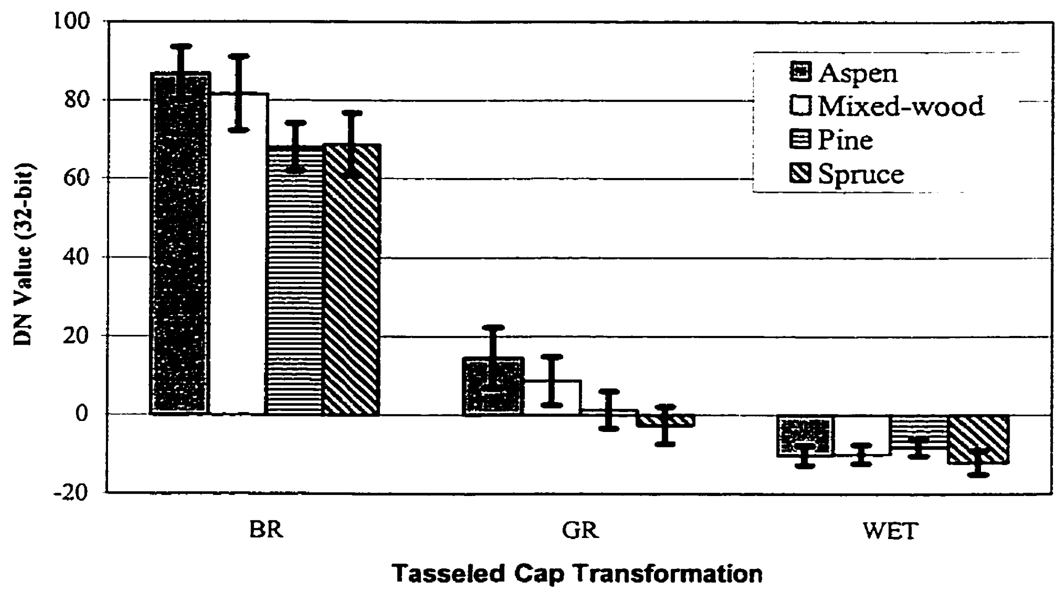

Figure 5.6 Plot of the mean DN values, for each species group, from the Tasseled Cap Transformations (32-bit data source).

Mean mixed-wood, white spruce and jack pine values decreased incrementally. Brightness values for spruce and pine were almost identical, when compared to aspen and mixed-wood, with a difference of less than 1 DN value. Wetness values were very close for all three species types; which could be interpreted to mean that differences in stand structure are not captured well by this index. Earlier studies in Oregon have shown wetness to work best under closed canopy and old-growth conifer forest conditions (Cohen *et al.* 1995). In another study in forests more similar to the NWT sample discussed here, Deuling *et al.* (2000) showed that different wetness index relations must be developed for different biogeoecological subzones in BC. This could be interpreted to mean that wetness transformations should be used only in controlled model development situations, within one stand type, and that the true variability in the forest stands sampled over a wide range of conditions can overwhelm the ability of the index to summarize the various reflectance and absorption characteristics in the TM image. In other words, for the NWT sample, the sampled stands seem to all have similar wetness index values, but likely for very different reasons.

Correlation coefficients determined among Landsat TM bands, vegetation indices and Tasseled Cap Transformations are presented in Table 5.13. As expected, the visible Landsat bands (TM 1, 2 and 3) were all relatively highly correlated with each other, with R values ranging from 0.75 to 0.77. As well, it was expected that the infrared bands would be correlated with each other. Landsat band 4 was strongly correlated with TM band 5 (R = 0.84) and TM bands 5 and 7 were highly associated with each other (R = 0.71). Each of the vegetation indices were strongly related to TM band 4. This could be expected since this band was used to partially determine each of the index values. It was unexpected, however, that the other TM bands used to calculate each vegetation index were not as strongly correlated with the resulting index value. For example, NDVI was calculated using TM bands 3 and 4. There was no relationship between TM band 3 and NDVI, while a strong association existed for TM 4 (R = 0.77). One interpretation of this lack of correlation between the red band and the NDVI is that most of the variance in reflectance, for the stands sampled, is contained in the near infrared band; the red absorption is relatively flat, without large differences in photosynthetic capacity. This flat red response is typical in some early studies of aspen and conifer stands with a range of closed and open crowns (Spanner *et al.* 1990).

Vegetation indices were strongly related to each other, with correlation coefficients ranging from 0.75 to 0.84. This would occur since each index was created using the near infrared band, TM band 4, in the numerator. The Tasseled Cap transformation for brightness was significantly correlated with all Landsat TM bands, which was expected since brightness is calculated by summing (with different weights) each TM bands' reflectance value. Landsat bands 4 and 5 were most strongly correlated with brightness (R values of 0.6 and 0.93, respectively), which was surprising since brightness has typically been presented in the literature as a 'soil' reflectance measure which is dominated by visible reflectance bands (e.g. Horler and Ahern 1986, Cohen *et al.* 1995). Therefore, one interpretation of the NWT tasseled cap transformation brightness values might focus on the amount and type of soil exposed to the sensor. In the NWT dataset very little exposed soil exists in open or closed stands. Instead, the differences between open and closed stands were reflected in different understory characteristics.

Greenness values were most highly correlated with TM bands 4 and 5, however significant relationships were also observed with TM 7 and TM 2 (green band). Again, the dominance of the near infrared band (TM4) is related to the reflection of near infrared light by healthy, green leaves; in this study, there were few stands that did not have a large canopy and/or an understory that would be highly reflective in the near infrared and green band. The positive association with the green band confirms that green and red reflectance is highly dependent upon the amount of chlorophyll in the leaves; in this case, the green band shows the stronger correlation. The mid-infrared bands (TM 5and 7) are thought to be more highly related to cellular structure and the water holding capacity of these leaves (Cohen *et al.* 1998, Franklin *et al.* 2000a), which helps explain why significant relationships were observed between the greenness values and TM bands 5 and 7.

Finally, significant negative relationships were observed between wetness and TM bands 1, 2, 3, 5 and 7. TM reflectance decreased as stand wetness increased. This relationship was strongest in the middle and far infrared bands (R values of –0.41 and -0.58, respectively), which was expected since middle and far infrared energy is absorbed by water held in the leaves of the forest canopy and understory. Therefore, as the canopy and understory reflectance decreased (because of greater absorption of energy and larger shadow fractions), which is a trend typically associated with greater stand development and structure, wetness values increased, thereby demonstrating that there is greater 'water content' in the stand.

Table 5.13 Correlation coefficients among Landsat TM bands, vegetation indices and Tasseled Cap Transformations.

	TM1	*TM2*	*TM3*	*TM4*	*TM5*	*TM7*	*NDVI*	*TM 4/5*	*TM 4/7*	*BR*	*GR*
TM2	0.75*										
TM3	0.76*	0.77*									
TM4	0.22*	0.48*	0.34*								
TM5	0.32*	0.55*	0.50*	0.84*							
TM7	0.40*	0.52*	0.51*	0.50*	0.71*						
NDVI	-0.23*	0.01	-0.30*	0.77*	0.49*	0.20*					
TM 4/5	0.07	0.27*	0.07	0.81*	0.38*	0.12	0.80*				
TM 4/7	0.01	0.23*	0.07	0.80*	0.50*	-0.09	0.75*	0.84*			
BR	0.42*	0.64*	0.55*	0.96*	0.93*	0.64*	0.60*	0.65*	0.67*		
GR	0.02	0.30*	0.14	0.98*	0.79*	0.40*	0.87*	0.82*	0.84*	0.88*	
WET	-0.22*	-0.23*	-0.43*	0.13	-0.41*	-0.58*	0.43*	0.65*	0.52*	-0.11	0.21*

*** Statistically significant at $p=0.05$**

5.2.3 Relationship between Stand Variables and Image Values

Relationships between stand variables and image reflectance and transformed values were determined through correlation analysis, using the Pearson product moment correlation coefficient, and are presented in Tables 5.14 through 5.17. The strongest correlation coefficients from each relationship are presented and discussed briefly. Complete discussion of the results and the analysis presented here is contained in the following chapter.

5.2.3.1 Relationships between stand height and image reflectance / transformed values

Correlation coefficients between stand height and both image reflectance and transformed values for all species are shown in Table 5.14. All significant correlation values were negative, indicating that reflectance decreased as stand height increased, as expected, for all spectral measures for each species type. The principal mechanism that leads to this reduction in reflectance with stand height is related to the amount of foliage viewed by the sensor and the proportion of shadow fractions found in each pixel. Therefore, reflectance decreased because there was more foliage to absorb and scatter radiation, and the shadows are deeper in stands with tall trees (Danson and Curran 1993, Gemmell 1995).

This relationship was strongest for softwood species in TM band 4 (near-infrared), where pine and spruce demonstrated the highest overall spectral correlation (R values of -0.62 and -0.51, and p values of 0.001 and 0.003, respectively). Aspen and mixed-wood were more strongly correlated with TM band 5 (mid-infrared) with R values of -0.65 and –0.63, and p values of 0.0001 and 0.002, respectively. The strength of the relationships between vegetation indices values and stand height varied for each species and indices type. The TM band 4/5 ratio was most strongly correlated with jack pine ($R = -0.72$, $p = 0.0001$), while a weaker relationship was established with white spruce ($R = -0.48$, $p = 0.005$). Neither the aspen nor mixedwood stands were associated with the TM 4/5 ratio. While most band ratios were related to softwood tree heights, the only band ratio that was related to aspen height was the NDVI. Landsat TM Tasseled Cap brightness and greenness values were significantly correlated with each species type for stand height, while wetness was only significantly correlated to jack pine stand height.

Scatter plots were generated, using the band or ratio that exhibited the strongest significant correlation between stand height and image reflectance/transformed values, and are shown in Figures 5.7 through 5.10. The ratio between the Landsat TM band 4/5 ratio was plotted against jack pine stand height (Figure 5.7), yielding an overall correlation coefficient of –0.72, p = 0.0001. This relationship was strong and exhibited minimal variance along the line of best fit. This association differed for white spruce, as the strongest relationship exhibited was between stand height and TM band 4 (R = -0.51, p = 0.003). Figure 5.8 demonstrates that there was larger variability in the white spruce dataset, especially with taller trees, indicating that the relationship between reflectance and height may saturate at higher average stand heights.

The relationship between both aspen and mixed-wood height and band 5 demonstrated good agreement (R values of -0.65, and –0.63, and p values of 0.0001 and 0.002, respectively) as shown in Figures 5.9 and 5.10. The variability in this relationship was similar to the jack pine stands, with a tighter line of best fit.

Table 5.14 Correlation coefficients between stand height and both image reflectance and transformed values for all species.

	Jack Pine		*White Spruce*		*Aspen*		*Mixed-wood*	
	R	Sig.	R	Sig.	R	Sig.	R	Sig.
TM1	0.12	0.575	-0.21	0.260	0.27	0.167	-0.24	0.291
TM2	-0.45*	0.024	-0.35*	0.049	0.04	0.838	-0.34	0.131
TM3	-0.22	0.297	-0.46*	0.008	0.21	0.284	-0.29	0.202
TM4	-0.62*	0.001	-0.51*	0.003	-0.57*	0.002	-0.58*	0.006
TM5	-0.20	0.326	-0.22	0.218	-0.65*	0.000	-0.63*	0.002
TM7	-0.17	0.425	-0.23	0.215	-0.17	0.378	-0.34	0.127
NDVI	-0.48*	0.014	0.00	0.986	-0.49*	0.009	-0.30	0.180
TM 4/5	-0.72*	0.000	-0.48*	0.005	-0.18	0.368	-0.17	0.469
TM 4/7	-0.48*	0.014	-0.39*	0.026	-0.29	0.128	-0.30	0.184
BR	-0.51*	0.009	-0.46*	0.008	-0.61*	0.001	-0.58*	0.006
GR	-0.65*	0.000	-0.39*	0.026	-0.57*	0.001	-0.58*	0.005
WET	-0.41*	0.044	-0.08	0.677	0.09	0.633	0.28	0.227

*** Statistically significant at p=0.05**

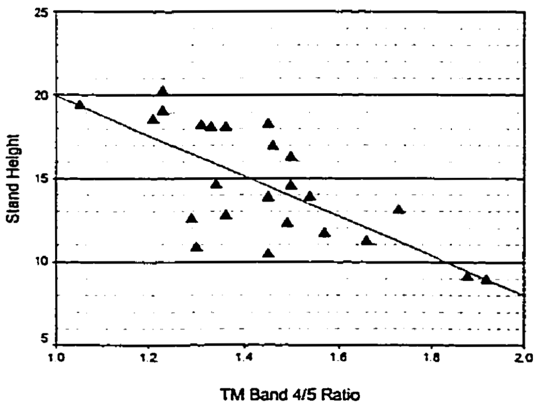

Figure 5.7 Relationship between stand height and Landsat TM band 4/5 ratio for jack pine stands.

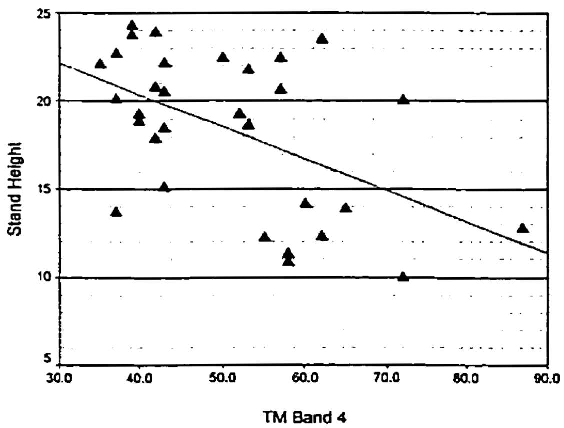

Figure 5.8 Relationship between stand height and Landsat TM band 4 for white spruce stands.

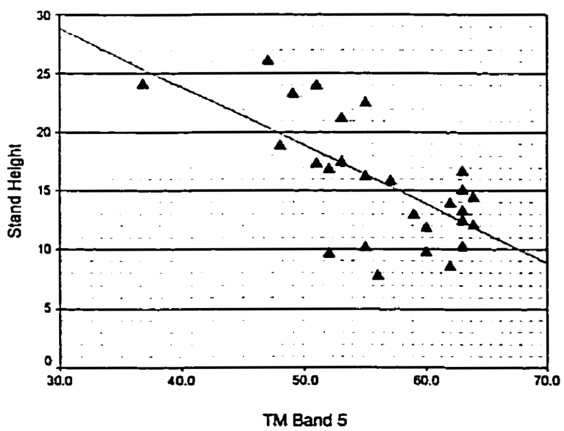

Figure 5.9 Relationship between stand height and Landsat TM band 5 for aspen stands.

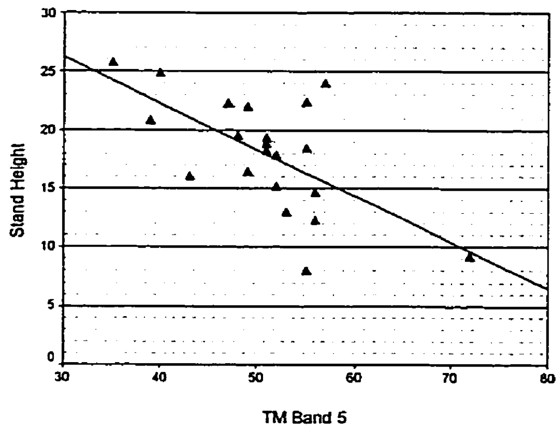

Figure 5.10 Relationship between stand height and Landsat TM band 5 for mixed-wood stands.

5.2.3.2 Relationships between stand age and image reflectance / transformed values

Correlation coefficients for dominant stand age and both image reflectance and transformed values, for each species, are provided in Table 5.15. It is important to note from the earlier discussions that age is a descriptor of stand development and is not a structural variable by itself (De Wulf *et al.* 1990; Cohen *et al.* 1995).

Jack pine and aspen stand age were significantly associated with Landsat TM bands, while no significant relationships could be established between stand age and TM bands for either white spruce or mixed-wood stands. This could reflect the large variability in stand structure with age in spruce and mixedwood stands associated with their successional trajectories.

The strongest associations between softwood age and the image reflectance/transformed values were from vegetation indices, while the NDVI was the only channel associated with aspen age. The strongest correlation coefficients for jack pine and white spruce stands were with the Landsat TM band 4/5 ratio (R values of -0.71 and –0.56, with p values of 0.0001 and 0.001, respectively), while TM band 4, NDVI and greenness channels were all correlated with aspen stand age (R values from -0.60 to –0.69 and p values near 0.0001).

Scatter plots were created for channels that exhibited the strongest correlation coefficients with stand age, and are shown in Figures 5.11 through 5.14. The relationships exhibited in these graphs follow trends similar to those associations demonstrated with stand height (Figures 5.7 – 5.10). Individual data points have a tighter distribution, and thereby less variability, in jack pine (Figure 5.11) and aspen (Figure 5.13), than with white spruce stands and mixed-wood stands (5.12 and 5.14).

Table 5.15 Correlation coefficients between stand age and both image reflectance and transformed values for all species.

	Jack Pine		*White Spruce*		*Aspen*		*Mixed-wood*	
	R	Sig.	R	Sig.	R	Sig.	R	Sig.
TM1	0.06	0.759	0.14	0.465	0.34	0.074	-0.01	0.969
TM2	-0.52*	0.007	0.00	0.994	0.18	0.349	-0.16	0.522
TM3	-0.16	0.452	0.12	0.516	0.42*	0.027	-0.03	0.908
TM4	-0.49*	0.013	-0.35	0.054	-0.68*	0.000	-0.42	0.072
TM5	0.03	0.869	0.08	0.662	-0.60*	0.001	-0.43	0.067
TM7	0.08	0.705	0.00	0.999	-0.24	0.214	-0.08	0.729
NDVI	-0.41*	0.040	-0.42*	0.021	-0.68*	0.000	-0.41	0.082
TM 4/5	-0.71*	0.000	-0.56*	0.001	-0.39*	0.042	-0.15	0.548
TM 4/7	-0.57*	0.003	-0.43*	0.017	-0.34	0.075	-0.49*	0.032
BR	-0.34	0.093	-0.13	0.484	-0.64*	0.000	-0.37	0.119
GR	-0.50*	0.012	-0.46*	0.010	-0.69*	0.000	-0.50*	0.028
WET	-0.61*	0.001	-0.41*	0.026	-0.11	0.582	0.10	0.687

*** Statistically significant at p=0.05**

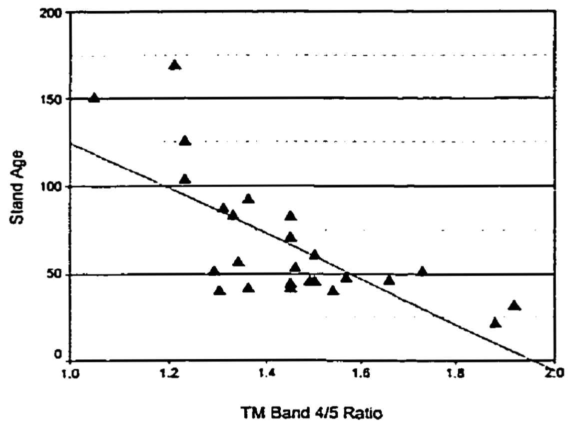

Figure 5.11 Scatterplot of stand age and Landsat TM band 4/5 for jack pine stands.

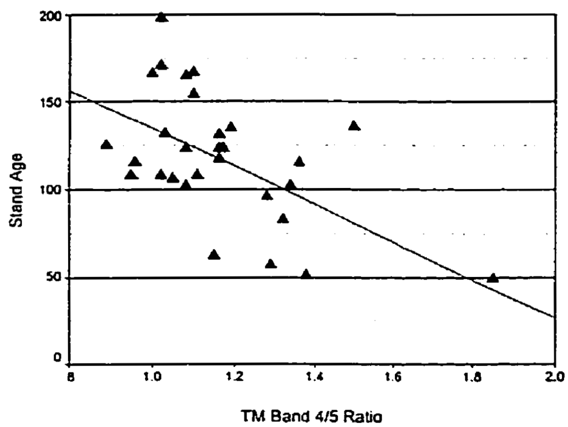

Figure 5.12 Scatterplot of stand age and Landsat TM band 4/5 for white spruce stands.

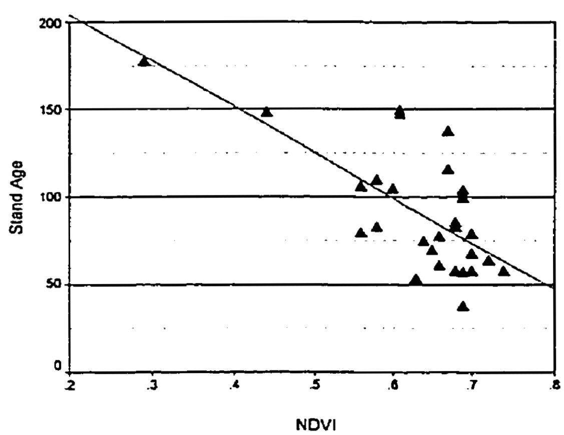

Figure 5.13 Scatterplot of stand age and Landsat TM derived NDVI for aspen stands.

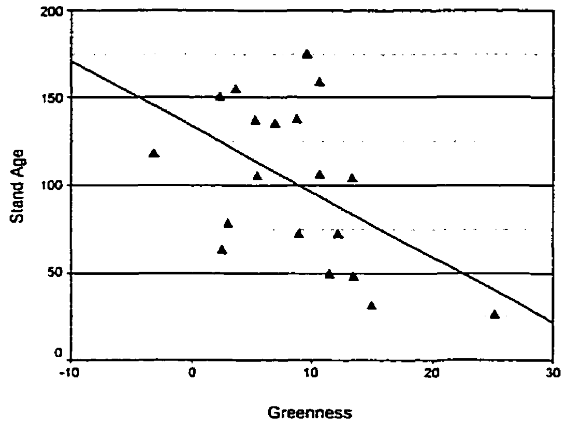

Figure 5.14 Scatterplot of stand age and Landsat TM derived greenness for mixed-wood stands.

5.2.3.3 Relationships between crown closure and image reflectance / transformed values

The relationship between percent crown closure and both image reflectance and transformed values, for jack pine, white spruce and aspen, are shown in Table 5.16. There are noticeable differences between these relationships and those previously experienced with reflectance and stand height and age.

Shown are the expected relationships; that visible and near infrared reflectance would decrease in a predictable way with increasing crown closure as the increased amount of canopy leaves absorb more red light and scatter more near infrared light. Mid infrared relationships are more complex but typically would decrease with increased leaves (that are full of water and healthy cellular structures).

Correlation coefficients were positive for jack pine and all image channels, while white spruce was negatively correlated with all Landsat TM bands. Jack pine crown closure was positively correlated with vegetation indices and all tasseled cap transformations except for wetness. Overall, relationships were strongest for jack pine stands (correlation coefficients ~ 0.7, p values near 0.0001), while white spruce established a good fit with some image channels (R = -0.55 and 0.71, and p =0.001 and 0.0001, for TM band 5 and tasseled cap wetness transformation, respectively). Both aspen and mixed-wood stands demonstrated no significant associations between either image reflectance or transformed values and crown closure.

Table 5.16 Correlation coefficients between percent crown closure and both image reflectance and transformed values for all species.

	Jack Pine		*White Spruce*		*Aspen*		*Mixed-wood*	
	R	Sig.	R	Sig.	R	Sig.	R	Sig.
TM1	0.08	0.707	-0.23	0.215	-0.07	0.710	0.19	0.421
TM2	0.50*	0.011	-0.20	0.263	-0.13	0.515	0.18	0.431
TM3	0.25	0.223	-0.26	0.144	0.11	0.579	0.28	0.215
TM4	0.76*	0.000	-0.04	0.824	0.08	0.692	0.31	0.175
TM5	0.43*	0.030	-0.55*	0.001	-0.06	0.760	0.18	0.426
TM7	0.41*	0.040	-0.45*	0.010	-0.07	0.715	0.24	0.291
NDVI	0.60*	0.002	0.15	0.425	-0.04	0.859	0.09	0.707
TM 4/5	0.73*	0.000	0.43*	0.014	0.19	0.323	0.34	0.134
TM 4/7	0.44*	0.028	0.39*	0.029	0.19	0.325	0.13	0.566
BR	0.69*	0.000	-0.29	0.113	0.03	0.863	0.29	0.199
GR	0.75*	0.000	0.08	0.676	0.07	0.740	0.28	0.218
WET	0.26	0.204	0.71*	0.000	0.16	0.411	0.03	0.892

***Statistically significant at p=0.05**

Scatterplots for pine, spruce, aspen and mixed-wood stands are shown in Figures 5.15 through 5.18, respectively. While the slope for jack pine stands is strong (R = 0.76, p = 0.0001), the strength is partially questionable, since the two data points with the highest crown closure are highly affecting the slope (Figure 5.15). If the two points were removed (around 50% crown closure) the slope and form of relationship would be much more different. The opposing relationship for white spruce is apparent in Figure 5.16. As expected, there was some variability in the distribution of points along the line of best fit, since the relationship was only moderate for spruce, due to the varying stand structures and crown closure surveyed in this research. Figures 5.17 and 5.18 demonstrate how no significant relationship could be observed for either aspen or mixed-wood stands.

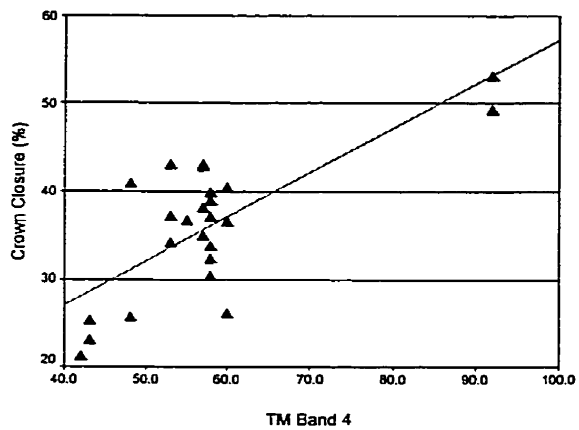

Figure 5.15 Scatterplot for percent crown closure and Landsat TM band 4 for jack pine stands.

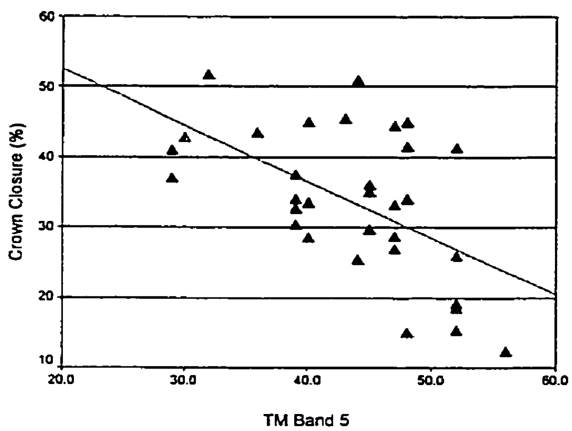

Figure 5.16 Scatterplot for crown closure (%) and Landsat TM band 5 for white spruce stands.

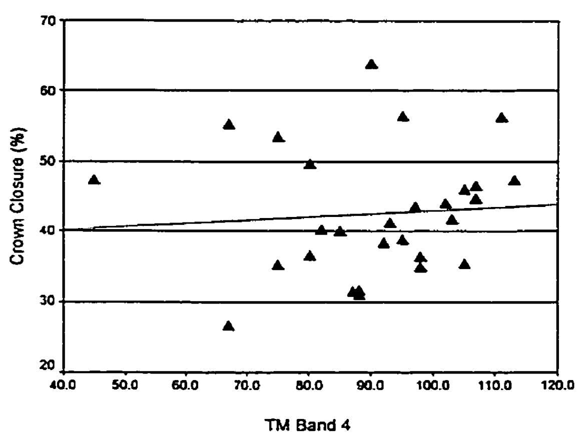

Figure 5.17 Scatterplot for crown closure (%) and Landsat TM band 4 for aspen stands.

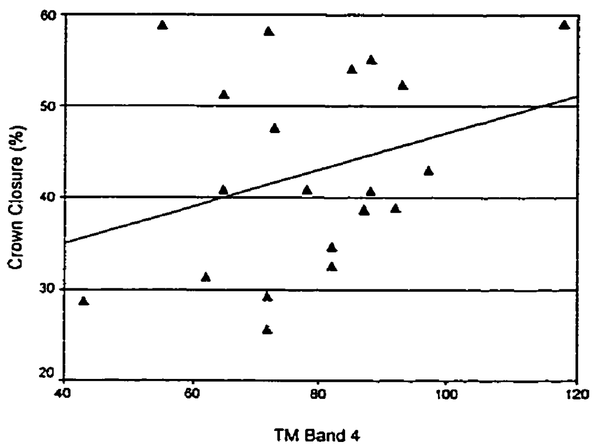

Figure 5.18 Scatterplot for crown closure (%) and Landsat TM band 4 for mixed-wood stands.

5.2.3.4 Relationships between stand volume and image reflectance / transformed values

Relationships between stand volume and both image reflectance and transformed values are shown in Table 5.17. This is a more complex relationship than earlier presented, because the relationship between stand volume and reflectance depends on the strength between the various stand variables that comprise stand volume (i.e. height and crown closure – as a surrogate of DBH - in particular) and reflectance. What is sought here is a third-order relationship between two composite variables that are made up themselves by individual variables that demonstrate an inter-correlation. As expected, the strongest relations between stand volume and reflectance were contained in the near infrared bands and in those image transformations that are strongly related to the near infrared reflectance.

There were no significant correlations between aspen volume and all image reflectance or transformed values. A similar response occurred with mixed-wood stands, except with TM band 5, which yielded a correlation coefficient of –0.5, $p = 0.022$. This negative relationship was also observed with jack pine and white spruce stands. Stand volume was most correlated with white spruce stand spectral response, while only 3 image channels were correlated in jack pine stands. Stands with higher volumes were generally darker in all bands and transformations, as expected when one considers the normal pattern of stand development yielding higher volumes – larger, taller trees, with larger crowns and inter-crown shadowing, resulting in less reflectance and greater shadow fractions within each TM pixel.

Among jack pine and white spruce stands the highest correlations to volume were found in the spruce; while deciduous and mixedwood stands showed that the variability in reflectance was not related to volume. The reason for the strong spruce relationship may be related to the higher range of variability in both spectral reflectance and volume for spruce stands. In other words, the range of conditions was greater and therefore the relationships are somewhat stronger. In general, the relationships between conifer volume and spectral reflectance are consistent with those reported in the literature (e.g. Franklin and McDermid 1993, Trotter *et al.* 1997).

Scatterplots that depict the strongest relationship between image reflectance/transformed DN values and volume for each tree species are shown in Figures 5.19 through 5.22. Each of these Figures, with the exception of white spruce (Figure 5.20), illustrates how either a weakly and highly variable relationship was observed between volume and image reflectance values (Figure 5.19 – jack pine); or no significant relationship was observed at all (Figure 5.21 – aspen; Figure 5.22 – mixed-wood).

Table 5.17 Correlation coefficients between stand volume and both image reflectance and transformed values.

	Jack Pine		*White Spruce*		*Aspen*		*Mixed-wood*	
	R	Sig.	R	Sig.	R	Sig.	R	Sig.
TM1	0.00	0.986	-0.27	0.131	0.14	0.462	-0.07	0.776
TM2	-0.33	0.110	-0.46*	0.009	-0.09	0.634	-0.06	0.807
TM3	-0.30	0.146	-0.48*	0.006	0.24	0.214	-0.15	0.516
TM4	-0.40*	0.046	-0.56*	0.001	-0.10	0.629	-0.39	0.079
TM5	-0.12	0.569	-0.26	0.158	-0.17	0.395	-0.50*	0.022
TM7	0.03	0.890	-0.17	0.362	0.13	0.515	-0.15	0.524
NDVI	-0.17	0.414	0.02	0.913	-0.19	0.335	-0.27	0.237
TM 4/5	-0.46*	0.019	-0.54*	0.001	0.02	0.917	-0.07	0.769
TM 4/7	-0.41*	0.041	-0.54*	0.001	-0.15	0.449	-0.31	0.174
BR	-0.34	0.091	-0.51*	0.003	-0.09	0.651	-0.39	0.084
GR	-0.39	0.054	-0.42*	0.015	-0.14	0.476	-0.43	0.054
WET	-0.30	0.139	-0.11	0.533	0.00	0.997	0.28	0.220

*** Statistically significant at p=0.05**

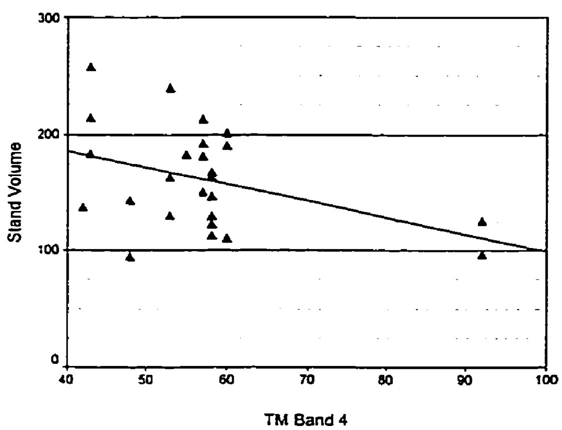

Figure 5.19 Scatterplot for volume (m^3/ha) and Landsat TM band 4 for jack pine stands.

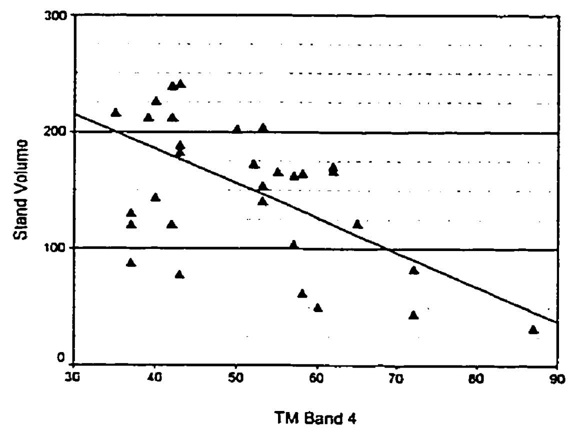

Figure 5.20 Scatterplot for volume (m3/ha) and Landsat TM band 4 for white spruce stands.

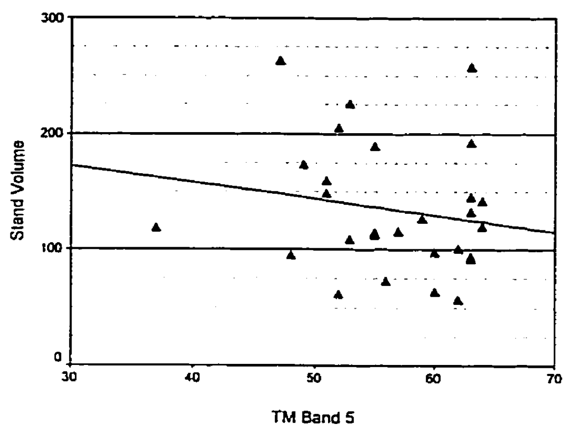

Figure 5.21 Scatterplot for volume (m3/ha) and Landsat TM band 5 for aspen stands.

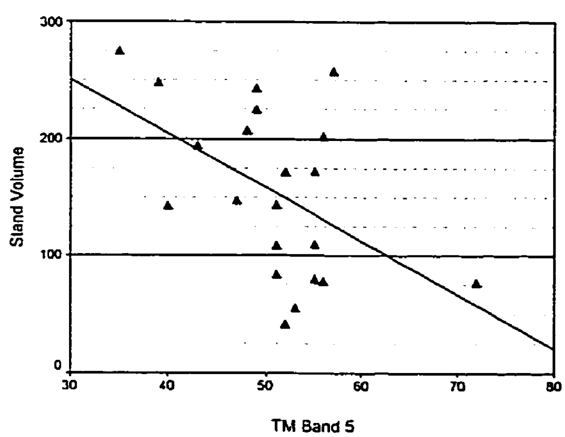

Figure 5.22 Scatterplot for volume (m3/ha) and Landsat TM band 5 for mixed-wood stands.

5.3 Multiple Regression Models

Backwards multiple regression analysis was used to build models that predict stand variables, for each species, from image data. Significantly correlated variables were input into each model, and a backwards technique was used to eliminate variables which exhibited strong multi-collinearity. Table 5.18 presents the results of this analysis, including Pearson's product moment correlation values (R), regression coefficient of determination (R^2), the adjusted regression coefficient of determination (adjusted R^2), standard error, F ratio and its significance level. Further statistical output from Analysis of Variance (ANOVO), and studentized deleted residual versus standardized predicted values and standardized predicted versus actual height scatterplots are included, for reference, in Appendix D. The strongest adjusted R^2 values experienced for height, age and crown closure were with jack pine stands (adjusted r-square values of 0.63, 0.62 and 0.64, respectively, with p values near 0.), while adjusted R^2 values for white spruce volume were higher than the jack pine (0.47 and 0.18, and p values of 0.0001 and 0.019, respectively). Jack pine stands demonstrated the lowest overall standard errors compared to white spruce and trembling aspen stands. Crown closure and volume models were not determined from trembling aspen stands, since there were no significant correlations between crown closure or volume and image reflectance/transformed values.

The model coefficients determined from each backwards multiple regression model are presented in Table 5.19. The number of image variables ranges for each model, from one variable in the jack pine volume equation and white spruce age model, to seven image variables in the white spruce volume equation. The number of variables varied, depending on the extent that the independent variables were correlated to the dependent variable and each other.

Table 5.18 Backwards multiple regression results for estimating stand variables from image data.

Species	*Stand Variable*	*R*	*R^2*	*Adjusted R^2*	*Std. Error*	*F*	*Sig.*
Jack Pine	Height (m)	0.85	0.72	0.63*	2.06 (m)	7.87	0.000
	Age (yr)	0.83	0.68	0.62 *	22.77 (yrs)	10.86	0.000
	Crown Closure (%)	0.83	0.69	0.64 *	4.83 (%)	15.26	0.000
	Volume (m^3/ha)	0.46	0.22	0.18*	39.22 (m^3/ha)	6.32	0.019
White Spruce	Height (m)	0.71	0.50	0.43*	3.30 (m)	6.78	0.001
	Age (yr)	0.63	0.40	0.36*	30.4 (yrs)	9.05	0.001
	Crown Closure (%)	0.71	0.50	0.48*	7.46 (%)	30.17	0.000
	Volume (m^3/ha)	0.75	0.56	0.47*	47.43 (m^3/ha)	6.54	0.000
Trembling Aspen	Height (m)	0.79	0.62	0.53*	3.47 (m)	7.21	0.000
	Age (yr)	0.81	0.65	0.59*	22.49 (%)	10.87	0.000
	Crown Closure (%)	-	-	-	-	-	-
	Volume (m^3/ha)	-	-	-	-	-	-
Mixed-wood	Height (m)	0.58	0.34	0.31*	4.04 (m)	9.87	0.005
	Age (yr)	0.50	0.25	0.21*	40.82 (yrs)	5.81	0.028
	Crown Closure (%)	-	-	-	-	-	-
	Volume (m^3/ha)	0.50	0.25	0.21*	63.93 (m^3/ha)	6.20	0.022

*** Statistically significant at p=0.05**

Table 5.19 Model coefficients determined from backwards multiple regression models

Species	*Stand Variable*	*Model Coefficients*
Jack Pine	Crown Closure (%)	CC = -119.48 – 1.46 (TM4) + 2.8 (TM 5) + 88.68 (TM 4/5)
	Volume (m^3/ha)	VOL = 305.12 – 99.51 (TM 4/5)
	Height (m)	HT = -35.36 – 0.86 (TM2) +1.34 (TM4) + 44.86 (NDVI) – 20.61 (TM4/5) + 6.61 (TM 4/7) – 3.55 (GR)
	Age (yr)	AGE = 187.05 – 9.51 (TM2) + 7.11 (TM4) – 151.31 (TM4/5) – 13.78 (GR)
White Spruce	Crown Closure (%)	CC = 63.27 + 2.47 (WET)
	Volume (m^3/ha)	VOL = -57.26 – 8.32 (TM2) – 21.61 (TM3) + 19.74 (TM4) – 208.82 (TM 4/5) – 43.78 (GR)
	Height (m)	HT = -7.78 – 1.54 (TM3) + 0.84 (TM4) – 2.26 (GR) – 0.52 (WET)
	Age (yr)	AGE = 42.02 – 3.94 (GR) – 5.41 (WET)
Trembling Aspen	Crown Closure (%)	-
	Volume (m^3/ha)	-
	Height (m)	HT = 191.64 + 6.98 (TM4) + 3.16 (TM5) – 45.53 (NDVI) – 9.62 (BR) – 8.31 (GR)
	Age (yr)	AGE = 380.22 + 10.16 – 596.72 (NDVI) + 309.13 (TM4/5) – 11.29 (BR)
Mixed-wood	Crown Closure (%)	-
	Volume (m^3/ha)	VOL = 388.31 – 4.60 (TM5)
	Height (m)	HT = 22.00 – 0.46 (GR)
	Age (yr)	AGE = 133.68 – 3.75(GR)

6.0 Discussion

In this chapter, a discussion the highlights of the previous presentation of results and their analysis are reviewed and interpreted with specific reference to the literature and the local conditions in NWT that provides a context for the study. The principal motivation is to provide insights into the research objective of this thesis, to determine the extent that broad forest stand variables such as height, age, crown closure and stand volume (m^3/ha) could be estimated from Landsat TM data.

6.1 Tree Height-Diameter Models

The original rationale for building tree height-diameter models was to predict height from the field-measured diameters for the 1998 data sample. Field crews only measured a sub-sample of tree heights in the 1998 sample, as described in section 4.11 (Field Data Collection and Processing). Tree height was required for each stem in the field plots to estimate stand volume. Even though the decision was made not to utilize the 1998 data sample due to the variability inherent in field measurements, height-diameter models were still developed, due to the relevance that they would have in operational forest inventory in the NWT.

Results presented in the previous chapter demonstrated that height-diameter models developed for jack pine, white spruce and trembling aspen trees were highly statistically significant (Table 5.1) (adjusted r-square values in the range of 0.76 to 0.81, with p values less than 0.001). These models were evaluated with a validation data sample that was not used in generation of model coefficients. Results of validation tests (Tables 5.3 and 5.4) demonstrated that small and insignificant differences existed between mean height obtained through field measurements and model calculations for all three tree species. The height-diameter models developed therefore appear to be robust for the sample of trees measured in the study area.

6.2 Exploring Field Variables

Prior to discussion of the relationship among field variables and image reflectance and transformed values it is important to highlight the key relationships that occur amongst the field variables for each species.

Jack pine field variables of height, age and crown closure were all strongly correlated to each other, with correlation coefficients ranging from 0.76 to 0.93, with p values below 0.001 (Table 5.9). This age-height-DBH relationship can be expected for any forested species, since an increase in height and DBH is typically a function of increased age. Crown closure and stems/ha decreased as stand age increased (correlation coefficients of -0.6 and –0.66, with p values of 0.002 and 0.0001, respectively). This general trend in relationship was anticipated in jack pine stands, since pine is a primary successional species, which are in constant competition with each other at younger development stages. At younger ages the pine stand is typically quite dense, with a high stems/ha and overall crown closure. As the stand matures, weaker species die out, thereby reducing the stand stems/ha count and overall crown closure. Finally, the relationship between stand volume and stand variables, such as height or crown closure, was weak; for example, volume was only weakly correlated with stand height ($R = 0.41$, $p = 0.042$). A stronger relationship between volume and height might have been expected between since height and DBH are used to calculate individual stem volume.

The relationship among white spruce field variables were not the same as those observed for jack pine. Height, age and DBH were all highly correlated with each other (Table

5.10), as observed in jack pine stands. Again, this was expected, since under normal conditions height and DBH will increase as stands age. The relationship of white spruce height or age with stems/ha was weaker than that observed with jack pine (R values of -0.62 and -0.52, and p values of 0.0001 and 0.003, respectively). Furthermore, no relationship existed between stand height and crown closure, and a weak relationship was observed between age and crown closure (R = -0.38, p = 0.04). This was expected; one interpretation is that since white spruce is a secondary successional species, the different successional pathways for spruce would play a larger role in determining the crown closure or stems/ha of the stand. With jack pine stands in the study area apparently originating in similar conditions generated by fire, there is only one sole successional stage of the stand in the sample. White spruce demonstrated stronger relationships between volume and both stand height and DBH (R values of 0.61 and 0.48, and p values of 0.0001 and 0.006, respectively), which is an improvement in the relationships observed with jack pine.

The relationships observed in aspen and mixed-wood stands were quite similar to those found with white spruce stands (Tables 5.11 and 5.12, respectively). A strong relationship was observed between height, age and DBH, however no relationship was observed between these variables and crown closure, indicating that crown closure does not change with changes in stand age or height. The ecological mechanisms responsible for this may be related to the types of sites that mixedwood stands typically occupy; the canopy closes early on these sites and maintains a high degree of closure as the stand thinning and accumulation stages occur. The relationship between stems/ha and age was stronger for aspen than mixed-wood stands (R values of -0.66 and -0.54, and 0.0001 and 0.018, respectively), which can be partially explained by the fact that aspen is a primary successional species, thereby following a similar logic to that presented for jack pine stands. This relationship may also be stronger for aspen stands, since mixed-wood stands are comprised of a variety of stand/species types, each exhibiting a different stems/ha counts based on the varying successional stage of development.

6.3 Image Descriptive Statistics

The most prominent trend evident from the descriptive statistics calculated from image reflectance and transformed values was that Landsat TM infrared bands (bands 4, 5, and 7) consistently had the largest range of reflectance DN values, while the visible TM bands (1, 2 and 3 or blue, green and red, respectively) recorded much lower mean reflectance DN values and lower ranges (Appendix C). This difference in ranges may be partially attributed to infrared bands that are not as sensitive to atmospheric effects, therefore leading to the larger range of spectral response values. Since the range of reflectance DN values were much higher for the IR bands, these bands would be more effective for generating predictive models, since a low range in values have been observed to weaken the strength of models developed (Danson 1987; De Wulf *et al.* 1990; Franklin and Luther 1995).

The normal relationship between increasing vegetation amount and differences in visible and near infrared reflectance was observed in this study (Guyot *et al.* 1989) (Figure 5.4). For example, a healthy spruce, jack pine or aspen stand would have a low blue reflectance, higher green reflectance, low red reflectance, much higher near infrared reflectance, and lower, but still quite high, mid infrared reflectance (as was demonstrated by Figure 4.7). Differences among the species also conform to those that have been reported in the literature; aspen stands were consistently brighter than jack pine stand, which, in turn, were consistently brighter than spruce stands (Lillesand and Kiefer 1994).

6.4 Predicting Stand Height

The most common trend observed among the results was that stand height was negatively correlated with image reflectance and transformed values, which is a recurring trend observed in most recent studies (De Wulf *et al.* 1990; Cohen and Spies 1992; Franklin and McDermid 1993; Gemmell 1995). Band reflectance values consistently decreased as stand height increased, as shown in Table 5.14. This relationship is plausible since taller trees cast larger shadows that can create a decrease in the overall spectral response value detected by the satellite sensor.

Furthermore, since stems/ha exhibited a negative relationship with stand height for all species (correlation values between height and stems/ha ranged from -0.62 to –0.88, p values below 0.0001) (Tables 5.9 through 5.12), a decrease in stems/ha would have created more gaps in the canopy while stand height was increasing. These additional gaps would expose more shadows to the satellite sensor overhead, thereby further increasing the effect on the detected reflectance values.

In this study, correlation coefficients between stand height and image reflectance/transformed values were strongest for the Landsat TM infrared bands and the infrared ratios, as was demonstrated by Table 5.14 in the previous chapter. This was expected, as most recent studies have demonstrated that height is strongly related to infrared bands (DeWulf *et al.* 1990; Gemmell 1995); or to Tasseled cap transformations, such as wetness (Cohen and Spies 1992), which is primarily derived from the infrared bands. TM band 4 (near-infrared) was highly correlated with jack pine and white spruce height (R values of –0.62 and –0.51, and p values of 0.001 and 0.003, respectively) and TM band 5 was strongly correlated with aspen and mixed-wood stands (R = -0.65 and –

0.63, and $p = 0.0001$ and 0.002, respectively). It may be interpreted that the infrared bands provided the strongest correlation coefficients since their range of values in the database were the largest, for example the range of values varied from 50 to 75 in TM band 4, with large standard deviations that ranged from 12.1 to 16.3 (Appendix C). Further, atmospheric effects were probably not completely eliminated in the visible bands, since thick patches of haze could not be removed. This may thereby have decreased the precision in relationship observed, and perhaps even decreased the strength of relationship by introducing spectral variance unrelated to forest growth and development.

Additionally, the TM 4/5 and 4/7 band ratios were strongly related to stand height for softwood species, while the NDVI was most strongly related to hardwood stand height. The TM Tasseled cap brightness and greenness values were negatively related to stand height for each species type. As expected, as stand height increased the brightness values decreased as more shadows became visible within the understory and tree crowns, thereby decreasing the overall reflectance values obtained from each TM band. A similar trend to this was observed in New Brunswick, where greenness decreased with increasing stand age, which was positively related to stand height (Franklin *et al.*2000b). The reason given for this decrease was that younger stands had a lower leaf area index, or less foliage than older stands. In the NWT there may be more foliage in taller stands, but there was also heavy understory developing in some of the shorter stands. This understory would potentially increase the greenness value, however, the low sun angle in the NWT image would mean that less of the understory vegetation might be visible, when compared to canopy foliage. Therefore, the gaps in the canopy would appear darker rather than brighter in the greenness and in the brightness transformations.

Wetness was weakly related to pine height (R = -0.41, p = 0.044) and was unrelated to the height of the other species. This was not completely expected, since past literature has demonstrated that wetness values can be highly related to stand height (Cohen *et al.* 1995, Deuling *et al.* 2000). However, in these other study regions the structural complexity of the stands, as well as the sun-sensor geometry, was different from that found in the NWT, and thereby the observed relationships could be expected to differ.

These interpretations serve to demonstrate the highly empirical nature of this research; identifying those successful predictors in one forest region may not be directly applicable in other regions. The significant relationship between brightness and height may be attributed to the decrease in overall stand reflectance with increased height. The decreased stand reflectance is probably created by the increase in shadows from the tall trees and decreased stems/ha count, reducing the number of crowns visible to the sensor. This explanation may also be used to explain why greenness is negatively associated with stand height, since the amount of green reflectance will decrease as visible crowns are reduced and as shadows becomes more dominant within the stand.

Each significantly correlated image variable was input to a backwards multiple regression model to build equations that would predict stand height. The backwards model was used to reduce the effects of multi-collinearity, by removing image variables that were too closely correlated with each other (SPSS Applications Guide 1999). The strongest backwards regression models that predicted height were developed for the two primary successional species (pine and aspen), which yielded the strongest adjusted r-square values (0.63 and 0.53, respectively, with p values of 0.0001) (Table 5.18). The secondary species (spruce) and mixed-species stands had much lower model strengths (adjusted r-square of 0.43 and 0.31, and p values of 0.001 and 0.005, respectively). The standard error of estimate measured with each model varied for each species (Table 5.18), where the lowest standard error of estimate was found in jack pine stands, with an error near 2 m. Higher errors were found in white spruce, trembling aspen and mixed-wood stands (3.3 m, 3.5 m, and 4 m, respectively), which could be interpreted to be a result of a higher variance in reflectance values for different height classes, when compared to the jack pine. This variance in reflectance values for different mean height classes could be the result of a variety of stand factors, including, but not limited to;

- Varying understory content and/or densities for similar height classes. This could either reduce or increase the overall reflectance value detected by the sensor;
- Differing crown closure and stems/ha densities for specific height classes, which would allow either more or less foliage and greater or fewer stems to be visible by the sensor, thereby increasing or reducing the reflectance levels detected for a given height class; and
- Differing variances in tree heights for a given height class. Some mean height classes could have a large variance in overall tree sizes (complex structure) found within the stand, which could create more shadows and reduce the overall reflectance values, when compared to stands with homogenous height structures.

One way to interpret the strength of these models is to consider the successional pathways taken by each of these species groups. Jack pine and aspen are generally the first species to dominate a site following a disturbance. Since these species are generally not in direct competition with any other species, their structural development through each successional stage is reasonably consistent among all stands. The successional development process was observed to be most consistent in jack pine stands, which could help explain why the model to predict pine height was the strongest, while also demonstrating the lowest standard error, when compared to all other species (Table 5.18).

Spruce had a weaker model strength when compared to the primary successional species stands (Table 5.18). This was expected since stand development differs for spruce, as the tree may have developed under a variety of different site conditions than the primary successional species did, as described in Chapter 3, section 3.2. Therefore, the structure of each stand varied principally by site, rather than by successional stage. For this reason, the high variance in stand structures did not permit as strong a relationship to be formed between spectral reflectance and height, when compared to pine and aspen stands. Another possible factor that lead to the weaker relationships in spruce stands was the influence that humans had on the spectral relationships. In the Fort Simpson region, many local residents use timber to heat their homes in the winter months. The preferred source for this firewood comes from white spruce stands, and most preferably the taller stands that provide a greater amount of timber. For this reason, most stands surveyed in this study had undergone different levels of human thinning, as demonstrated in Figure 6.1. While it was preferable to find stands that were not affected by human thinning, almost every plot, including fly-in remote sites, were influenced by humans, which may have partially decreased the opportunity to observe relationships similar to those presented with pine and aspen stands.

The weak results found in the mixed-wood stands, such as the poor adjusted r-square value (0.31, $p = 0.005$) and high standard error (~ 4 m) (Table 5.18), can be explained by the first argument that was presented with the spruce stands. Mixed-wood height varied among the different stands, since each stand originated from a different primary species (such as pine to spruce or aspen to spruce). Therefore, the structure of each stand would have varied by site, rather than by successional stage as observed with aspen and pine. For this reason, the structural pattern of the forest would not have been consistently related to height, thereby leading to the weaker correlation and regression model results.

Figure 6.1 Example photos of white spruce stands thinned by humans in the study region.

6.5 Predicting Stand Age

The observed direction and strength of relationship between stand age and image reflectance/transformed values were very similar to those observed with stand height, as indicated in Table 5.15 in chapter 5. This was expected since it has been established, in section 6.4, that a relationship can be formed between height and reflectance values, and generally there are strong relationships between stand height and the age of the stand. For example, jack pine and aspen stand height was strongly associated with age ($R \approx 0.8$, p values near 0.0001) (Table 5.9 and 5.11), while white spruce had a weaker relationship ($R = 0.59$, $p = 0.001$) (Table 5.10). Since pine and aspen age is strongly related to height, the strength of correlation coefficients between age and reflectance were similar to those obtained with height. This was an expected result, since past studies that examined the relationships between Landsat data and both height and age demonstrated very similar results between each of the derived correlation coefficients and model strengths (DeWulf *et al.* 1990; Cohen and Spies 1992; Gemmell 1995; Jensen *et al.* 1999). The correlation coefficients for spruce age and reflectance were weaker, which could have been expected with the weaker relationship between spruce age and height.

The relationship works well for jack pine and aspen stands since in early successional stages stand height is short and the stems/ha count is much larger than that found in more mature stands, as demonstrated in Figure 6.2. As the stand advances towards later successional stages, individual trees begin to die through competition for light, water and soil nutrients. Trees successful at competition will grow taller while their neighbours die-out, therefore decreasing the stems/ha, while increasing the size and visibility of shadows. This successional pattern can be interpreted to be one of the key factors that permitted the development moderately strong regression models to predict pine and aspen height, with adjusted r-square values of 0.62 and 0.59 (p values of 0.0001), and standard error of estimates around 23 years (Table 5.18).

The weaker relationship observed for white spruce could partially be attributed to the ecological factors that influence the growth and distribution of white spruce stands. Since white spruce is a secondary successional species, the recruitment of this species would vary on a site-by-site basis. White spruce recruitment in the NWT usually occurs beneath trembling aspen stands, however, spruce will often grow beneath jack pine stands or in open clearings. Since spruce grow in different ecological settings, growth patterns or trends associated with white spruce succession (such as height, crown closure and age relationships) are not as definite as those exhibited by primary successional species (Burns and Honkala 1990a), such as jack pine and trembling aspen, therefore the variability in stand structure, as demonstrated in Figure 6.3, will introduce variability in the stand reflectance values. Since the structure of spruce stands will vary for any given age class, the derived multiple regression model was weaker for spruce, when compared to the pine and aspen models (Table 5.18). The adjusted r-square value obtained for spruce was 0.36 ($p = 0.001$) with a high standard error of estimate around 30 years. While this model relationship is significantly weaker than pine and aspen models, and cannot provide precise estimates of stand age, the model may be useful for stratifying spruce stands into broad age classes, which could provide forest managers with a basic understanding of the spatial extent of spruce age in the Fort Simpson region.

The relationship between mixed-wood stands and image reflectance/transformed values is weak; again, due to the large variability in stand species composition and structure found throughout these study plots. The spectral signatures obtained from each plot would be variable, due to the different species compositions and height classes associated with each age class, contributing different spectral values due to species reflectance and shadows. Further, the variable relationships between spruce, aspen and pine that are contained in the mixed-wood stands would create further confusion in the relationships observed. For this reason the mixed-wood multiple regression model had a weak adjusted r-square value of 0.21 ($p = 0.028$) and high standard error of estimate (~41 years) (Table 5.18).

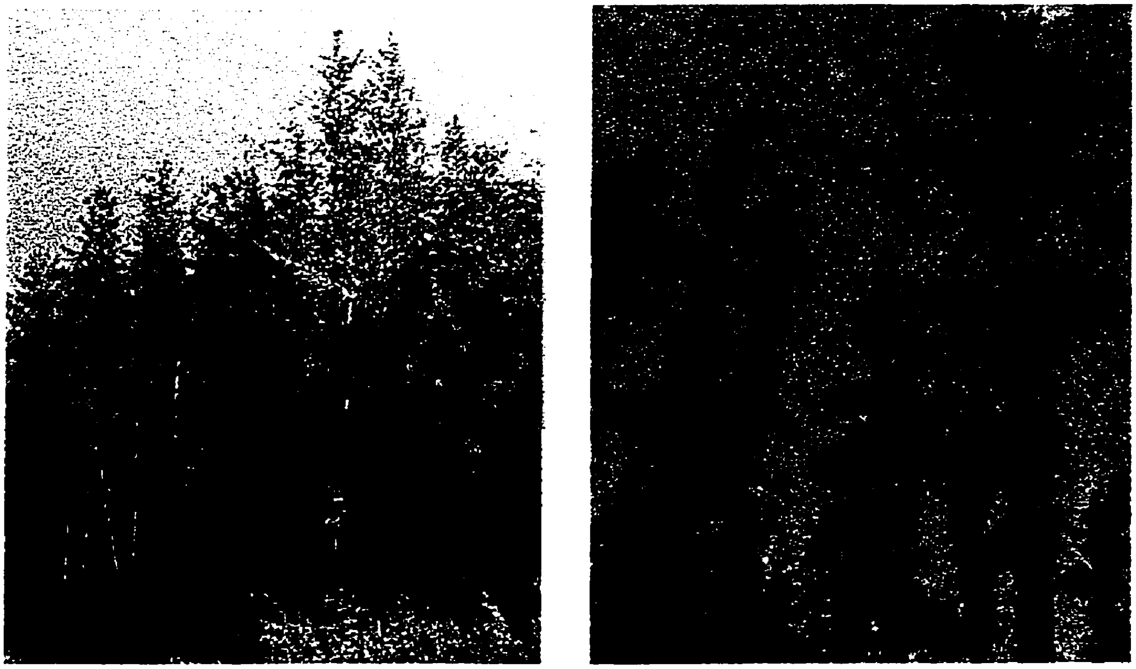

Figure 6.2 Young jack pine stands (left) have higher stems/ha and shorter trees than older stands (right).

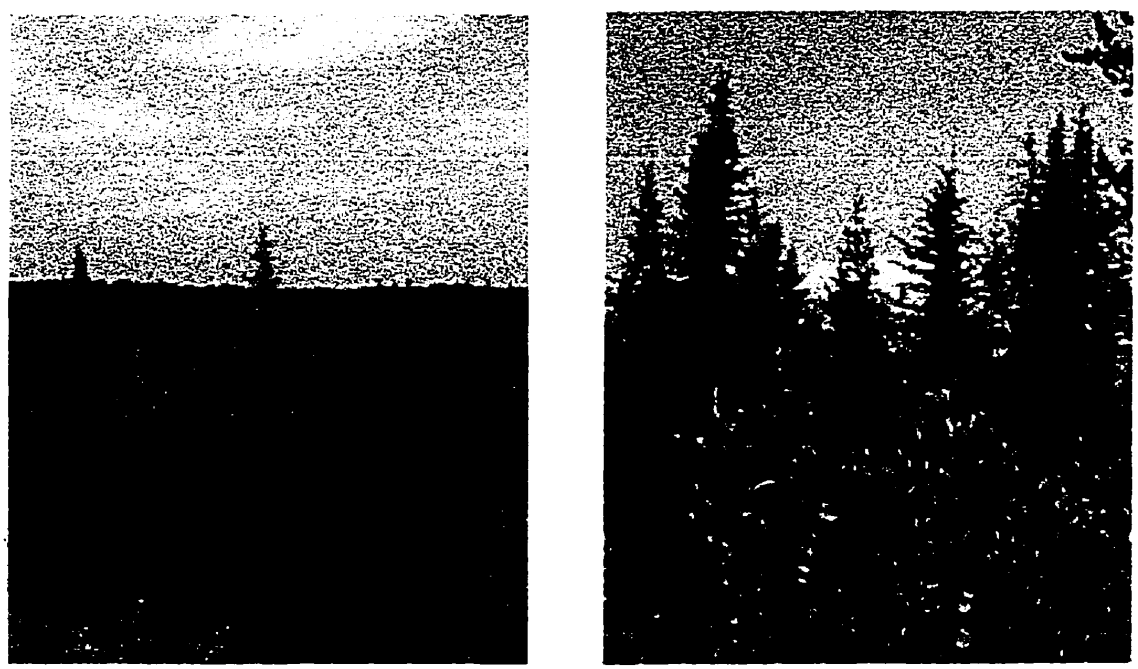

Figure 6.3 Spruce height structure varies by site, such as the young stand with a simple structure (left) and the young stand with a complex structure (right).

6.6 Predicting Crown Closure

Open canopies, with a low range of percent crown closure, typically characterize the forest stands of the NWT. Correlation and regression analysis were used to study and predict crown closures in the range of 12% to 64% over the four species groups, where an average crown closure range of 35% was analyzed for each species group (Appendix C). Relationships between image reflectance/transformed values and percent crown closure varied significantly from those observed with stand height and age (Table 5.16), previous chapter). More significantly, the relationships between crown closure and image reflectance/transformed values varied among hardwood/mixed-wood and softwood, as well as between the two individual softwood species.

No relationship was observed between crown closure and image reflectance/transformed values for either the aspen or mixed-species stands (Table 5.16). Initially, it was thought that a negative relationship would occur between for aspen, as increased openings in the canopy would have been detectable by the increase in visible shadowing beneath the canopy. This relationship, however, was not observed, and a possible explanation and example has been formulated. In order to attempt an explanation of this negligible relationship building an understanding of the relationships between aspen stand variables was required.

No significant relationship was observed between aspen crown closure and stand variables (Table 5.11). Therefore, this may be interpreted to mean that when the age or height of two separate stands vary (age and height being highly correlated to each other with a correlation coefficient of 0.8, $p = 0.0001$ (Table 5.11)) their crown closure may still be the same. This would create large variability in the relationship observed between crown closure and image reflectance/transformed values, since mature aspen crowns would have lower reflectance values than young aspen crowns, thereby providing insignificant correlation values. This occurs since mature aspen often have large crowns that are comprised of many gaps, and which do not overlap and merge with their neighbours. These gaps and inconsistencies would create a heterogeneous upper canopy structure, creating many shadows that would only be noticeable from above the canopy, producing a darker spectral response. On the contrary, young aspen crowns are often much smaller than their mature counterparts, having fewer noticeable gaps, and frequently overlap and merge with their neighbours in the upper canopy. This would create a smooth, homogenous canopy layer with few shadows, thereby producing a much brighter response pattern. Therefore, young and mature aspen stands that share a very similar percent crown closure may have very different reflectance values, based on the number of gaps and shadows present within the stand and among each tree crown. This arrangement pattern for tree crowns may be interpreted to be one of the key factors that prohibited any relationship to be formed between Landsat data and crown closure (Table 5.16), thereby preventing a multiple regression model to be built for aspen crown closure (Table 5.18)

Within the softwood stands, jack pine was positively related to crown closure and Landsat TM spectral reflectance data, while white spruce demonstrated a negative relationship (Table 5.16). Information provided by the vegetation indices created confusion, since jack pine and white spruce were both positively related to the TM band ratios, such as the TM 4/5 (R values of 0.73 and 0.43, and p values of 0.0001 and 0.014, respectively) and TM 4/7 ($R = 0.44$ and 0.39, and $p = 0.028$ and 0.029, respectively) ratios. Contributing to the difficulty in interpretation of these results, brightness and greenness have moderately strong relationships with jack pine crown closure ($R = 0.69$

and 0.75, with p values of 0.0001, respectively), while wetness provided a strong relationship with white spruce crown closure (R = 0.71, p = 0.0001). The high level of variation among each species relationships supports suggestions made by Deuling *et al.* (2000), that correlation and regression results should be interpreted separately for each stand type separately, as the relationships between reflectance and stand variables are empirical to the species found within each stand type. For example, in this study the results for jack pine can be rationalized by a much simpler explanation, while more complex insight is required to interpret the white spruce results.

First, the relationship between reflectance and jack pine crown closure is expressed in a positive association, where reflectance values decrease with a decrease in crown closure. This can be explained as follows: jack pine crown closure has a strong, inverse relationship with stand height (R = -0.73, p = 0.0001) (Table 5.9). Since height has strong, negative relationships with image reflectance/transformed values, an inverse relationship can be expected when correlating crown closure to these values, thereby creating a positive association with jack pine crown closure. Therefore, it can be concluded that as jack pine stand height increases, crown closure will decrease. It is interpreted that more shadows will be cast by the taller trees, creating larger shadows that are visible above the forest canopy, thereby decreasing the reflectance value recorded by the satellite.

There were positive correlation coefficients between jack pine crown closure and brightness or greenness (R = 0.69 and 0.75, with p values of 0.0001, respectively) (Table 5.16); this result was not surprising. Brightness values describe the overall brightness values in the scene, by using a weighted sum of all six TM bands. Greenness is the contrast between the near infrared and the visible bands, and is used to detect the presence of green vegetation. Jack pine stands that have a high percent crown closure are younger stands, with densely packed stems and crown. These crowns might be expected to have a high proportion of photosynthetically active needles; that is, younger stands might have more leaves and more active photosynthesis taking place, thereby creating greater red absorption and green reflectance. In contrast, open jack pine stands are typically older stands, with lower stems/ha and it is felt, contain a lesser amount of photosynthetically active needles. Furthermore, the branching habit of mature jack pine, shown in Figure 6.4, causes a greater proportion of woody branches to be exposed to the sensor overhead. These effects could combine to decrease the overall brightness level in the scene and decrease the amount of greenness that may be detected in the scene. These stand development factors and their relationships with Landsat data have been interpreted to be the key factors that permitted a moderately strong regression model to be built to predict pine crown closure (adjusted r-square = 0.64, p = 0.0001, respectively), with a low standard error of estimate (near 5 percent) (Table 5.18).

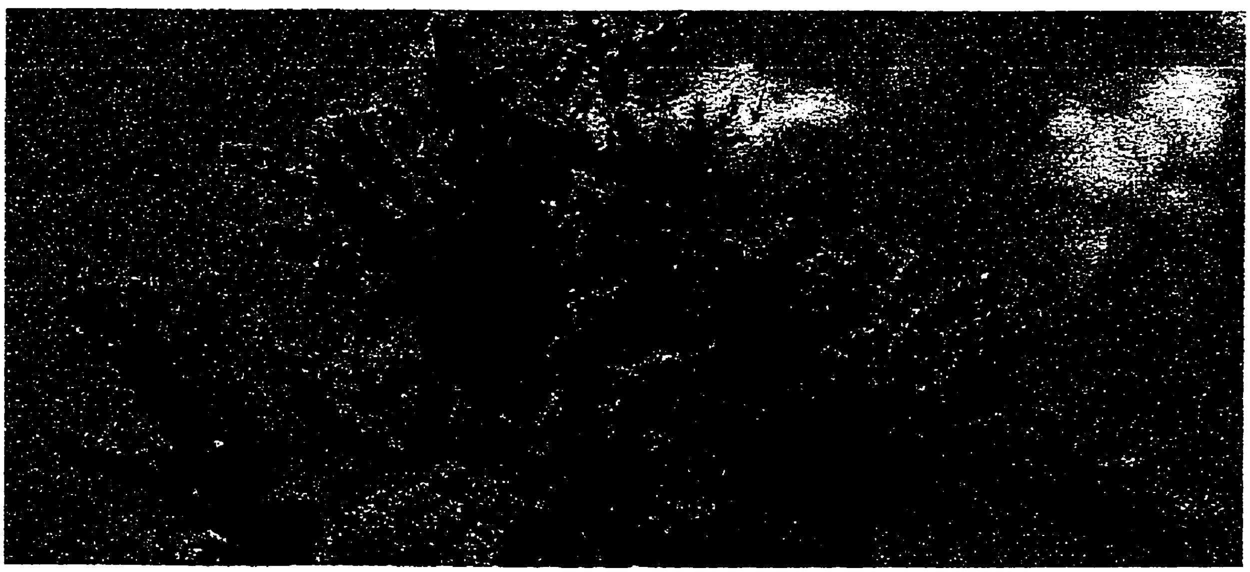

Figure 6.4 The branching habit exhibited by mature jack pine.

The relationship between spectral reflectance and white spruce crown closure was a different relationship when compared to jack pine. These differing relationships are due to different ecological factors than those experienced with jack pine. White spruce crown closure is not associated with any other stand factors (Table 5.10), probably due to the varying recruitment forms and successional pathways taken by the species. As mentioned earlier, spruce recruitment most often takes place beneath an aspen or jack pine stands; however, recruitment has taken place in open regions when aspen suckers of jack pine seeds sources are absent. The successional pathway taken by suppressed spruce varies, depending upon the seral successional stage the overstory species is at, how healthy these overstory species are, among various other factors. Therefore, spruce may take a slow or fast pathway, depending on its level of suppression. For these reasons, the crown closure of a spruce stand will not follow a consistent path trend.

Since no trend could be observed between crown closure and stand height or age it was assumed that no relationship would have been observed between white spruce crown closure and spectral response. However, a relationship was observed, and one possible interpretation considers the influence of the biological factors associated with spruce stands. In the NWT white spruce is often found on moist-sites, for this reason it may be interpreted that a full, dense, closed spruce canopy may hold more water when compared to a similar density stand of jack pine, due to the increased density of needles found spruce trees. Therefore, if the leaf area increased, due to increased canopy closure, the absorption of middle infrared (TM 5) and far infrared (TM 7) energy by the water and cellular structure of these leaves would increase, which is demonstrated by the negative relationships for TM bands 5 and 7 (R values of –0.55 and –0.45, and p values of 0.001 and 0.01, respectively) (Table 5.16). Logically, as crown closure increased, the leaf area increased, the density of water holding needles increased, reducing the amount of energy that was reflected by the canopy.

The most significant correlation that occurred between crown closure and image reflectance/transformed values for white spruce was with the wetness channel (R = 0.71, p = 0.0001) (Table 5.16), which has been used to indicate the amount of water the forest canopy holds in the leaves and cellular structures; in fact, in one study (Cohen *et al.* 1995) a new name for the wetness index was suggested – structure index. In this NWT study, the relationship that was found for spruce is that wetness values will increase as the canopy closure increases. This was expected, since wetness is the contrast between the mid infrared bands and the other TM bands, which have already been demonstrated to hold a significant relationship with crown closure. Therefore, the same explanations presented in the previous paragraph, with TM bands 5 and 7, would also apply to wetness. Since these moderately strong relationships existed between spruce crown closure and Landsat data a multiple regression model with an adjusted r-square value of 0.48 (p = 0.0001) and standard error of estimate of 7.5% could be created.

The relationship between mixed-wood spectral response and crown closure was insignificant, and therefore no multiple regression could be built. The lack of relationship between mixed-wood crown closure and spectral response was interpreted to flow logically from the variability in species type that make up the stand. As Gemmell (1995), Deuling (2000), and others have found, reflectance is influenced by species differences rather than pure differences due to closure in mixed-wood stands.

6.7 Predicting Stand Volume

Few research projects have been undertaken that predict forest stand variables in the North American Boreal forest region (e.g. Franklin and Luther 1995), and no comprehensive studies have been reported that develop predictive models for all of the dominant forest species of the NWT. Studies undertaken in other forest ecosystems, such as in New Zealand (Trotter *et al.*1997), the United Kingdom (Danson and Curran 1993), Oregon and California (Fiorella and Ripple, 1993, Cohen *et al.*1995, Woodcock *et al.*1997), Minnesota (Bauer *et al.*1994), British Columbia (Gemmell 1995, Deuling *et al.* 2000) and Scandinavia (Reese and Nilsson *et al.*1999), however, have indicated both that there is both promise and the limitations to volume estimation. For example, in the Minnesota study, Bauer *et al.* (1994) indicated that the principal role of remote sensing in estimation of stand volume was to indicate a rough 'class' of volume, such as low and high volume categories, within each species or stand type. In their study area they have more than 50 different types of forest cover; in the NWT a much simpler stand structure existed and therefore more precise development of stand volume models was expected to be possible.

Results presented from correlation analysis demonstrated that stand volume had the highest correlation values with white spruce image reflectance and transformed values, when compared to the other three species (Table 5.17). A negative relationship was constantly observed between the image bands, ratios and transformations with stand volume, with significant correlation coefficients ranging from –0.41 to –0.56 (p values from 0.041 to 0.001). These relationships were negative, indicating that image reflectance decreased with an increase in volume. The principal mechanism thought to be responsible for this negative relationship is the increased shadowing effects that would be present in stands with higher volume content. Since volume was positively related to height for all species in this study (Tables 5.9 to 5.12), it could be interpreted that an increase in height would create an increase in stand shadowing, thereby decreasing the overall stand reflectance values.

The moderately strong negative relationship between spruce volume and image reflectance and transformed values may exist since spruce height has a partial correlation with stand volume (R = 0.61, p = 0.0001) (Table 5.10). Since a relationship could be established, the derived adjusted r-square value, obtained from multiple regression analysis, to predict spruce volume was 0.47 (p = 0.0001), with a standard error of 47 m^3/ha (Table 5.17). This was the strongest model strength obtained through any of the spruce models in this study. If the interpretation of by Gemmell (1995) that shadowing effects influence volume models were accepted, these results would indicate that spruce volume has the highest correlation with stand shadows over all the other stand variables analyzed for spruce. This relationship might occur because spruce trees with large volumes typically have larger crowns (Burns and Honkola 1995), and this trend is stronger for spruce trees than for any other species in the sample. A large proportion of this crown would be covered by shadows that are cast by the sunlight portion of the crown. This inter-crown shadowing effect, coupled with shadows cast on the understory by the thick crowns, would create a much lower stand reflectance value in all of the image channels.

The relationship observed with jack pine volume was different, since fewer image channels were related to stand volume. Landsat TM band 4 and the TM 4/5 and TM 4/7 band ratios were weakly related to stand volume (R values ranging from –0.4 to –0.46, with p values in the range of 0.046 to 0.019) (Table 5.17), which contributed to the weak regression model for predicting stand volume (adjusted r-square of 0.18, p = 0.019, with a standard error of 39 m^3/ha) (Table 5.18). These relationships were weak since jack pine volume was not highly related to any of the key structural stand variables. For example, there was a weak relationship between height (R = 0.41, p = 0.042) and volume, and an insignificant relationship with DBH (Table 5.9). This was not expected since these two variables were used in deriving the individual volume calculations. The weak relationships with image reflectance and transformed values demonstrate that jack pine stand volume is not as highly related to stand shadowing as was observed in spruce stands, which contradicts earlier thoughts presented throughout this thesis research. This weak relationship may occur since jack pine crowns are not as dense as white spruce crowns, therefore the effects of inter-crown shadowing would not be as pronounced as with white spruce, thereby reducing the effectiveness of the derived model. However, more insight is required to fully determine why white spruce models were stronger than jack pine, since the relationships between stand structure and shadowing effects were most pronounced for jack pine with all the other stand variables studied in this research.

Landsat TM band 5 was the only image channel that was related to stand volume for mixed-wood stands (R = -0.5, p = 0.022) (Table 5.17). As with the previous softwood species, this negative relationship indicates that volume is probably most highly related to inter-stand and inter-crown shadowing. The variability in stand volume and species type in the mixed-wood stands would have prevented successfully achieving higher strength relationships from being formed with the other image channels. Therefore, the resulting volume model provided a weak adjusted r-square value of 0.21 (p = 0.022) and a high standard error (64 m^3/ha) (Table 5.18). This high error would have been created by the high variations among tree volume (and hence height), species and their varying observed relationship within each mixed stand.

No significant relationship was observed when analyzing the relationship between stand volume and image reflectance and transformed values for aspen stands, and thus no predictive model was built. There was no relationship, probably as a result of the same reasoning provided for the lack of relationship for aspen crown closure and image values (as discussed in section 6.6), where the amount of inter-crown shadowing will be variable within one unique volume class. Therefore, aspen stands with high volume can have old trees, with large canopy gaps that create deep shadows and a decreased stand spectral response, while another aspen stand with low volume may have tall trees in an open stand that would cast deep shadows, thereby creating a lower stand spectral response. For this reason accurate models that predict stand volume from spectral response could not be built since no relationship was found between volume and stand shadowing effects.

6.8 Operational Linkages of the Derived Models

This study has focused on identifying the trends in relationships between stand variables and Landsat TM reflectance, transformed and vegetation index data. It is recognized that there are multiple sources of error and uncertainty in this empirical approach, including, but not limited to, the difference of six years between field collection and remote sensing data acquisition and the changes in stand development that may have occurred over this time period. For example, stand development in some regions may have been affected over this time period by insect and pest damage, such as that caused spruce budworm and tent caterpillar defoliation, which would weaken the growth and vigor of affected trees. Human thinning of white spruce stands, for firewood production, over the six years has been occurring. This would create an unnatural decrease in stems/ha counts in the stands surveyed in 1999, and introduce uncertainty when determining the relationship between image reflectance and spruce variables since stand reflectance in 1993 would not fully be explained by the stand variable measurements obtained in 1999. Additionally errors inherent in the image database, such as the haze that remained in portions of the study site following atmospheric correction, would have increased actual stand reflectance values and thereby introduce more uncertainty in the derived models.

Although these sources of error and uncertainty were introduced into the model development, these factors could not be fully controlled in this study; and therefore, backwards regression models to predict a given stand variable from Landsat data were still created. The strength of each derived model to predict stand variables for height, age, crown closure and volume ranged, with adjusted r-square values extending from 0.18 to 0.63 (p values ranging from 0.028 to 0.0001), over the four species groups surveyed in this research. While many of the models derived through this research were weak in strength, they may still be used for providing a broad-level stratification of forest variables from the Landsat TM data. This final discussion section of the thesis has been compiled to briefly describe the operational linkage that may be applied to the derived models.

As stated in chapter 1, section 1.3, NWT forest managers are experiencing difficulties making decisions that would best contribute to the sustainable management of the forest landscape since it is economically impractical to produce detailed forest inventory information, over the entire NWT landscape, that is necessary for making these decisions. For this reason, the GNWT-RWED identified the need to develop alternative methods for extracting forest inventory information in the NWT, which provide characterizations of forest variables at relatively low financial costs – such as through remote sensing analysis. This research was designed to build a methodology that employed multiple regression analysis from Landsat TM data, to provide broad estimates of stand variables, over a large remote region of the NWT. The variables predicted from these models could supply forest managers with a broad information base on the state of the forest land for regions where no present information exists.

The models developed through this research can be linked with landcover classifications, which have already been produced by RWED staff, for the Fort Simpson region, to produce separate layers of forest variable information. Stand height and age information could be extracted for all species, since significant models could be built for all of these species, while crown closure information may only be extracted for pine and spruce, and volume information for the pine, spruce and mixed-wood stands.

Figures 6.5 visually demonstrates how regression model equations may be linked to the landcover classification data and provide broad level stratification maps for stand height, age, crown closure and volume. To accomplish this task, the NWT landcover classification would need to be reclassified into the four species groups that were studied through this research. This reclassification process would be used to construct four species-specific masks that will be used to run the model equations under. Under each species masks, for example jack pine, a stand variable model, such as for height, would be applied to the Landsat data to produce a spatial map of jack pine height. This process would be repeated for the other three species, and the predicted results would be integrated into one final map depicting the spatial coverage for stand height for all four species. This process would be repeated for the other three stand variables, to produce four final spatial maps of stand variables. These final maps could be exported as a raster GIS database, and imported into a GIS software package, such as ArcInfo. This would help facilitate geospatial analysis that could assist NWT forest managers for decision making by providing a basic understanding on the forest stands that exist throughout the region mapped.

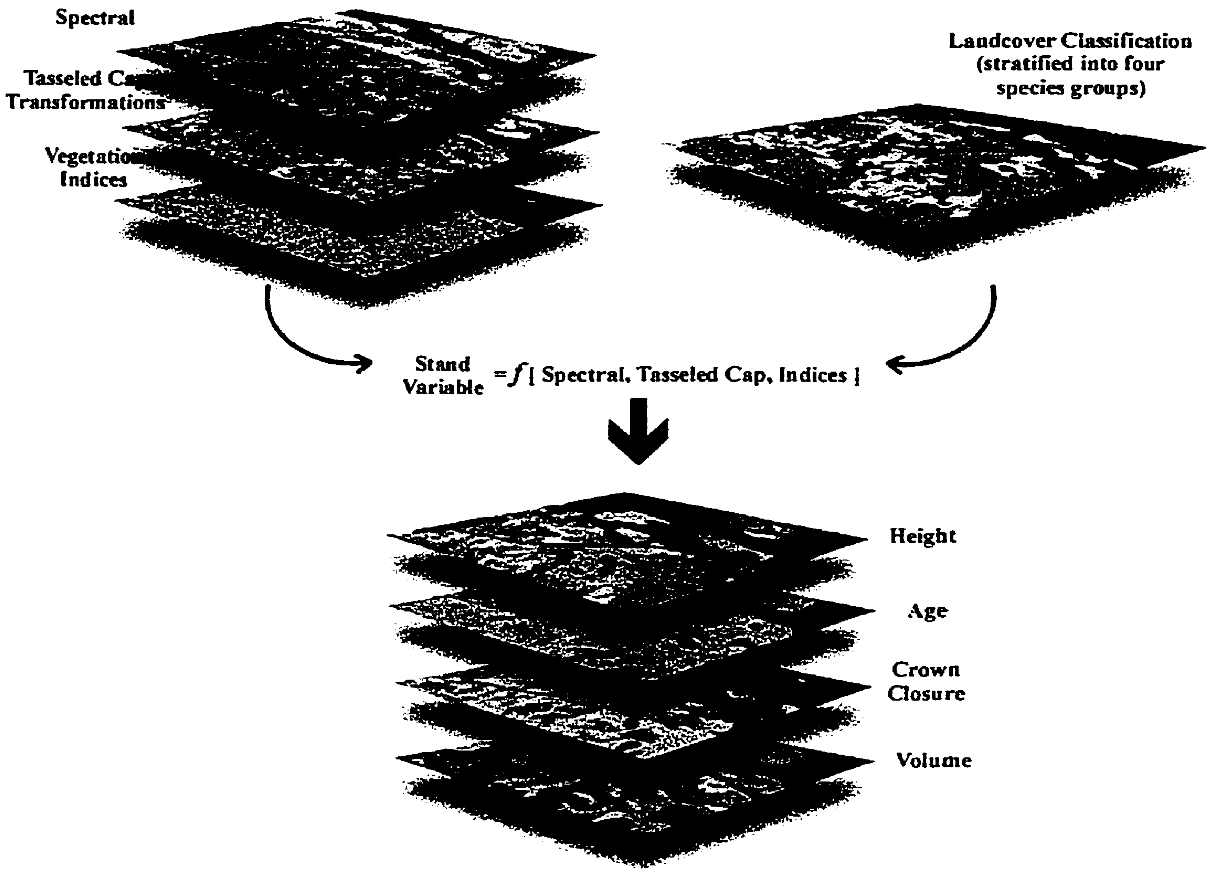

Figure 6.5 Example framework demonstrating how stand variable models can be linked with existing NWT landcover classifications.

7.0 Study Conclusions

An empirical study is described in this thesis in which Landsat Thematic Mapper satellite image reflectance and transformed data was directly related to various attributes of forest stands found throughout the Fort Simpson region, NWT. This study has been effective at further defining the relationship between these tree species and their structural variables as estimated from Landsat TM data for this particular ecoregion found within the Boreal forest of the NWT. Specifically, this research had identified the extent that broad forest stand variables could be estimated from Landsat TM data. A summary of the study conclusions, recommendations for future data collection and future work are provided in this final chapter.

7.1 Key Conclusions

This research has been effective for identifying trends in the relationships between stand variables and Landsat TM data for dominant North American Boreal forest stands, including pure jack pine, white spruce, trembling aspen and mixed-woods, found in the southwestern Northwest Territories. The general trend of increasing height, age, crown closure and volume with decreasing reflectance was identified in this study, which is consistent with trends that have been identified in other studies with similar research objectives.

The primary research objective was to determine what relationships existed between broad forest stand variables and Landsat TM data. Through this objective this study has identified specific relationships between Landsat data and stand variables for each of the dominant species groups found in the NWT. It was further identified that the strength of models derived to predict stand variables differed according to the species type and successional pathways followed by each species, which would lead to differing structural development in each species stands. Identification of this biological factor that would either permit or prohibit the generation of models to predict stand variables provided a further insight into remote sensing of Boreal forests, while accomplishing the first research sub-objective. The final research sub-objective, to consider the use of existing field techniques implemented in the NWT to facilitate integration into geospatial analysis, was established through the research experiences and results through this work, and are discussed in section 7.2 of this chapter.

The following points highlight the key findings of this research:

1. Models to predict stand variables, which were developed from Landsat TM data, were generally strongest for primary successional species, including pine and aspen; where the relationship was interpreted as one that is determined by consistent successional changes in stand structure and composition;

2. Secondary species, such as spruce, and mixed-wood stands provided weaker model strengths from Landsat TM data; their growth patterns and changes in stand structure did not always follow a consistent trend;

3. Models from Landsat TM data that predicted forest stand variables were generally strongest for jack pine species;

4. The strongest models were for height and age, since both variables are related to stand structure, which can be modeled depending upon the amount of shadows cast by the canopy, and the amount of gaps that open as the stand matures;

5. Crown closure models were not always dependent upon stand structure;
    - Jack pine crown closure was related to height and age, therefore an inverse relationship between crown closure and spectral response was observed, dry site understory species may also have affected the decrease in reflectance as stands open;
    - White spruce crown closure was not strongly related to any stand variable, therefore crown closure is more related to the reflectance of the trees;
    - Models for aspen and mixed-wood crown closure were not developed since there were very weak and insignificant relationships between crown closure and stand variables, therefore canopy structure would vary within a given crown closure class;

6. Models to predict stand volume were not significant for predicting volume in aspen and mixedwood stands; pine models were significant but weak; spruce models were significant and moderate. Additional research is required to identify the reasons why models were most effective for spruce and, largely, insignificant for the other three species in this study;
    - While spruce model strength is moderate, however, the relatively large standard error may affect the utility of the developed equation.

In addition to satisfying the research objectives for this thesis work, an additional methodology, used for predicting tree height from diameter at breast height, was developed as a pre-processing requirement for construction of the final field summary database. Tree height-diameter models were fitted with field data collected from jack pine, white spruce and aspen trees and evaluated with data not used for generation of the model coefficients. Tree height-diameter models were fitted with field data and evaluated with data not used for generation of the model coefficients. There were no significant differences in predicted heights, when compared to field measurements. These results indicate that the height-diameter models developed should be further evaluated to determine their suitability for operational applications in forest surveys in the Fort Simpson region of the NWT.

7.2 Recommendations for Future NWT Data Collections

The results of this study suggest a few possible directions for future remote sensing forestry studies in the NWT. The main recommendations from this work are directed towards improving the quality of precision attained when collecting forest inventory data in the field. The following points have been recommended for ensuring that field is collected in a fashion that would permit ease of integration into geospatial databases:

1. Techniques to accurately locate field plots need to be strengthened. Collect data for forest mensurational, remote sensing and GIS analysis purposes;
   - When collecting field data for either forest mensurational, volume cruising, or remote sensing/GIS study purposes, it is highly recommended that precise GPS measurements be obtained at each field plot location to permit accurate identification of plot locations on GIS and remote sensing databases. This is important to ensure that the correct pixels are sampled for any subsequent analyses;
   - When precise GPS measurements are unavailable, greater care should be taken to ensure that field plots are precisely located on air photos and inventory maps. More careful attention should be used when locating plots on the air photo, and when tying-in from known locations, to best facilitate

the identification of plots geographic location. This is especially important if future work will involve relating field plots to remote sensing.

2. Methods employed in estimating crown closure should be modified to ensure that quantitative estimates are obtained;
   - It is recommended that an instrument such as a *spherical densiometer* be used to measure crown closure. This would ensure that all estimates obtained are quantitative, which would permit more accurate comparison of crown closure values among stands and would facilitate development of stronger models to predict crown closure from satellite imagery.

3. Field methods for measuring tree height should involve measurements of each tree;
   - To permit proper recording of tree height for each stem, to permit enhanced forest inventory and growth and yield modeling, each tree in the plot should be measured, rather than only the dominant for each canopy layer, which is presently undertaken. To best facilitate this time consuming and costly activity, the incorporation of a laser height finder, or CFE vertex, is recommended for measurement of individual tree heights. These instruments offer the advantage of providing fast and accurate tree heights when compared to typical clinometer measurements.

4. Increased care and effort should be undertaken to ensure that age counts are obtained with high precision;
   - Rather than estimate age counts in the field it is recommended that stand age be determined in a controlled lab environment. This would ensure that

age counts are more accurate, which could further facilitate the development of statistically significant and defendable age models.

7.3 Future Studies

Upon completion of this study, a series of additional research projects, with a range of operational focuses are identified. These research projects are briefly described below:

1. Apply the methodology employed in this research to another study region in the NWT to determine the robustness and repeatability of the methods;
    - This study would be used to determine if similar results or trends would be obtained in the different ecoregions covered by the NWT;
    - Two potentially appropriate study regions would be the Fort Liard region or the Cameron hills. These two locations would be preferable for comparison studies since the composition and structure of the forest stands in these regions exhibit large variations from those observed in the Fort Simpson region.

2. Refine the research methodology to consider discrete classes of forest variables, rather than continuous data using a discriminant analysis approach;
    - For example each stand variable could possibly be stratified into 2, 3 or 4 classes, depending upon the range of the forest data and their relationships with the spectral information (i.e. 3 stand volume classes – 0 to 100 m^3/ha (low), 100 to 200 m^3/ha, and 200 m^3/ha +);
    - This approach has the advantage of reducing the variability that must be explained among the variables; however, the key disadvantage is that the level of detail available is reduced.

3. Explore alternate modeling approaches to estimate volume;
    - Study results suggest the prediction of stand variables from remote sensing data were stronger than for the prediction of volume.
    - An alternate approach is to integrate the stand height, age and crown closure models by species, and to use these predicted variables in a model to estimate volume in a system of equations. Predicted stand variables therefore become independent variables in the estimation of stand volume. Solving variables simultaneously in a system of equations has been developed and implemented by those in econometrics (Borders 1989), and has the advantage of distributing the error terms that may improve the ability to estimate volume.

4. Classification and mapping of coniferous (white spruce) understory;
    - Mixtures of trembling aspen and white spruce dominate the compositions of mixed woods in the boreal forest. Within these mixtures, white spruce often occurs as understory trees in deciduous and deciduous-dominate mixed-wood stands (Brace and Bella 1988). White spruce that grows under the protection of overstory deciduous is a primary source of future white spruce timber supply.
    - Field and aerial surveys and vehicle tours conducted during the project identified many areas with white spruce understory trees. Little is known about the spatial extent and occurrence of white spruce understory in the NWT.
    - Some satellite remote sensing studies have been directed specifically at mapping the broad spatial distribution and composition of understory from

a combination of leaf-off and leaf-on satellite images (Ghitter *et al.* 1995; Hall and Klita 1997; Hall *et al.* 1999).

- A study could be undertaken in the Fort Simpson or Fort Liard regions where white spruce understory is often found beneath a deciduous canopy.

5. Application of high-resolution satellite data to provide forestry estimates and update base map land data;
   - This study could be used to determine the utility of high-resolution satellite data for extracting detailed forestry information in the NWT.
   - High-resolution sensors that are possible candidates for these studies include the IKONOS-1 (1 m panchromatic) and the India IRS-1C/D sensor (5 m panchromatic band) which are presently in orbit:
   - o (http://www.ersc.wisc.edu/ersc/Resources/EOSC.html)
   - Another aspect to this study could include developing techniques for updating vintage base maps with high resolution satellite data.

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Appendix A: Field Summaries from 1998 and 1999 Field Data

Jack Pine Field Summaries from 1998 and 1999 Field Data (G## Plots = 1999 data; H## Plots = 1998 data)

PLOT	*FLD VOL*	*FLD CC*	*FLD HT*	*FLD AGE*	*FLD DBH*	*FLD STEM*	*FLD BA*	*%SW*	*%SB*	*%JP*	*%A*	*%PO*	*%BW*	*%L*
G103	125.04	53	8.89	31	7.24	6017	28	0	0	86	14	0	0	0
G104	96.72	49.1	9.10	21	7.43	4685	22	0	0	82	18	0	0	0
G125	166.43	36.9	18.54	169	16.77	871	20	0	0	100	0	0	0	0
G126	192.15	38	18.02	83	16.80	1033	24	0	0	100	0	0	0	0
G19	130.43	34.1	12.78	41	11.61	1997	22	0	0	100	0	0	0	0
G20	212.80	34.9	16.91	53	15.90	1348	28	0	0	100	0	0	0	0
G21	189.63	40.2	16.26	60	14.37	1572	26	0	0	92	8	0	0	0
G22	239.53	37.1	12.55	51	10.07	4807	40	0	0	100	0	0	0	0
G23	181.66	36.6	14.61	56	15.62	1440	28	0	0	100	0	0	0	0
G24	122.54	33.7	13.85	70	15.03	1119	20	0	0	100	0	0	0	0
G31	110.71	26	18.05	92	18.67	497	14	0	0	100	0	0	0	0
G34	180.82	42.6	13.88	40	11.25	2733	28	0	0	100	0	0	0	0
G35	200.94	36.4	14.51	45	12.68	2262	30	0	0	100	0	0	0	0
G36	163.01	39.8	13.79	44	13.84	1699	26	0	0	100	0	0	0	0
G37	150.32	42.9	13.11	51	11.04	2409	24	0	0	100	0	0	0	0
G38	128.92	38.8	12.31	45	11.00	2188	22	0	0	100	0	0	0	0
G39	112.11	30.2	10.46	41	9.16	3164	22	0	0	100	0	0	0	0
G40	163.19	42.9	11.21	46	8.47	5082	30	0	0	100	0	0	0	0
G41	146.16	32.2	11.70	47	9.41	3607	26	0	0	100	0	0	0	0
G42	142.69	40.8	10.86	40	9.69	3724	28	0	0	100	0	0	0	0
G44	136.62	21.1	18.16	87	25.59	340	18	0	0	100	0	0	0	0
G45	213.34	25.2	19.37	150	22.71	612	26	0	0	100	0	0	0	0
G58	93.99	25.5	18.23	82	19.69	358	12	0	0	100	0	0	0	0
G59	182.71	22.9	20.21	103	26.85	383	22	18	0	82	0	0	0	0
G60	257.18	25.2	19.03	125	23.27	733	32	6	0	94	0	0	0	0
H100	30.26	80	17.00	35	19.80	117	4	0	0	100	0	0	0	0
H101	52.66	40	15.51	99	16.44	345	8	0	0	100	0	0	0	0
H103	66.63	40	20.70	68	30.21	111	8	0	0	100	0	0	0	0
H105	107.17	80	12.64	48	10.62	1998	18	0	0	100	0	0	0	0
H106	98.17	80	13.35	52	12.45	1295	16	0	0	100	0	0	0	0
H108	219.77	70	13.87	51	12.56	2677	34	0	0	100	0	0	0	0
H109	104.75	70	14.27	31	14.15	961	16	0	0	100	0	0	0	0
H110	111.74	60	11.29	52	9.26	2848	20	0	0	100	0	0	0	0
H113	155.18	5	18.62	71	25.47	383	20	0	0	100	0	0	0	0
H114	187.87	10	18.67	95	24.57	498	24	0	0	100	0	0	0	0
H117	200.27	50	14.61	53	13.37	2114	30	0	0	100	0	0	0	0
H118	154.45	75	13.96	54	12.96	1780	24	8	0	92	0	0	0	0
H121	123.08	60	14.91	55	14.10	1098	18	0	0	100	0	0	0	0
H122	68.79	65	14.93	35	14.71	567	10	0	0	100	0	0	0	0
H123	275.09	75	13.95	38	12.91	3077	42	0	0	100	0	0	0	0

H124	292.40	65	14.36	61	13.46	2995	44	0	0	100	0	0	0	0
H125	228.34	65	13.62	57	12.17	3036	36	0	0	100	0	0	0	0
H40	193.98	60	13.70	60	13.35	1945	30	0	0	87	0	0	13	0
H68	159.16	60	10.91	30	8.99	4603	30	0	0	100	0	0	0	0
H71	26.69	10	14.70	N/A	13.96	259	4	0	0	100	0	0	0	0
H88	77.32	90	18.29	69	23.95	214	10	0	0	100	0	0	0	0
H92	95.82	40	14.97	47	15.40	703	14	0	0	86	14	0	0	0
H99	75.34	30	17.76	78	23.32	222	10	0	0	80	20	0	0	0

White Spruce Field Summaries for 1998 and 1999 Field Data (G## plots = 1999 data; H## plots = 1998 data)

PLOT	*FLD VOL*	*FLD CC*	*FLD HT*	*FLD AGE*	*FLD DBH*	*FLD STEMS*	*FLD BA*	*%SW*	*%SB*	*%JP*	*%A*	*%PO*	*%BW*	*%L*
G106	31.93	44.2	12.75	49	17.91	234	6	100	0	0	0	0	0	0
G12	43.77	41.2	9.94	51	12.24	816	10	100	0	0	0	0	0	0
G127	49.33	50.7	14.17	115	15.43	412	8	100	0	0	0	0	0	0
G32	239.97	44.7	18.43	102	20.17	897	30	80	0	7	13	0	0	0
G33	211.63	36.9	23.75	102	26.10	390	22	100	0	0	0	0	0	0
G49	164.52	33.8	12.22	62	12.17	2436	30	93	0	0	7	0	0	0
G51	163.71	35.8	11.28	57	11.16	3100	32	94	0	0	6	0	0	0
G56	121.47	33	13.90	51	13.43	1370	20	100	0	0	0	0	0	0
G57	166.27	28.6	12.28	83	11.51	2410	28	86	0	0	14	0	0	0
G74	77.67	25.2	15.08	N/A	17.74	461	12	100	0	0	0	0	0	0
G76	202.54	41.3	18.57	167	20.95	727	26	100	0	0	0	0	0	0
G77	202.03	45.2	22.42	117	22.52	518	22	91	0	0	0	0	9	0
G78	82.55	44.7	20.06	136	25.09	187	10	100	0	0	0	0	0	0
G79	171.81	34.8	19.25	131	27.67	351	22	100	0	0	0	0	0	0
G80	103.39	15.1	20.64	154	25.79	226	12	100	0	0	0	0	0	0
G81	153.31	18.2	18.67	198	25.13	393	20	100	0	0	0	0	0	0
G83	61.78	14.8	10.84	N/A	11.54	1028	12	100	0	0	0	0	0	0
G85	215.39	42.6	22.07	123	25.51	451	24	92	0	0	8	0	0	0
G86	143.00	43.2	18.87	108	19.14	606	18	89	0	0	11	0	0	0
G87	87.46	51.5	13.67	123	17.36	537	14	86	0	0	0	0	14	0
G88	119.89	40.8	20.10	96	23.22	309	14	100	0	0	0	0	0	0
G89	129.71	37.4	22.68	108	27.79	224	14	100	0	0	0	0	0	0
G90	211.63	28.3	23.89	106	30.21	302	22	100	0	0	0	0	0	0
G91	140.54	19	21.74	108	29.60	229	16	88	0	0	13	0	0	0
G92	170.00	25.7	23.47	135	32.49	212	18	89	0	0	11	0	0	0
G93	162.38	12.2	22.42	171	26.10	334	18	100	0	0	0	0	0	0
G94	238.65	26.8	20.79	125	24.00	609	28	100	0	0	0	0	0	0
G95	181.41	29.6	22.12	115	26.56	353	20	100	0	0	0	0	0	0
G96	187.43	33.3	20.48	123	22.72	522	22	100	0	0	0	0	0	0
G97	120.24	30.2	17.84	165	21.20	438	16	100	0	0	0	0	0	0
G98	225.09	32.5	19.26	132	23.92	600	28	100	0	0	0	0	0	0
G99	314.84	33.8	24.29	166	30.25	429	32	100	0	0	0	0	0	0
H112	135.32	50	10.68	54	11.53	2593	28	100	0	0	0	0	0	0
H115	126.99	10	11.83	70	12.65	1845	24	100	0	0	0	0	0	0
H72	43.67	25	9.66	25	10.14	1203	10	100	0	0	0	0	0	0
H83	64.38	30	14.63	84	15.69	501	10	100	0	0	0	0	0	0
H84	25.14	30	14.71	58	15.71	202	4	100	0	0	0	0	0	0
H87	24.54	70	14.62	52	16.10	197	4	100	0	0	0	0	0	0
H96	110.56	50	11.55	76	12.18	1871	22	100	0	0	0	0	0	0
H98	122.12	40	17.60	78	21.12	432	16	88	0	13	0	0	0	0

Trembling Aspen Field Summaries for 1998 and 1999 Field Data (G## plots = 1999 data; H## plots = 1998 data)

PLOT	*FLD VOL*	*FLD CC*	*FLD HT*	*FLD AGE*	*FLD DBH*	*FLD STEM*	*FLD BA*	*%SW*	*%SB*	*%JP*	*%A*	*%PO*	*%BW*	*%L*
G10	114.99	43.4	15.79	63	13.63	964	16	0	0	0	100	0	0	0
G102	56.43	56.1	8.52	37	5.92	4701	14	0	0	14	86	0	0	0
G122	172.89	47.1	23.26	177	27.15	309	18	11	0	0	89	0	0	0
G124	188.42	53.3	22.45	148	22.40	498	20	10	0	0	90	0	0	0
G128	159.43	63.7	23.99	137	29.25	229	16	0	0	13	88	0	0	0
G129	262.06	49.4	26.03	115	24.89	476	24	8	0	0	92	0	0	0
G13	100.34	36.3	13.89	103	9.12	2313	16	0	0	0	100	0	0	0
G133	117.84	55.1	24.04	149	30.23	166	12	17	0	0	83	0	0	0
G14	126.30	43.8	12.91	67	9.99	2712	22	0	0	0	100	0	0	0
G15	91.40	35.2	12.43	57	9.18	2271	16	0	0	0	100	0	0	0
G16	119.13	38.7	12.04	85	9.63	2914	22	0	0	0	100	0	0	0
G17	63.73	41.1	9.76	69	8.26	2450	14	0	0	0	100	0	0	0
G18	132.01	56.2	10.28	74	8.95	4185	28	0	0	0	100	0	0	0
G25	144.57	46.3	15.02	56	12.07	1873	22	0	0	0	100	0	0	0
G26	257.44	44.5	16.60	99	12.97	2681	36	0	0	0	100	0	0	0
G27	191.32	47.1	16.60	57	10.59	2861	26	0	0	0	100	0	0	0
G28	140.74	41.6	14.39	78	12.15	1794	22	0	0	0	100	0	0	0
G29	96.97	45.8	11.86	82	8.66	2845	18	0	0	11	89	0	0	0
G30	92.99	34.7	13.18	77	10.15	1955	16	0	0	0	100	0	0	0
G47	225.54	31.2	17.37	147	16.98	1264	30	0	0	0	100	0	0	0
G48	204.66	38.2	16.74	104	15.45	1449	28	0	0	0	100	0	0	0
G50	94.05	26.5	18.75	82	23.65	265	12	17	0	0	83	0	0	0
G52	148.41	36.4	17.24	109	15.96	980	20	0	0	0	100	0	0	0
G53	113.83	35.1	16.23	79	12.52	1262	16	0	0	0	100	0	0	0
G54	108.23	40	21.14	105	21.54	308	12	0	0	0	100	0	0	0
G7	61.19	31.5	9.63	60	7.15	3189	14	14	0	0	86	0	0	0
G8	73.00	30.8	7.79	52	5.60	7776	20	0	0	0	100	0	0	0
G9	111.94	39.8	10.18	57	7.86	4602	24	17	0	0	83	0	0	0
H104	260.63	80	14.19	68	12.31	3123	40	0	0	15	85	0	0	0
H120	198.22	45	14.87	61	12.84	2275	30	0	0	20	80	0	0	0
H146	167.18	30	16.00	68	14.73	1388	24	0	0	0	100	0	0	0
H147	178.71	65	15.76	86	14.37	1579	26	0	0	0	100	0	0	0
H148	189.80	50	19.93	94	21.74	570	22	0	0	0	100	0	0	0
H149	213.37	75	23.61	102	30.37	302	22	0	0	0	100	0	0	0
H150	282.16	80	22.62	126	27.90	485	30	0	0	0	100	0	0	0
H151	57.54	75	12.26	52	11.18	1142	12	17	0	0	33	50	0	0
H152	47.43	25	18.46	72	18.50	221	6	0	0	0	100	0	0	0
H153	118.33	40	17.20	84	16.88	697	16	0	0	0	88	13	0	0
H154	170.30	85	19.74	87	21.84	516	20	0	0	0	100	0	0	0
H155	59.85	75	14.22	64	13.47	637	10	0	0	0	40	60	0	0
H156	237.72	70	19.52	108	22.00	745	30	0	0	0	73	7	20	0
H157	140.10	40	20.79	87	20.10	460	16	0	0	0	75	25	0	0

H158	206.21	90	22.71	75	29.10	326	22	9	0	0	91	0	0	0
H159	233.33	80	21.99	89	27.46	424	26	0	0	0	77	23	0	0
H160	251.07	50	24.18	92	32.84	303	26	8	0	0	85	8	0	0
H161	93.38	60	17.78	90	17.16	506	12	0	0	0	100	0	0	0
H162	213.11	80	17.45	84	16.55	1272	28	0	0	0	100	0	0	0
H163	216.64	70	19.65	94	19.87	829	26	0	0	0	100	0	0	0
H164	116.94	60	23.03	73	28.07	190	12	0	0	0	100	0	0	0
H165	225.53	70	22.36	87	27.81	384	24	0	0	0	100	0	0	0
H166	236.57	80	21.35	82	23.98	556	26	0	0	0	100	0	0	0
H167	296.05	80	20.15	83	21.50	909	34	0	0	0	100	0	0	0
H168	398.51	70	22.88	85	28.04	674	42	0	0	0	100	0	0	0
H169	292.43	70	21.36	76	24.73	640	32	0	0	0	100	0	0	0
H170	348.22	20	21.76	78	24.81	762	38	0	0	0	100	0	0	0
H182	97.76	30	14.28	24	12.23	1348	16	0	0	0	88	13	0	0
H185	107.69	45	17.60	49	19.02	403	14	0	0	0	71	29	0	0
H191	199.11	60	19.00	97	19.84	747	24	0	0	0	100	0	0	0
H192	179.99	N/A	19.12	80	19.77	706	22	0	0	0	100	0	0	0
H193	245.82	40	20.66	65	22.51	684	28	7	0	0	93	0	0	0
H195	118.54	60	20.08	60	19.68	451	14	0	0	0	100	0	0	0
H39	58.04	20	16.28	43	17.02	342	8	0	0	0	100	0	0	0
H43	169.71	15	20.05	84	24.25	415	20	0	0	20	80	0	0	0
H44	133.29	70	15.38	73	15.02	880	18	0	0	0	89	0	11	0
H45	137.17	30	17.22	62	17.80	664	18	0	0	11	89	0	0	0
H46	170.97	30	19.92	43	21.57	533	20	0	0	0	100	0	0	0
H47	108.18	10	17.36	74	16.84	594	14	0	0	14	86	0	0	0
H51	140.73	60	20.44	79	23.46	356	16	0	0	0	100	0	0	0
H52	110.38	70	15.84	64	14.76	919	16	0	0	0	100	0	0	0
H53	283.46	40	18.66	107	20.25	970	34	12	0	6	82	0	0	0
H55	180.26	5	21.19	87	24.18	422	20	0	0	0	100	0	0	0
H56	452.93	75	21.11	93	24.20	1048	50	0	0	0	100	0	0	0
H57	293.77	80	18.86	94	19.34	1194	36	0	0	0	100	0	0	0
H61	262.83	90	20.81	80	24.40	624	30	20	0	0	80	0	0	0
H63	189.02	60	17.72	60	18.06	886	24	0	0	17	83	0	0	0
H66	135.00	65	19.86	52	21.03	439	16	0	0	13	88	0	0	0
H78	17.45	90	20.50	69	18.00	79	2	0	0	0	100	0	0	0
H79	71.87	90	16.57	63	14.34	612	10	0	0	0	100	0	0	0
H81	105.39	80	16.38	62	15.53	689	14	0	0	0	100	0	0	0
H89	66.21	80	12.25	67	9.76	1561	12	0	0	0	100	0	0	0
H90	48.84	80	13.58	73	11.22	786	8	0	0	0	100	0	0	0
H93	197.87	80	19.09	82	19.59	775	24	0	0	0	100	0	0	0
H94	332.98	70	22.00	50	26.50	639	36	0	0	0	100	0	0	0
H95	264.64	70	14.63	73	12.92	2909	40	15	0	0	85	0	0	0
H97	252.07	70	19.63	75	20.31	906	30	0	0	0	100	0	0	0

Mixed-wood Field Plots from 1998 and 1999 Field Data (G## plots = 1999 data; G## plots = 1998 data).

PLOT	*FLD VOL*	*FLD CC*	*FLD HT*	*FLD AGE*	*FLD DBH*	*FLD STEM*	*FLD BA*	*%SW*	*%SB*	*%JP*	*%A*	*%PO*	*%BW*	*%L*
G100	76.89	59	9.18	26	6.95	4404	18	0	0	22	56	0	22	0
G107	54.79	38.7	12.91	49	17.96	372	10	40	0	0	60	0	0	0
G118	171.63	58.2	22.35	155	26.98	305	18	22	0	11	67	0	0	0
G121	107.94	42.9	18.78	N/A	26.10	238	14	43	0	0	57	0	0	0
G123	256.97	55.1	23.93	175	26.34	450	26	38	0	8	54	0	0	0
G130	242.86	54.1	21.96	159	20.73	753	26	38	0	0	62	0	0	0
G131	273.90	58.8	25.74	150	29.05	385	26	31	0	0	69	0	0	0
G132	141.58	51.2	24.84	137	30.08	195	14	43	0	0	57	0	0	0
G46	201.65	38.8	14.64	104	15.86	1438	30	47	0	0	53	0	0	0
G55	109.72	34.6	18.37	138	17.15	598	14	29	0	0	71	0	0	0
G67	147.15	29.1	22.27	135	23.76	343	16	25	0	25	50	0	0	0
G68	83.74	31.2	18.22	63	22.34	300	12	50	0	0	17	0	33	0
H102	112.85	40	18.98	50	21.91	344	14	0	0	43	57	0	0	0
H181	67.00	75	13.90	52	14.50	684	12	33	0	0	17	50	0	0
H183	31.40	10	12.62	28	12.41	460	6	33	0	0	67	0	0	0
H184	58.11	70	14.10	17	14.24	560	10	40	0	0	0	60	0	0
H194	132.44	40	19.76	39	21.94	421	16	38	0	0	63	0	0	0
H42	140.19	30	14.08	72	13.28	1294	20	0	0	40	60	0	0	0
H50	246.98	80	19.31	69	21.61	793	30	13	0	20	67	0	0	0
H54	287.12	25	18.64	56	20.54	1021	36	0	0	22	78	0	0	0
H58	244.28	60	17.99	64	18.75	979	30	13	0	20	67	0	0	0
H59	214.17	60	19.34	89	21.30	694	26	38	0	0	62	0	0	0
H60	237.37	25	18.11	36	19.12	957	30	20	0	13	60	0	7	0
H64	180.72	45	19.88	66	27.29	354	22	0	0	45	55	0	0	0
H67	133.36	60	18.98	67	23.55	335	16	25	0	13	63	0	0	0
H69	276.52	55	18.69	50	21.43	866	34	0	0	47	53	0	0	0
G105	79.58	52.3	7.96	31	5.37	8260	20	0	0	70	20	0	10	0
G108	41.08	25.5	15.06	105	25.14	108	6	33	0	33	33	0	0	0
G11	77.87	38.5	12.22	48	11.65	1144	14	57	0	0	43	0	0	0
G119	224.29	47.6	16.41	N/A	17.78	1236	32	50	0	13	38	0	0	0
G5	247.80	28.6	20.76	118	21.81	717	28	64	0	0	36	0	0	0
G69	193.24	40.8	16.03	78	18.28	971	28	57	0	14	21	0	7	0
G70	206.51	32.5	19.48	106	27.16	426	26	8	0	54	38	0	0	0
G71	142.59	40.8	19.27	72	27.99	287	18	44	0	22	33	0	0	0
G72	171.04	40.6	17.78	72	24.95	456	24	50	0	8	25	0	17	0
H107	53.19	80	14.68	39	13.12	566	8	0	0	75	25	0	0	0
H119	210.44	65	14.40	52	13.14	2297	32	0	0	75	25	0	0	0
H41	88.14	70	21.34	78	27.15	170	10	0	0	60	40	0	0	0
H48	273.74	80	16.69	48	17.71	1481	38	63	0	0	37	0	0	0
H49	276.06	70	18.72	56	23.16	770	34	41	0	12	47	0	0	0
H62	339.83	60	18.88	98	22.15	1037	42	19	0	43	38	0	0	0
H65	112.68	60	19.46	92	26.09	234	14	0	0	57	43	0	0	0

H70	248.25	30	19.46	N/A	23.63	642	30	0	0	53	47	0	0	0
H80	91.48	50	17.55	67	17.85	461	12	0	0	67	33	0	0	0
H91	258.91	50	14.91	77	13.38	2539	38	0	0	53	47	0	0	0

Appendix B: GIS stand variables and image reflectance and transformed values obtained for each study plot

GIS stand variables and spectral values for Jack pine stands (G## plots = 1999 data; H## plots = 1998 data).

PLOT	*GIS AGE*	*GIS CC*	*GIS HT*	*TM1*	*TM2*	*TM3*	*TM4*	*TM5*	*TM7*	*NDVI*	*SI 4/5*	*4/7*	*BR*	*GR*	*WT*
G103	70	50	9	15.00	34.00	21.00	92.00	48.00	55.00	0.63	1.92	1.67	84.89	14.17	-6.98
G104	70	50	9	17.00	37.00	21.00	92.00	49.00	55.00	0.63	1.88	1.67	86.17	13.48	-7.14
G125	100	50	16	13.00	28.00	16.00	58.00	48.00	55.00	0.57	1.21	1.05	71.24	2.36	-13.42
G126	100	50	16	18.00	34.00	20.00	57.00	43.00	50.00	0.48	1.33	1.14	71.65	-1.39	-10.44
G19	80	40	14	12.00	31.00	18.00	53.00	39.00	41.00	0.49	1.36	1.29	66.39	-0.32	-9.13
G20	80	40	14	12.00	28.00	16.00	57.00	39.00	46.00	0.56	1.46	1.24	66.94	1.73	-8.72
G21	80	40	14	13.00	31.00	14.00	60.00	40.00	32.00	0.62	1.50	1.88	68.05	3.80	-6.75
G22	80	40	14	11.00	31.00	14.00	53.00	41.00	50.00	0.58	1.29	1.06	66.36	0.87	-10.69
G23	80	40	14	11.00	28.00	16.00	55.00	41.00	41.00	0.55	1.34	1.34	66.81	1.59	-10.03
G24	80	40	14	12.00	28.00	14.00	58.00	40.00	41.00	0.61	1.45	1.41	67.29	3.24	-8.25
G31	110	50	17	12.00	31.00	20.00	60.00	44.00	37.00	0.50	1.36	1.62	70.70	2.48	-10.17
G34	60	80	13	15.00	31.00	16.00	57.00	37.00	41.00	0.56	1.54	1.39	67.45	0.78	-7.07
G35	60	80	13	17.00	34.00	18.00	60.00	40.00	37.00	0.54	1.50	1.62	70.59	1.23	-7.08
G36	60	80	13	14.00	34.00	18.00	58.00	40.00	32.00	0.53	1.45	1.81	68.99	1.49	-7.43
G37	60	80	13	13.00	28.00	14.00	57.00	33.00	32.00	0.61	1.73	1.78	64.46	2.21	-4.50
G38	60	80	13	13.00	28.00	12.00	58.00	39.00	37.00	0.66	1.49	1.57	66.49	3.61	-6.73
G39	60	80	13	14.00	31.00	16.00	58.00	40.00	41.00	0.57	1.45	1.41	68.60	1.93	-8.12
G40	120	10	25	16.00	31.00	14.00	53.00	32.00	41.00	0.58	1.66	1.29	64.37	-0.68	-4.79
G41	120	10	25	12.00	31.00	18.00	58.00	37.00	32.00	0.53	1.57	1.81	67.27	2.10	-6.66
G42	120	10	25	13.00	31.00	20.00	48.00	37.00	37.00	0.41	1.30	1.30	64.87	-3.22	-9.30
G44	120	20	26	14.00	28.00	16.00	42.00	32.00	32.00	0.45	1.31	1.31	59.78	-5.19	-7.12
G45	120	20	26	15.00	28.00	18.00	43.00	41.00	41.00	0.41	1.05	1.05	64.56	-5.11	-12.16
G58	120	20	26	16.00	31.00	16.00	48.00	33.00	37.00	0.50	1.45	1.30	63.45	-3.15	-6.34
G59	120	20	26	16.00	31.00	14.00	43.00	35.00	41.00	0.51	1.23	1.05	61.92	-4.86	-8.07
G60	120	20	26	15.00	25.00	14.00	43.00	35.00	37.00	0.51	1.23	1.16	60.96	-3.99	-8.14
H100	80	30	17	21.00	34.00	23.00	67.00	44.00	46.00	0.49	1.52	1.46	76.80	1.53	-8.98
H101	80	30	17	21.00	40.00	27.00	75.00	48.00	55.00	0.47	1.56	1.36	82.72	3.50	-10.30
H103	80	30	14	22.00	37.00	25.00	57.00	37.00	32.00	0.39	1.54	1.78	71.75	-3.71	-6.67
H105	80	30	14	21.00	40.00	25.00	75.00	53.00	50.00	0.50	1.42	1.50	83.85	4.51	-12.03
H106	80	30	14	20.00	37.00	25.00	60.00	43.00	46.00	0.41	1.40	1.30	74.57	-1.92	-10.02
H108	80	30	14	23.00	37.00	27.00	68.00	49.00	41.00	0.43	1.39	1.66	80.76	0.85	-10.91
H109	80	30	14	21.00	37.00	27.00	50.00	43.00	50.00	0.30	1.16	1.00	72.17	-7.24	-12.67
H110	80	30	14	21.00	40.00	27.00	53.00	44.00	55.00	0.32	1.20	0.96	74.15	-6.11	-12.85
H113	80	30	17	22.00	34.00	25.00	45.00	40.00	41.00	0.29	1.13	1.10	68.84	-8.73	-11.31
H114	80	30	17	20.00	34.00	23.00	42.00	35.00	41.00	0.29	1.20	1.02	64.88	-9.37	-9.46
H117	80	30	14	22.00	40.00	23.00	65.00	45.00	41.00	0.48	1.44	1.59	77.31	0.34	-9.03
H118	80	30	14	22.00	40.00	27.00	63.00	44.00	50.00	0.40	1.43	1.26	77.61	-1.88	-10.25
H121	80	30	14	21.00	37.00	23.00	58.00	43.00	41.00	0.43	1.35	1.41	73.66	-2.20	-9.47
H122	80	30	14	20.00	37.00	25.00	45.00	40.00	46.00	0.29	1.13	0.98	68.67	-8.57	-11.84

H123	80	30	14	20.00	37.00	23.00	45.00	39.00	41.00	0.32	1.15	1.10	67.58	-7.93	-10.46
H124	80	30	14	20.00	37.00	23.00	47.00	39.00	41.00	0.34	1.21	1.15	68.14	-7.20	-10.13
H125	80	30	14	20.00	37.00	23.00	48.00	40.00	46.00	0.35	1.20	1.04	69.31	-6.57	-10.83
H40	80	40	18	21.00	37.00	21.00	73.00	48.00	41.00	0.55	1.52	1.78	79.96	5.14	-8.56
H68	80	30	15	18.00	34.00	21.00	40.00	28.00	32.00	0.31	1.43	1.25	61.00	-9.31	-5.67
H71	70	20	10	20.00	37.00	21.00	70.00	47.00	46.00	0.54	1.49	1.52	78.28	3.73	-9.18
H88	70	20	17	21.00	42.00	23.00	75.00	51.00	50.00	0.53	1.47	1.50	82.73	4.69	-10.28
H92	70	20	17	20.00	45.00	29.00	67.00	51.00	37.00	0.40	1.31	1.81	80.83	-0.02	-11.69
H99	80	30	17	18.00	37.00	23.00	62.00	40.00	32.00	0.46	1.55	1.94	72.96	-0.03	-7.00

GIS stand variables and spectral values for White spruce stands (G## plots = 1999 data; H## plots = 1998 data).

PLOT	*GIS AGE*	*GIS CC*	*GIS HT*	*TM1*	*TM2*	*TM3*	*TM4*	*TM5*	*TM7*	*NDVI*	*SI 4/5*	*4/7*	*BR*	*GR*	*WT*
G106	100	20	16	16.00	37.00	21.00	87.00	47.00	50.00	0.61	1.85	1.74	83.15	11.61	-6.64
G12	90	20	14	14.00	31.00	20.00	72.00	52.00	55.00	0.57	1.38	1.31	78.52	6.77	-12.91
G127	100	50	16	13.00	31.00	20.00	60.00	44.00	46.00	0.50	1.36	1.30	71.33	1.87	-10.87
G32	110	50	17	12.00	28.00	14.00	43.00	40.00	41.00	0.51	1.08	1.05	62.28	-3.26	-11.31
G33	110	50	17	14.00	28.00	12.00	39.00	29.00	32.00	0.53	1.34	1.22	56.82	-5.68	-5.90
G49	90	40	18	15.00	34.00	20.00	55.00	48.00	55.00	0.47	1.15	1.00	72.16	-1.17	-14.12
G51	90	40	18	15.00	31.00	20.00	58.00	45.00	55.00	0.49	1.29	1.05	72.14	0.35	-12.38
G56	110	40	14	17.00	34.00	21.00	65.00	47.00	50.00	0.51	1.38	1.30	75.95	2.16	-11.09
G57	80	30	14	21.00	34.00	21.00	62.00	47.00	50.00	0.49	1.32	1.24	75.71	-0.10	-11.33
G74	70	30	15	16.00	37.00	21.00	43.00	44.00	55.00	0.34	0.98	0.78	67.96	-7.48	-14.65
G76	100	30	20	21.00	37.00	25.00	53.00	48.00	50.00	0.36	1.10	1.06	74.58	-4.96	-14.14
G77	100	30	20	22.00	37.00	21.00	50.00	43.00	46.00	0.41	1.16	1.09	70.85	-5.70	-11.11
G78	90	50	18	23.00	40.00	21.00	72.00	48.00	55.00	0.55	1.50	1.31	80.75	3.16	-9.69
G79	100	30	20	21.00	37.00	23.00	52.00	45.00	50.00	0.39	1.16	1.04	72.66	-5.27	-12.90
G80	100	30	20	21.00	37.00	25.00	57.00	52.00	46.00	0.39	1.10	1.24	76.86	-3.13	-14.90
G81	100	30	20	23.00	40.00	29.00	53.00	52.00	55.00	0.29	1.02	0.96	77.88	-6.77	-16.62
G83	110	10	19	25.00	42.00	29.00	58.00	48.00	50.00	0.33	1.21	1.16	78.88	-5.42	-12.85
G85	80	20	17	14.00	28.00	16.00	35.00	30.00	37.00	0.37	1.17	0.95	57.28	-8.31	-8.28
G86	80	20	17	12.00	23.00	14.00	40.00	36.00	46.00	0.48	1.11	0.87	59.51	-4.65	-10.89
G87	80	20	17	13.00	31.00	16.00	37.00	32.00	28.00	0.40	1.16	1.32	57.90	-7.13	-7.69
G88	130	50	25	15.00	28.00	16.00	37.00	29.00	28.00	0.40	1.28	1.32	57.34	-7.61	-6.34
G89	130	50	25	15.00	31.00	20.00	37.00	39.00	37.00	0.30	0.95	1.00	62.00	-8.74	-12.01
G90	130	50	25	16.00	28.00	16.00	42.00	40.00	37.00	0.45	1.05	1.14	63.20	-5.46	-10.98
G91	150	20	27	14.00	34.00	14.00	53.00	52.00	55.00	0.58	1.02	0.96	71.21	0.26	-15.47
G92	150	20	27	13.00	31.00	14.00	62.00	52.00	64.00	0.63	1.19	0.97	73.79	4.03	-14.93
G93	140	30	24	14.00	28.00	20.00	57.00	56.00	64.00	0.48	1.02	0.89	74.94	0.37	-18.84
G94	140	30	24	13.00	28.00	14.00	42.00	47.00	55.00	0.50	0.89	0.76	64.74	-4.38	-15.86
G95	140	30	24	12.00	31.00	14.00	43.00	45.00	41.00	0.51	0.96	1.05	64.30	-3.18	-13.61
G96	140	30	24	13.00	25.00	14.00	43.00	40.00	50.00	0.51	1.08	0.86	62.66	-3.64	-12.17
G97	150	20	24	11.00	25.00	16.00	42.00	39.00	37.00	0.45	1.08	1.14	61.05	-3.95	-11.26
G98	150	20	24	13.00	28.00	16.00	40.00	39.00	46.00	0.43	1.03	0.87	61.66	-5.77	-11.97
G99	150	20	24	10.00	25.00	12.00	39.00	39.00	37.00	0.53	1.00	1.05	58.68	-4.02	-11.42
H112	80	30	17	22.00	37.00	27.00	52.00	39.00	41.00	0.32	1.33	1.27	71.35	-6.69	-9.48
H115	80	30	17	22.00	40.00	25.00	45.00	35.00	32.00	0.29	1.29	1.41	67.22	-9.13	-7.63
H72	80	30	15	17.00	40.00	23.00	53.00	43.00	46.00	0.39	1.23	1.15	71.53	-3.93	-11.16
H83	60	20	10	15.00	37.00	25.00	45.00	41.00	55.00	0.29	1.10	0.82	68.30	-7.73	-13.87
H84	60	20	10	17.00	37.00	23.00	43.00	37.00	41.00	0.30	1.16	1.05	66.00	-8.18	-10.47
H87	60	20	10	18.00	37.00	23.00	50.00	45.00	59.00	0.37	1.11	0.85	71.86	-5.78	-14.37
H96	80	30	14	20.00	40.00	21.00	57.00	35.00	37.00	0.46	1.63	1.54	69.74	-2.59	-5.30
H98	80	30	17	22.00	37.00	23.00	73.00	49.00	50.00	0.52	1.49	1.46	81.52	4.06	-10.21

GIS stand variables and spectral values for Trembling aspen stands (G## plots = 1999 data; H## plots = 1998 data).

PLOT	*GIS AGE*	*GIS CC*	*GIS HT*	*TM1*	*TM2*	*TM3*	*TM4*	*TM5*	*TM7*	*NDVI*	*SI 4 5*	*4/7*	*BR*	*GR*	*WT*
G10	90	20	14	13.00	34.00	16.00	97.00	57.00	50.00	0.72	1.70	1.94	87.48	19.21	-9.18
G102	70	70	8	17.00	34.00	20.00	111.00	62.00	50.00	0.69	1.79	2.22	95.94	23.74	-8.08
G122	70	30	15	18.00	42.00	25.00	45.00	49.00	50.00	0.29	0.92	0.90	72.16	-8.38	-16.39
G124	130	60	28	20.00	37.00	29.00	75.00	55.00	55.00	0.44	1.36	1.36	84.88	3.80	-14.06
G128	100	50	16	16.00	31.00	18.00	90.00	51.00	32.00	0.67	1.76	2.81	83.45	15.46	-5.84
G129	100	50	16	15.00	31.00	16.00	80.00	47.00	55.00	0.67	1.70	1.45	78.86	10.91	-7.92
G13	80	40	16	14.00	34.00	18.00	98.00	62.00	59.00	0.69	1.58	1.66	90.48	19.00	-11.73
G133	110	30	17	12.00	34.00	16.00	67.00	37.00	37.00	0.61	1.81	1.81	70.00	5.88	-4.87
G14	80	40	16	15.00	31.00	18.00	102.00	59.00	55.00	0.70	1.73	1.85	90.58	20.41	-9.42
G15	80	40	16	14.00	34.00	16.00	105.00	63.00	50.00	0.74	1.67	2.10	92.33	22.84	-9.82
G16	80	20	14	15.00	34.00	18.00	95.00	64.00	41.00	0.68	1.48	2.32	89.86	18.09	-11.83
G17	80	20	14	15.00	34.00	20.00	93.00	60.00	55.00	0.65	1.55	1.69	88.96	16.10	-11.90
G18	80	20	14	14.00	37.00	21.00	95.00	63.00	59.00	0.64	1.51	1.61	91.02	16.31	-13.52
G25	80	20	15	14.00	37.00	20.00	107.00	63.00	59.00	0.69	1.70	1.81	94.44	21.92	-10.81
G26	80	20	15	14.00	31.00	20.00	107.00	63.00	55.00	0.69	1.70	1.95	93.77	22.52	-10.74
G27	80	20	15	14.00	37.00	20.00	113.00	63.00	50.00	0.70	1.79	2.26	96.32	25.13	-8.62
G28	80	30	14	15.00	28.00	18.00	103.00	64.00	55.00	0.70	1.61	1.87	92.66	21.64	-11.74
G29	80	30	14	15.00	34.00	20.00	105.00	60.00	50.00	0.68	1.75	2.10	92.69	21.32	-9.10
G30	80	30	14	11.00	31.00	20.00	98.00	63.00	46.00	0.66	1.56	2.13	89.77	20.05	-12.04
G47	110	60	17	17.00	37.00	21.00	87.00	53.00	46.00	0.61	1.64	1.89	85.49	11.86	-9.18
G48	110	60	17	18.00	34.00	23.00	92.00	52.00	55.00	0.60	1.77	1.67	87.58	13.02	-8.74
G50	90	40	18	17.00	34.00	18.00	67.00	48.00	46.00	0.58	1.40	1.46	75.82	4.22	-10.28
G52	110	40	14	20.00	37.00	21.00	80.00	51.00	41.00	0.58	1.57	1.95	82.79	8.45	-8.59
G53	110	40	14	17.00	37.00	21.00	75.00	55.00	59.00	0.56	1.36	1.27	82.55	6.39	-13.44
G54	110	40	14	20.00	40.00	23.00	82.00	53.00	55.00	0.56	1.55	1.49	85.47	8.05	-10.90
G7	80	30	10	17.00	37.00	18.00	88.00	52.00	46.00	0.66	1.69	1.91	84.64	13.61	-7.56
G8	80	30	10	14.00	37.00	20.00	88.00	56.00	46.00	0.63	1.57	1.91	85.58	14.10	-10.19
G9	80	30	10	16.00	37.00	16.00	85.00	55.00	46.00	0.68	1.55	1.85	83.64	13.14	-9.29
H104	80	30	14	23.00	37.00	25.00	72.00	45.00	41.00	0.48	1.60	1.76	80.06	2.62	-8.03
H120	80	30	14	20.00	40.00	23.00	88.00	49.00	50.00	0.59	1.80	1.76	86.20	10.89	-7.26
H146	70	20	16	22.00	40.00	21.00	98.00	64.00	55.00	0.65	1.53	1.78	94.69	15.87	-11.86
H147	70	20	16	22.00	40.00	25.00	108.00	62.00	50.00	0.62	1.74	2.16	97.94	19.12	-8.82
H148	80	30	17	20.00	40.00	25.00	98.00	59.00	50.00	0.59	1.66	1.96	93.12	15.18	-9.91
H149	80	30	17	18.00	42.00	25.00	100.00	62.00	41.00	0.60	1.61	2.44	94.19	16.44	-9.94
H150	80	30	17	22.00	42.00	27.00	107.00	63.00	64.00	0.60	1.70	1.67	99.06	17.20	-11.19
H151	70	20	16	21.00	42.00	23.00	103.00	64.00	55.00	0.63	1.61	1.87	96.80	17.54	-11.14
H152	70	20	16	17.00	40.00	25.00	102.00	60.00	50.00	0.61	1.70	2.04	94.10	17.25	-10.14
H153	70	20	16	21.00	37.00	21.00	90.00	57.00	50.00	0.62	1.58	1.80	88.98	12.54	-10.35
H154	70	20	16	20.00	34.00	21.00	78.00	52.00	50.00	0.58	1.50	1.56	82.76	7.69	-10.56
H155	70	20	16	20.00	37.00	25.00	67.00	45.00	46.00	0.46	1.49	1.46	77.69	1.11	-9.91
H156	70	30	15	22.00	34.00	21.00	90.00	57.00	59.00	0.62	1.58	1.53	89.36	12.16	-11.22
H157	70	30	15	21.00	34.00	23.00	97.00	56.00	50.00	0.62	1.73	1.94	90.99	15.03	-8.88

H158	70	30	15	21.00	37.00	23.00	98.00	66.00	59.00	0.62	1.48	1.66	95.25	15.71	-13.55
H159	70	30	15	21.00	37.00	20.00	92.00	52.00	46.00	0.64	1.77	2.00	87.11	13.69	-6.78
H160	70	30	15	22.00	37.00	23.00	83.00	49.00	46.00	0.57	1.69	1.80	84.69	8.56	-7.75
H161	80	60	19	22.00	40.00	25.00	95.00	55.00	50.00	0.58	1.73	1.90	91.26	12.97	-8.43
H162	80	60	19	21.00	40.00	21.00	105.00	60.00	59.00	0.67	1.75	1.78	95.47	18.64	-9.20
H163	80	60	19	21.00	34.00	18.00	100.00	59.00	50.00	0.69	1.69	2.00	91.55	18.27	-8.45
H164	80	60	19	20.00	37.00	23.00	95.00	60.00	55.00	0.61	1.58	1.73	91.90	14.41	-11.47
H165	80	60	19	23.00	37.00	21.00	103.00	62.00	55.00	0.66	1.66	1.87	95.52	17.83	-9.63
H166	80	60	19	23.00	40.00	23.00	98.00	62.00	55.00	0.62	1.58	1.78	94.58	14.90	-10.80
H167	80	60	19	21.00	37.00	21.00	111.00	62.00	50.00	0.68	1.79	2.22	97.55	22.15	-7.80
H168	80	60	19	20.00	37.00	23.00	107.00	60.00	50.00	0.65	1.78	2.14	95.62	19.63	-8.67
H169	80	60	19	20.00	34.00	25.00	98.00	62.00	50.00	0.59	1.58	1.96	93.51	15.76	-11.50
H170	80	60	19	21.00	37.00	23.00	97.00	56.00	50.00	0.62	1.73	1.94	91.24	14.81	-8.70
H182	80	30	11	21.00	42.00	25.00	108.00	67.00	68.00	0.62	1.61	1.59	100.35	18.81	-12.95
H185	80	30	11	23.00	37.00	21.00	102.00	67.00	50.00	0.66	1.52	2.04	96.56	17.57	-12.03
H191	90	60	22	23.00	42.00	27.00	87.00	62.00	55.00	0.53	1.40	1.58	91.89	8.52	-13.67
H192	90	60	22	21.00	42.00	27.00	83.00	51.00	59.00	0.51	1.63	1.41	86.81	6.87	-10.09
H193	90	60	22	18.00	42.00	25.00	77.00	55.00	55.00	0.51	1.40	1.40	84.68	5.47	-12.85
H195	80	20	19	21.00	40.00	21.00	77.00	55.00	55.00	0.57	1.40	1.40	84.06	6.24	-12.07
H39	80	40	18	21.00	40.00	21.00	83.00	47.00	50.00	0.60	1.77	1.66	83.45	8.85	-6.56
H43	70	60	18	21.00	42.00	27.00	98.00	60.00	55.00	0.57	1.63	1.78	94.76	14.05	-10.96
H44	70	60	18	18.00	40.00	23.00	90.00	57.00	50.00	0.59	1.58	1.80	89.13	12.32	-10.80
H45	70	60	18	20.00	42.00	27.00	87.00	53.00	46.00	0.53	1.64	1.89	88.01	9.23	-9.54
H46	70	60	18	18.00	40.00	23.00	88.00	53.00	55.00	0.59	1.66	1.60	87.41	11.22	-9.69
H47	70	60	18	22.00	40.00	25.00	90.00	52.00	41.00	0.57	1.73	2.20	88.36	10.99	-7.37
H51	70	70	18	18.00	37.00	25.00	85.00	52.00	50.00	0.55	1.63	1.70	85.91	9.53	-9.84
H52	70	70	18	23.00	40.00	23.00	83.00	52.00	50.00	0.57	1.60	1.66	86.29	8.05	-9.09
H53	80	40	16	21.00	42.00	25.00	85.00	51.00	50.00	0.55	1.67	1.70	86.55	8.48	-8.58
H55	80	40	16	20.00	40.00	25.00	70.00	48.00	50.00	0.47	1.46	1.40	80.11	2.32	-10.71
H56	80	40	16	21.00	34.00	25.00	77.00	51.00	41.00	0.51	1.51	1.88	82.67	5.85	-9.97
H57	80	40	16	21.00	34.00	25.00	90.00	52.00	41.00	0.57	1.73	2.20	87.57	11.70	-7.87
H61	80	20	18	22.00	37.00	23.00	72.00	45.00	32.00	0.52	1.60	2.25	78.95	3.78	-7.01
H63	100	20	18	20.00	45.00	25.00	98.00	57.00	55.00	0.59	1.72	1.78	93.35	14.51	-9.35
H66	100	20	18	18.00	37.00	29.00	77.00	52.00	37.00	0.45	1.48	2.08	83.58	5.31	-10.95
H78	80	30	11	21.00	42.00	25.00	90.00	52.00	37.00	0.57	1.73	2.43	88.15	11.21	-6.92
H79	80	30	11	23.00	40.00	25.00	70.00	53.00	50.00	0.47	1.32	1.40	82.76	1.79	-12.76
H81	80	30	11	22.00	40.00	29.00	95.00	63.00	50.00	0.53	1.51	1.90	94.89	12.31	-12.82
H89	70	20	17	21.00	40.00	23.00	65.00	44.00	50.00	0.48	1.48	1.30	76.92	0.21	-9.39
H90	70	20	17	20.00	40.00	25.00	62.00	45.00	46.00	0.43	1.38	1.35	76.27	-1.27	-10.75
H93	80	30	14	22.00	40.00	29.00	92.00	55.00	46.00	0.52	1.67	2.00	90.94	10.59	-9.36
H94	80	30	14	21.00	42.00	25.00	87.00	57.00	50.00	0.55	1.53	1.74	89.32	9.56	-11.34
H95	80	30	14	20.00	40.00	25.00	78.00	53.00	50.00	0.51	1.47	1.56	84.67	6.22	-11.50
H97	80	30	14	23.00	42.00	25.00	97.00	52.00	46.00	0.59	1.87	2.11	91.30	13.22	-6.11

GIS stand variables and spectral values for mixed-wood stands (G## plots = 1999 data; H## plots = 1998 data).

PLOT	*GIS AGE*	*GIS CC*	*GIS HT*	*TM1*	*TM2*	*TM3*	*TM4*	*TM5*	*TM7*	*NDVI*	*SI 4/5*	*4/7*	*BR*	*GR*	*WT*
G100	70	70	8	20.00	37.00	23.00	118.00	72.00	59.00	0.67	1.64	2.00	103.86	25.02	-12.72
G107	100	20	16	17.00	37.00	21.00	87.00	53.00	55.00	0.61	1.64	1.58	85.83	11.53	-10.02
G118	100	20	22	18.00	37.00	25.00	72.00	55.00	59.00	0.48	1.31	1.22	82.69	3.57	-14.63
G121	100	20	22	22.00	34.00	23.00	97.00	51.00	41.00	0.62	1.90	2.37	89.17	14.79	-5.41
G123	130	60	28	23.00	40.00	25.00	88.00	57.00	59.00	0.56	1.54	1.49	90.55	9.63	-11.73
G130	110	30	17	16.00	34.00	23.00	85.00	49.00	50.00	0.57	1.73	1.70	83.71	10.70	-8.73
G131	110	30	17	12.00	28.00	12.00	55.00	35.00	37.00	0.64	1.57	1.49	63.75	2.22	-5.69
G132	110	30	17	13.00	28.00	16.00	65.00	40.00	41.00	0.60	1.63	1.59	70.29	5.30	-7.08
G46	110	60	17	18.00	37.00	21.00	92.00	56.00	59.00	0.63	1.64	1.56	88.85	13.41	-10.52
G55	110	40	14	21.00	34.00	21.00	82.00	55.00	55.00	0.59	1.49	1.49	85.23	8.84	-11.40
G67	110	60	20	15.00	34.00	16.00	72.00	47.00	59.00	0.64	1.53	1.22	76.50	6.92	-9.86
G68	110	60	20	15.00	31.00	20.00	62.00	51.00	46.00	0.51	1.22	1.35	74.69	2.42	-13.34
H102	80	30	17	22.00	42.00	23.00	92.00	51.00	46.00	0.60	1.80	2.00	88.41	11.81	-6.32
H181	80	30	11	22.00	42.00	25.00	87.00	66.00	68.00	0.55	1.32	1.28	92.96	9.07	-16.60
H183	80	30	11	21.00	45.00	29.00	92.00	74.00	68.00	0.52	1.24	1.35	98.21	10.63	-19.94
H184	80	30	11	21.00	42.00	27.00	85.00	67.00	68.00	0.52	1.27	1.25	93.04	8.14	-18.03
H194	90	60	22	18.00	40.00	23.00	75.00	52.00	55.00	0.53	1.44	1.36	82.51	5.37	-11.79
H42	80	40	18	17.00	37.00	25.00	87.00	52.00	50.00	0.55	1.67	1.74	86.18	10.52	-9.64
H50	70	70	18	17.00	34.00	23.00	82.00	49.00	41.00	0.56	1.67	2.00	82.55	9.31	-8.43
H54	80	40	16	20.00	37.00	21.00	60.00	39.00	46.00	0.48	1.54	1.30	72.28	-1.04	-7.49
H58	80	20	18	20.00	34.00	21.00	77.00	48.00	37.00	0.57	1.60	2.08	80.36	7.24	-7.78
H59	80	20	18	20.00	34.00	23.00	73.00	45.00	46.00	0.52	1.62	1.59	79.19	4.77	-8.39
H60	80	20	18	22.00	40.00	25.00	73.00	49.00	46.00	0.49	1.49	1.59	82.08	3.46	-9.95
H64	100	20	18	20.00	40.00	25.00	88.00	56.00	59.00	0.56	1.57	1.49	89.24	10.37	-11.54
H67	100	20	18	22.00	37.00	25.00	83.00	60.00	64.00	0.54	1.38	1.30	89.40	7.93	-14.73
H69	80	30	15	17.00	34.00	21.00	48.00	29.00	32.00	0.39	1.66	1.50	63.93	-5.35	-4.73
G105	70	50	9	16.00	34.00	21.00	93.00	55.00	55.00	0.63	1.69	1.69	87.96	14.99	-9.60
G108	100	20	16	17.00	34.00	21.00	72.00	52.00	46.00	0.55	1.38	1.57	79.78	5.51	-11.79
G11	90	20	14	16.00	34.00	18.00	87.00	56.00	50.00	0.66	1.55	1.74	85.05	13.44	-10.50
G119	100	20	22	23.00	40.00	25.00	73.00	49.00	64.00	0.49	1.49	1.14	83.05	2.52	-11.48
G5	120	10	18	13.00	28.00	14.00	43.00	39.00	32.00	0.51	1.10	1.34	61.78	-3.28	-9.70
G69	110	60	20	18.00	34.00	18.00	65.00	43.00	46.00	0.57	1.51	1.41	73.78	2.94	-8.00
G70	120	60	25	15.00	34.00	20.00	82.00	48.00	46.00	0.61	1.71	1.78	80.73	10.72	-7.85
G71	120	60	25	17.00	37.00	18.00	78.00	51.00	50.00	0.63	1.53	1.56	81.03	9.04	-9.39
G72	120	60	25	18.00	37.00	21.00	88.00	52.00	46.00	0.61	1.69	1.91	85.89	12.24	-8.08
H107	80	30	14	21.00	42.00	25.00	53.00	40.00	46.00	0.36	1.33	1.15	72.25	-5.67	-9.64
H119	80	30	14	23.00	40.00	27.00	75.00	49.00	41.00	0.47	1.53	1.83	83.24	3.52	-9.37
H41	80	40	18	17.00	40.00	21.00	83.00	48.00	46.00	0.60	1.73	1.80	82.85	9.91	-7.20
H48	70	70	18	17.00	40.00	23.00	63.00	43.00	46.00	0.47	1.47	1.37	74.87	0.40	-9.12
H49	70	70	18	18.00	37.00	27.00	70.00	47.00	41.00	0.44	1.49	1.71	79.26	2.52	-9.91
H62	80	20	18	22.00	40.00	27.00	88.00	48.00	55.00	0.53	1.83	1.60	87.47	9.00	-7.44
H65	100	20	18	21.00	37.00	25.00	87.00	52.00	55.00	0.55	1.67	1.58	87.22	9.54	-9.63

H70	80	30	15	20.00	37.00	20.00	60.00	39.00	37.00	0.50	1.54	1.62	71.46	-0.16	-6.33
H80	80	30	11	22.00	42.00	27.00	87.00	53.00	55.00	0.53	1.64	1.58	88.93	8.36	-10.08
H91	70	20	17	22.00	40.00	25.00	65.00	45.00	50.00	0.44	1.44	1.30	78.13	-0.54	-10.20

Appendix C: Image Channel Descriptive Statistics

Descriptive statistics for image reflectance and DN values obtained from Jack pine study plots.

	N	*Range*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
TM1	25	7	11	18	14.0	2.0
TM2	25	12	25	37	30.5	2.7
TM3	25	9	12	21	16.6	2.5
TM4	25	50	42	92	56.8	12.1
TM5	25	17	32	49	39.3	4.7
TM7	25	23	32	55	40.8	7.3
NDVI	25	0.25	0.41	0.66	0.5	0.1
TM4_5	25	0.87	1.05	1.92	1.4	0.2
TM4_7	25	0.83	1.05	1.88	1.4	0.3
BR	25	26.39	59.78	86.17	68.0	6.1
GR	25	19.36	-5.19	14.17	1.2	4.7
WET	25	8.92	-13.42	-4.5	-8.2	2.1
GIS_AGE	25	60	60	120	90.0	24.7
GIS_CC	25	70	10	80	44.0	24.5
GIS_HT	25	17	9	26	17.4	6.0

Descriptive statistics for image reflectance and DN values obtained from white spruce stands

	N	*Range*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
TM1	32	15	10	25	15.8	4.0
TM2	32	19	23	42	31.8	4.9
TM3	32	17	12	29	18.6	4.5
TM4	32	52	35	87	50.9	12.4
TM5	32	27	29	56	43.6	7.1
TM7	32	36	28	64	47.0	9.3
NDVI	32	0.34	0.29	0.63	0.5	0.1
TM 4/5	32	0.96	0.89	1.85	1.2	0.2
TM 4/7	32	0.98	0.76	1.74	1.1	0.2
BR	32	26.33	56.82	83.15	68.7	8.0
GR	32	20.35	-8.74	11.61	-2.7	4.7
WET	32	12.94	-18.84	-5.9	-12.0	3.0
GIS AGE	32	80	70	150	112.2	25.5
GIS CC	32	40	10	50	31.6	11.9
GIS HT	32	13	14	27	20.1	4.0

Descriptive statistics for image reflectance and DN values obtained beneath aspen stands.

	N	*Range*	*Minimum*	*Maximum*	*Mean*	*Std. Deviation*
TM1	28	9	11	20	15.6	2.3
TM2	28	14	28	42	34.8	3.1
TM3	28	13	16	29	19.6	2.9
TM4	28	68	45	113	90.4	15.4
TM5	28	27	37	64	56.4	6.6
TM7	28	27	32	59	50.1	6.9
NDVI	28	0.45	0.29	0.74	0.6	0.1
TM 4/5	28	0.89	0.92	1.81	1.6	0.2
TM 4/7	28	1.91	0.9	2.81	1.8	0.4
BR	28	26.32	70	96.32	86.8	6.7
GR	28	33.51	-8.38	25.13	14.6	7.7
WET	28	11.52	-16.39	-4.87	-10.2	2.5
GIS Age	28	60	70	130	89.6	15.5
GIS CC	28	50	20	70	36.1	14.2
GIS HT	28	20	8	28	14.8	3.5

Descriptive statistics for image reflectance and DN values obtained beneath mixed-wood stands.

	N	Range	Minimum	Maximum	Mean	Std. Deviation
TM1	21	11	12	23	17.3	3.1
TM2	21	12	28	40	34.4	3.5
TM3	21	13	12	25	20.1	3.5
TM4	21	75	43	118	78.9	16.3
TM5	21	37	35	72	50.8	7.7
TM7	21	32	32	64	50.2	8.4
NDVI	21	0.19	0.48	0.67	0.6	0.1
TM 4/5	21	0.8	1.1	1.9	1.5	0.2
TM 4/7	21	1.23	1.14	2.37	1.6	0.3
BR	21	42.08	61.78	103.86	81.6	9.4
GR	21	28.3	-3.28	25.02	8.7	6.2
WET	21	9.22	-14.63	-5.41	-9.9	2.4
GIS AGE	21	60	70	130	105.7	15.0
GIS CC	21	60	10	70	41.0	19.7
GIS HT	21	20	8	28	18.7	5.1

Appendix D: Statistical output from backwards regression models

ANOVA Results from stand height models.

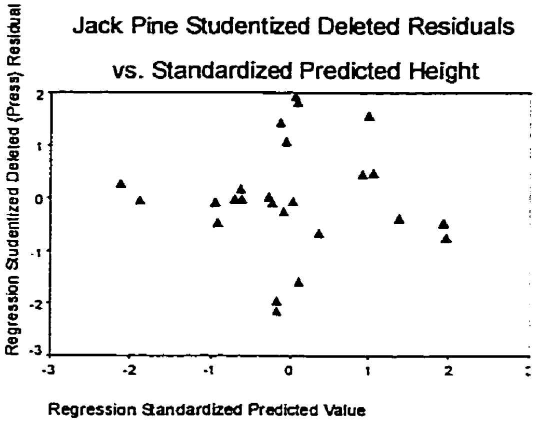
Model		Sum of Squares	df	Mean Square	F	Sig.
Jack Pine	Regression	200.9	6	33.5	7.9	0.000
	Residual	76.6	18	4.3		
	Total	277.4	24			
White Spruce	Regression	295.4	4	73.9	6.8	0.001
	Residual	294.1	27	10.9		
	Total	589.6	31			
Aspen	Regression	434.2	5	86.8	7.2	0.000
	Residual	265.0	22	12.0		
	Total	699.2	27			
Mixed-wood	Regression	161.1	1	161.1	9.9	0.005
	Residual	310.1	19	16.31		
	Total	471.2	20			

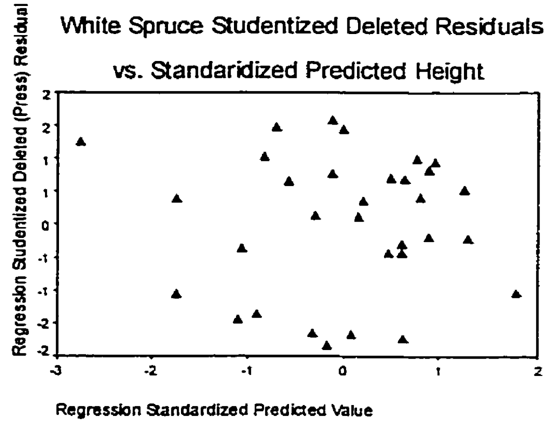
Jack Pine Predictors: (Constant), NDVI, TM4_7, TM2, TM4_5, GR, TM4
White Spruce Predictors: (Constant), WET, GR, TM3, TM4
Aspen Predictors: (Constant), GR, TM5, NDVI, BR, TM
Mixed-wood Predictors: (Constant), GR

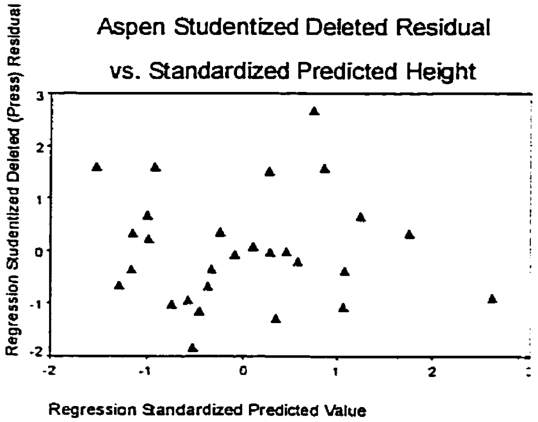
Regression coefficients and significance levels for backwards regression height models.

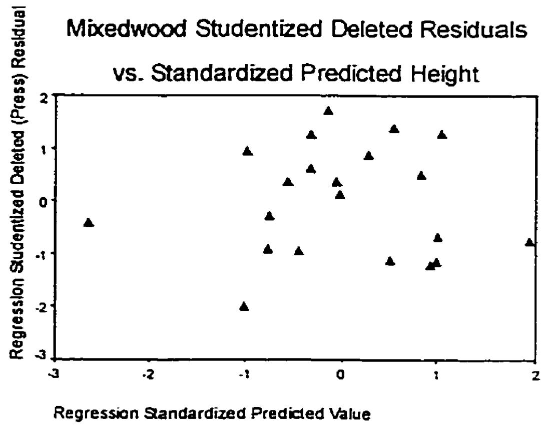
Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
Jack Pine	(Constant)	-35.36	20.78		-1.70	0.106
	TM2	-0.86	0.31	-0.68	-2.80	0.012
	TM4	1.34	0.38	4.78	3.50	0.003
	NDVI	44.86	16.37	0.88	2.74	0.013
	TM4_5	-20.61	5.22	-1.23	-3.95	0.001
	TM4_7	6.61	2.82	0.51	2.34	0.031
	GR	-3.55	0.98	-4.94	-3.62	0.002
White Spruce	(Constant)	-7.78	13.26		-0.59	0.562
	TM3	-1.54	0.47	-1.60	-3.29	0.003
	TM4	0.84	0.36	2.38	2.34	0.027
	GR	-2.26	0.83	-2.41	-2.73	0.011
	WET	-0.52	0.22	-0.35	-2.34	0.027
Aspen	(Constant)	191.64	54.16		3.54	0.002
	TM4	6.98	2.53	21.10	2.76	0.011
	TM5	3.16	1.37	4.11	2.31	0.031
	NDVI	-45.53	26.38	-0.83	-1.73	0.098
	BR	-9.62	3.44	-12.60	-2.80	0.011
	GR	-8.31	3.27	-12.57	-2.54	0.019

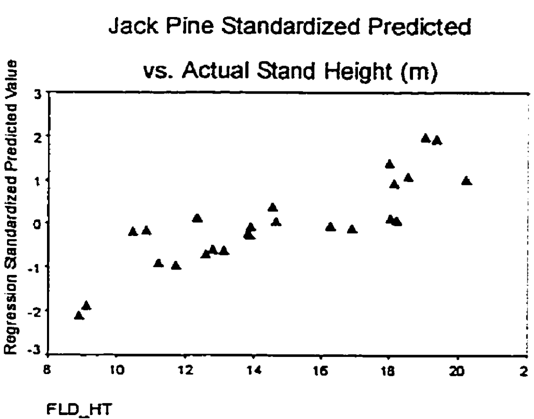
Mixed-wood	(Constant)	22.00	1.55		14.23	0.000
	GR	-0.46	0.15	-0.58	-3.14	0.005

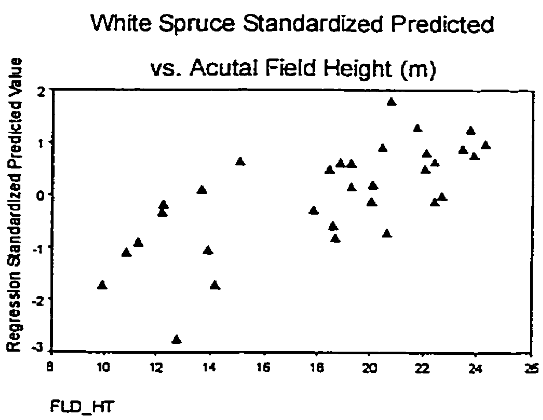

Jack Pine Studentized Deleted Residuals
vs. Standardized Predicted Height
Regression Studentized Deleted (Press) Residual
Regression Standardized Predicted Value

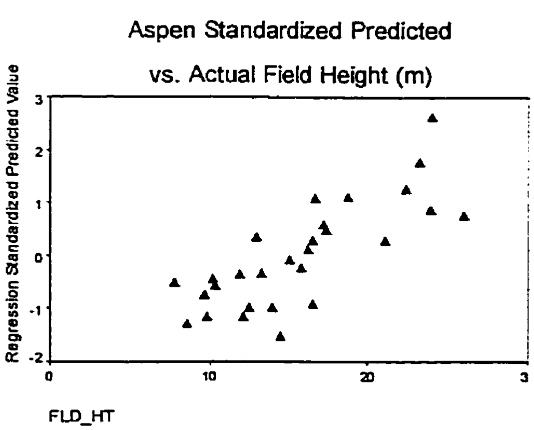

White Spruce Studentized Deleted Residuals
vs. Standaridized Predicted Height
Regression Studentized Deleted (Press) Residual
Regression Standardized Predicted Value

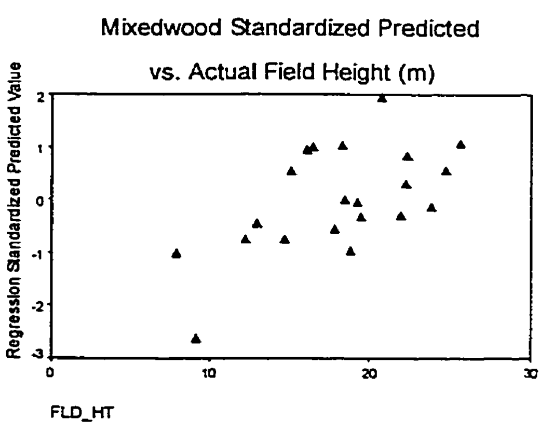

Aspen Studentized Deleted Residual
vs. Standardized Predicted Height
Regression Studentized Deleted (Press) Residual
Regression Standardized Predicted Value


Mixedwood Studentized Deleted Residuals
vs. Standardized Predicted Height
Regression Studentized Deleted (Press) Residual
Regression Standardized Predicted Value


Jack Pine Standardized Predicted
vs. Actual Stand Height (m)
Regression Standardized Predicted Value
FLD_HT


White Spruce Standardized Predicted
vs. Acutal Field Height (m)
Regression Standardized Predicted Value
FLD_HT


Aspen Standardized Predicted
vs. Actual Field Height (m)
Regression Standardized Predicted Value
FLD_HT


Mixedwood Standardized Predicted
vs. Actual Field Height (m)
Regression Standardized Predicted Value
FLD_HT

ANOVA Results from stand age models.

Model		*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
Jack Pine	Regression	22533.9	4	5633.5	10.9	0.000
	Residual	10371.9	20	518.6		
	Total	32905.8	24			
White Spruce	Regression	16730.6	2	8365.3	9.1	0.001
	Residual	24946.4	27	923.9		
	Total	41677.0	29			
Aspen	Regression	22008.5	4	5502.1	10.9	0.000
	Residual	11637.6	23	506.0		
	Total	33646.1	27			
Mixed-wood	Regression	9681.4	1	9681.4	5.8	0.028
	Residual	28328.4	17	1666.37551		
	Total	38009.8	18			

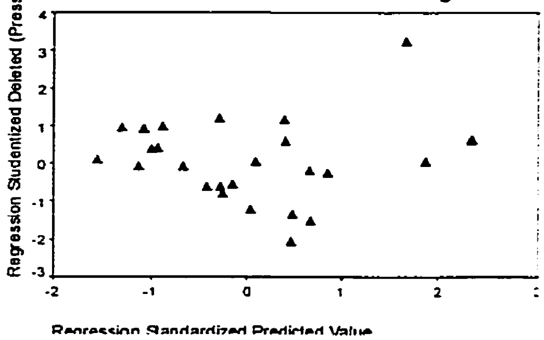
Jack Pine Predictors: (Constant), TM2, TM4, TM4_5, GR
White Spruce Predictors: (Constant), WET, GR
Aspen Predictors: (Constant), TM4_5, NDVI, BR, TM
Mixed-wood Predictors: (Constant), GR

Regression coefficients and significance levels for backwards regression age models.

Model		*Unstandardized Coefficients*		*Standardized Coefficients*	*t*	*Sig.*
		B	*Std. Error*	*Beta*		
JACK PINE	(Constant)	187.05	99.47		1.88	0.075
	TM2	-9.51	3.01	-0.69	-3.16	0.005
	TM4	7.11	2.58	2.32	2.76	0.012
	TM4_5	-151.31	38.75	-0.83	-3.90	0.001
	GR	-13.78	5.92	-1.76	-2.33	0.031
White Spruce	(Constant)	42.02	23.20		1.81	0.081
	GR	-3.94	1.20	-0.49	-3.27	0.003
	WET	-5.41	1.86	-0.43	-2.91	0.007
Aspen	(Constant)	380.22	76.04		5.00	0.000
	TM5	10.16	5.47	1.91	1.86	0.076
	NDVI	-596.72	175.83	-1.56	-3.39	0.002
	TM4_5	309.13	129.30	1.61	2.39	0.025
	BR	-11.29	5.27	-2.13	-2.14	0.043
Mixed-wood	(Constant)	133.68	16.44		8.13	0.000
	GR	-3.75	1.55	-0.50	-2.41	0.028

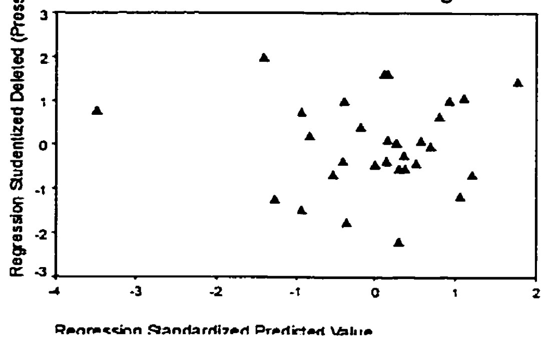
Jack Pine Studentized Deleted Residuals

vs. Standardized Predicted Age



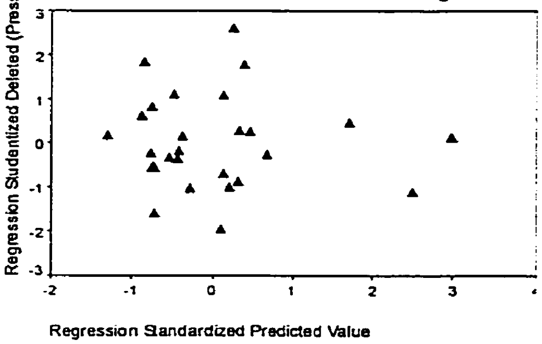
White Spruce Studentized Deleted Residuals

vs. Standardized Predicted Age



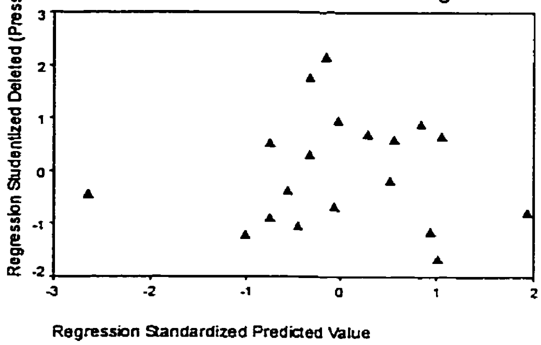
Aspen Studentized Deleted Residual

vs. Standardized Predicted Age



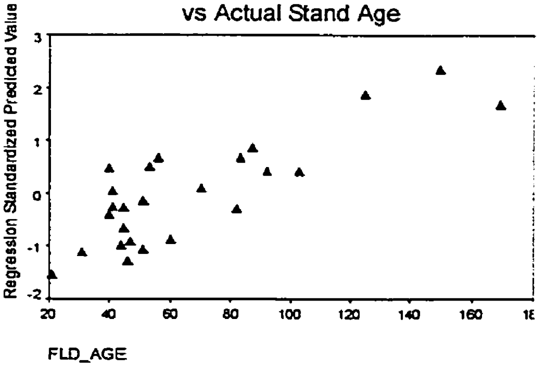
Mixedwood Studentized Deleted Residual

vs. Standardized Predicted Age



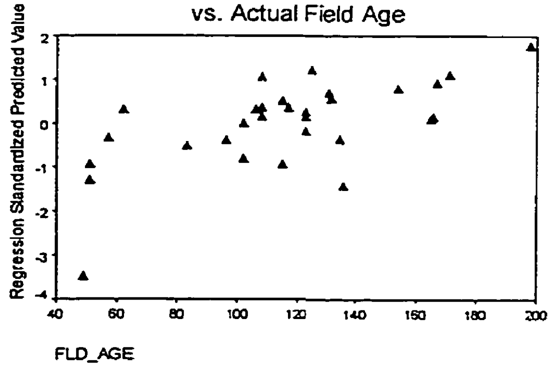
Jack Pine Standardized Predicted

vs Actual Stand Age



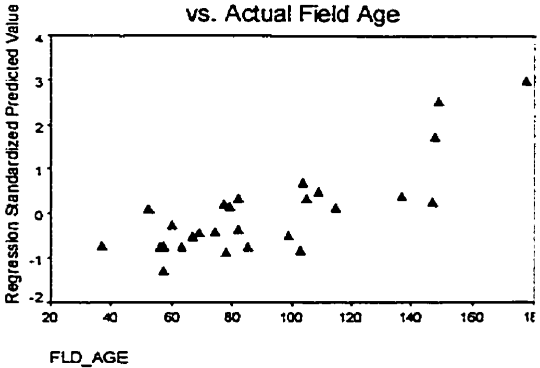
White Spruce Standardized Predicted

vs. Actual Field Age



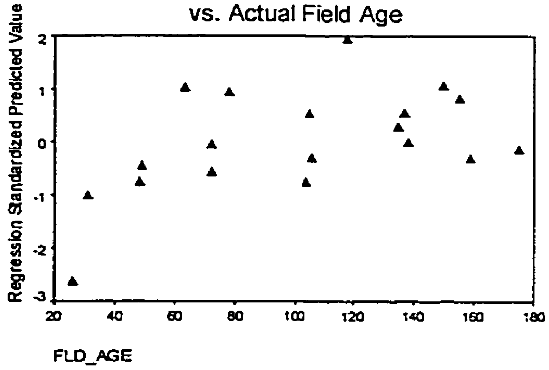
Aspen Standardized Predicted

vs. Actual Field Age



Mixedwood Standardized Predicted

vs. Actual Field Age



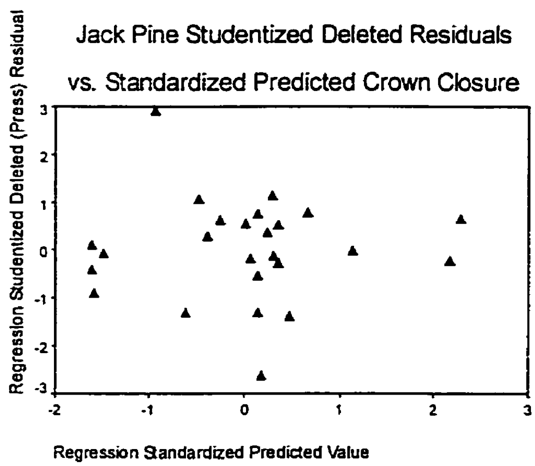
ANOVA results from crown closure models.

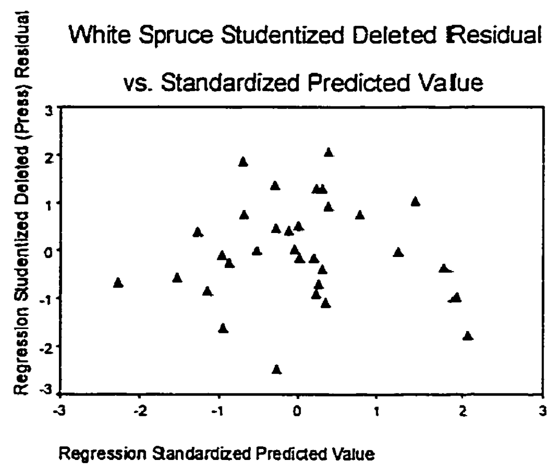
Model		Sum of Squares	df	Mean Square	F	Sig.
Jack Pine	Regression	1067.0	3	355.7	15.3	0.000
	Residual	489.5	21	23.3		
	Total	1556.5	24			
White Spruce	Regression	1677.5	1	1677.5	30.2	0.000
	Residual	1667.9	30	55.6		
	Total	3345.4	31			
Aspen	Regression	Regression				
	Residual	Residual	No significant relationship observed			
	Total	Total				
Mixed-wood	Regression	Regression				
	Residual	Residual	No significant relationship observed			
	Total	Total				

Jack Pine Predictors: (Constant), TM5, TM4_5, TM4
White Spruce Predictors: (Constant), WET

Regression coefficients and significance levels for backwards regression crown closure models.

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
Jack Pine	(Constant)	-119.48	55.02		-2.17	0.041
	TM4	-1.46	0.84	-2.20	-1.74	0.097
	TM5	2.80	1.31	1.64	2.14	0.044
	TM4_5	88.68	35.72	2.23	2.48	0.022
White Spruce	(Constant)	63.27	5.56		11.38	0.000
	WET	2.47	0.45	0.71	5.49	0.000
Aspen	No Significant Relationship Observed					
Mixed-wood	No Significant Relationship Observed					





ASPEN CROWN CLOSURE

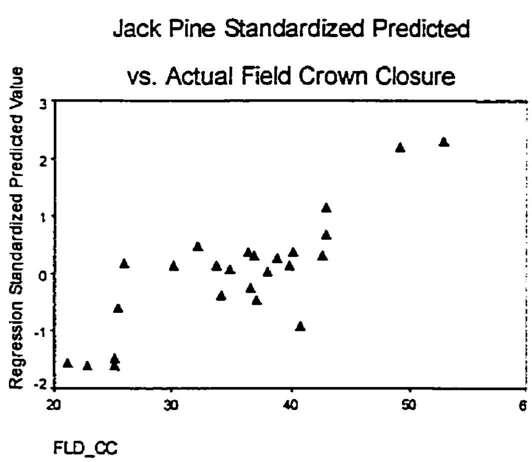
NO SIGNIFICANT

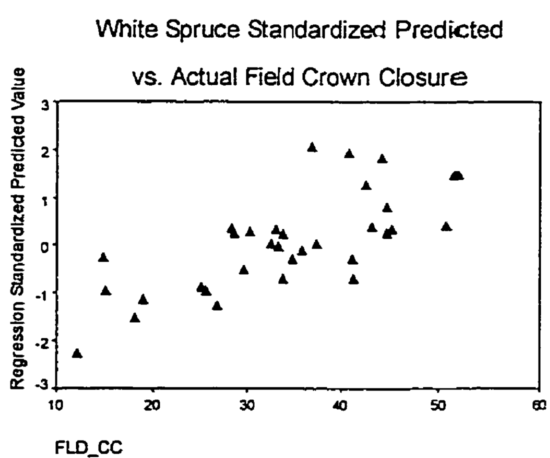
RELATIONSHIP OBSERVED

MIXEWOOD CROWN CLOSURE

NO SIGNIFICANT

RELATIONSHIP OBSERVED





ASPEN CROWN CLOSURE

NO SIGNIFICANT

RELATIONSHIP OBSERVED

MIXEWOOD CROWN CLOSURE

NO SIGNIFICANT

RELATIONSHIP OBSERVED

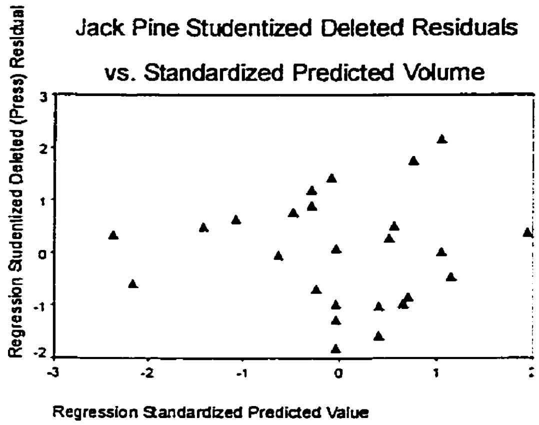
ANOVA results from stand volume models.

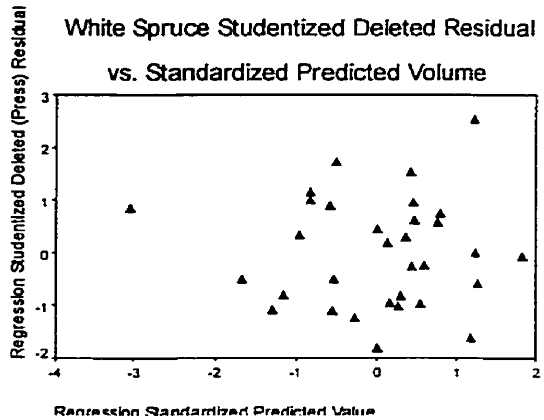
Model		*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
Jack Pine	Regression	9713.2	1	9713.2	6.3	0.019
	Residual	35374.4	23	1538.0		
	Total	45087.7	24			
White Spruce	Regression	73575.8	5	14715.2	6.5	0.000
	Residual	58499.0	26	2250.0		
	Total	132074.9	31			
Aspen	Regression	No significant relationship observed				
	Residual					
	Total					
Mixed-wood	Regression	25325.4	1	25325.4	6.2	0.022
	Residual	77664.3	19	4087.5942		
	Total	102989.7	20			

Jack Pine Predictors: (Constant), TM4_5
White Spruce Predictors: (Constant), GR, TM3, TM2, TM4_5, TM
Mixed-wood Predictors: (Constant), TM

Regression coefficients and significance levels for backwards regression stand volume models.

Model		*Unstandardized Coefficients* B	Std. Error	*Standardized Coefficients* Beta	*t*	*Sig.*
Jack Pine	(Constant)	305.12	57.65		5.29	0.000
	TM4_5	-99.51	39.60	-0.46	-2.51	0.019
White Spruce	(Constant)	-57.26	197.02		-0.29	0.774
	TM2	-8.32	4.57	-0.63	-1.82	0.080
	TM3	-21.61	7.06	-1.50	-3.06	0.005
	TM4	19.74	7.74	3.75	2.55	0.017
	TM4_5	-208.82	72.93	-0.62	-2.86	0.008
	GR	-43.78	16.50	-3.12	-2.65	0.013
Aspen	No Significant Relationship Observed					
Mixed-wood	(Constant)	388.31	94.81		4.10	0.001
	TM5	-4.60	1.85	-0.50	-2.49	0.022

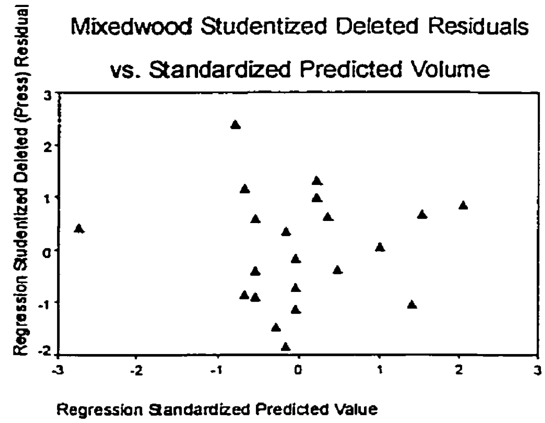


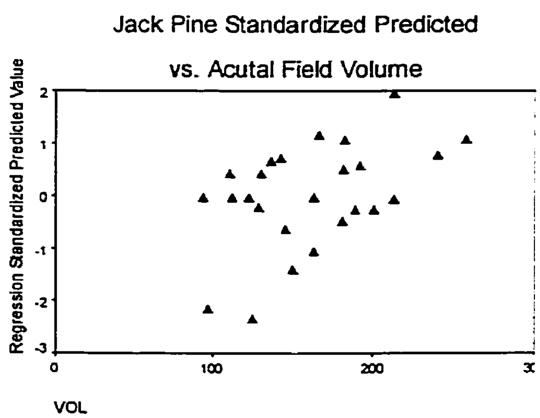


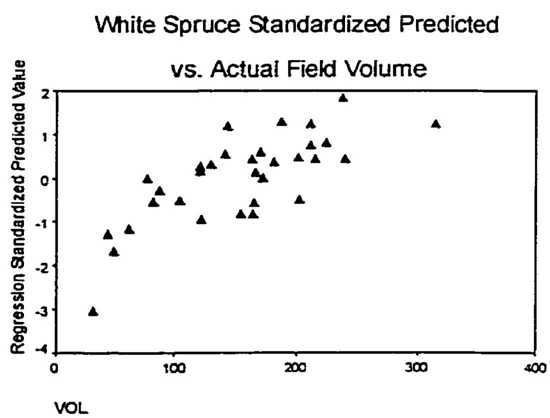
ASPEN VOLUME

NO SIGNIFICANT

RELATIONSHIP OBSERVED







ASPEN VOLUME

NO SIGNIFICANT

RELATIONSHIP OBSERVED