Comparison of Growth Intercept and Site Index Models of Black Spruce Plantations and Natural Stands in Northern Ontario

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COMPARISON OF GROWTH INTERCEPT AND SITE INDEX MODELS OF BLACK SPRUCE PLANTATIONS AND NATURAL STANDS IN NORTHERN ONTARIO

By

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ABSTRACT

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Key Words: black spruce, breast height age, growth intercept, northern Ontario, plantation, polymorphic height growth, rotation age, silviculture, site index, site quality, soil characteristics.

Black spruce (*Picea mariana* Mill. B.S.P.) is one of the most important tree species in Canada, both ecologically and commercially. The forest industry has steadily increased efforts to artificially regenerate areas that have been harvested resulting in expanding areas of black spruce plantations. The increase in amount of area and the number of trees that are planted requires accurate tools for height and yield estimation in these stands to ensure sustainable forest management and a dependable future wood supply. Currently these tools are unavailable resulting in underestimated site productivity in black spruce plantations by a site index and growth and yield model that was derived from natural stands.

In this study, 62 sites were sampled across northern Ontario ranging from Kirkland Lake in the east to Kenora in the west. Within each plot 3 undamaged dominant or co-dominant trees with no indication of suppression were felled for stem analysis. These sites were planted, contained a minimum black spruce composition of 70%, and were at least 40 years old. Within each plot a soil sample was collected from the C horizon and relationships between soil characteristics and site quality were examined.

Accurate and precise growth intercept and site index models were developed from the stem analysis data collected from black spruce plantations. These models were compared to models for natural stands using Carmean's (2006) data. Comparison of site index curves between planted and natural stands showed a significant difference. Planted stands displayed increased height growth patterns, especially in early breast height ages, as well as enhanced total height prediction accuracy when compared to natural stands. These height growth increases may be directly related to silvicultural activities that occur on productive upland sites.

Soil characteristics from the C horizon were related to site productivity in black spruce plantations. Soil pH in calcium chloride, elevation, sand, and silt content were shown to be significant factors. Factor analysis concluded that many soil characteristics, such as soil pH in calcium chloride, soil pH in water, Ca, Mg, Na and clay content attributed for similar variances to site quality in terms of site index.

Due to its shallow rooting nature, and previous studies that have shown black spruce to have a maximum attainable height of 20 to 21 m before becoming susceptible to windthrow, a rotation age of 60 years on productive upland sites is recommended. In a 300 year scenario, productive upland black spruce sites harvested at a 60 year rotation produced 223 % more merchantable volume than natural stands. If these stands are not harvested until 80 years, stands could incur volume losses of at least 30 % due to windthrow and tomentosus root rot.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

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CHAPTER 1. INTRODUCTION TO THE THESIS

1.1. INTRODUCTION

Black spruce (*Picea mariana* Mill. B.S.P.) is one of the most important tree species in Canada, both ecologically and commercially. It is found in every province and territory accounting for 9% of the country's total forest inventory (Saskatchewan Forest Centre and Forintek Canada Corp. 2006). The spruce working group accounts for 34.7 % (9.5 billion m^3) of gross merchantable volume on non-reserved stocked forestland in Canada (Canadian Forest Service 2001). In Ontario, black spruce working groups make up 34.4 % of the forest inventory (OMNR 2003). In 2000-01 the forest industry harvested 199,353 hectares in northern Ontario (OMNR 2004), while in 2002-03 24.2 million m^3 were harvested across the province with the spruce working group accounting for 10.3 million m^3 (OMNR 2006). However, in 2001-02 the forest industry planted 95,638 hectares using 143,393,000 trees. If on average a single tree costs 8 cents to plant that amounts to almost $11.5 million on planting alone, which results in an average density of 1500 trees per hectare (OMNR 2004).

The total number of trees that are planted in northwestern Ontario has been steadily increasing; the area of plantations is growing (OMNR 2006). The commitment by forest industries to artificially regenerate harvested areas supports their statements that for every tree harvested, two trees are planted. The amount of area and the number of trees that are planted requires accurate tools for height and yield estimation in these stands to ensure sustainable forest management and a dependable future wood supply. Due to the lack of site index (SI) and growth intercept (GI) models for black spruce plantations in northern Ontario, estimates of height and productivity in young plantations have been determined using models from mature natural stands. These models do not take into account the numerous silvicultural investments made encouraging planted trees to grow at a faster rate than their natural counterparts.

The many definitions of SI currently used by authors can cause confusion among forest practitioners (CNFER 2006). Some definitions that exist include, SI is the top height of a stand at a reference age and is a measure of site productivity (Nigh 1995b). Top or total height is the height of the 100 largest diameter at breast height (dbh) trees per hectare (FPCP 1999). SI is a quantitative value that refers to total height of dominant or codominant trees at a specific reference age (Carmean 1996a). Helms (1998) defines site index as a species-specific measure of actual or potential forest productivity, expressed in terms of the average height of trees included in a specific stand component at a specified index or base age. SI is an indirect measure of site quality since we can have excellent trees growing in pockets, however only a few of these pockets growing on-site (CNFER 2006). Therefore, this study uses a variation of Carmean *et al.*'s (2001) definition of SI as the total height at an age of 30 years at breast height. Breast height age (BHA) refers to the number of years required for a tree to attain breast height (1.3 m) (Carmean *et al.* 2001). SI models are used for predicting stand height development, and for assessing site quality. This makes height growth of the stand a generally accepted reliable indicator of site quality (CNFER 2006). GI is defined as an average annual height growth above breast height. GI models give reliable site index estimates for young stands by relating the early average height growth of trees (the growth intercept) to the site index (Nigh 1995b)

Currently there are no reliable site-quality, specifically GI or site index SI, evaluation tools available for black spruce plantations in northern Ontario. Natural SI curves for black spruce were not published until 2006 by Carmean *et al.* to estimate site productivity. Vanclay (1992) describes site productivity as the potential of a site to produce timber, thus making SI an essential tool in forest management and planning. The depletion of our virgin forests close to mills has caused increases in haul cost and distances of delivering wood fibre to local mills. Thus, the focus needs to shift to regenerating forests and their potential to produce timber, especially intensively managed plantations. Gordon and Simpson (1991) studied two black spruce plantations, one at Tyrol Lake and the other at Limestone Lake, and found total volumes of 191.1 and 184.5 m^3 respectively at 23 years breast height age (BHA). This shows the potential of artificially regenerating good sites into highly productive mature stands that would help produce a sustainable and consistent wood flow for the future.

To successfully establish plantations, several silvicultural activities such as site preparation (mechanical or chemical), fertilization, herbicide spray, manual cleaning, and pre-commercial thinning can be applied. Regeneration and free-to-grow surveys can be conducted to ensure the trees are responding positively and do not require supplemental treatments. These activities have the potential to alter height growth patterns in young plantations that cannot be accounted for by natural SI models that are currently used. In northern Ontario, GI models have been developed for predicting SI for white spruce (*Picea glauca* [Moench] Voss) plantations (Thrower 1987, Carmean *et al.* 2006b) and jack pine (*Pinus banksiana* Lamb.) plantations (Guo and Wang 2006).

Management practices have been noted to increase SI. Farnden and Herring (2002) found that thinning and fertilization of repressed lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) stands increased top height by 3 m and SI at BHA 50 by almost 8 m. Huang et al. (2004b) found overall post-harvest increases in mean site index of 27 to 35 % in comparison to fire-origin stands by simply logging the stand, performing some site treatment (scarification), and successful natural regeneration. Based on these findings, can site productivity of natural black spruce stands be improved through intensive silvicultural activities that include artificial regeneration? Is black spruce site productivity and growth and yield potential for intensively managed plantations being under estimated using models derived from natural stands? Carmean (2007) identifies the need for developing polymorphic height growth models that accurately describe height growth in trees of intensively managed black spruce forest plantations.

Nigh and Love (1997) found that the average SI at BHA between managed stands and old-growth sites to be significantly different. Dieguez-Aranda *et al.* (2005) also found that a new model created for radiata pine (*Pinus radiata* D. Don) plantations was more realistic than the current model, developed from natural stands, for height growth estimation and site classification in Galicia (north-western Spain). In northern Ontario, Guo and Wang (2006) found significant differences in height growth patterns between jack pine plantations and natural stands. I hypothesize there is a difference in site productivity and height growth patterns between black spruce natural stands and plantations in northern Ontario. These differences would be more pronounced in early years above BHA where silvicultural activities would decrease competition with less desirable species resulting in increased height growth of black spruce. The hypothesis will be tested by examining growth intercept and site index models that will be generated from stem analysis data across common soil types for black spruce. Secondarily, soil analysis looking at the C horizon characteristics in relation to site index should exhibit the importance of texture and soil pH in the parent material across different ranges of site quality.

It is evident these silvicultural activities are a sufficient investment into black spruce plantations, however changes in height over time in these plantations will be underestimated using a site index model that was derived from natural mature stands. The main focus of this study was to develop GI and SI models for these black spruce plantations, and to compare them to models derived from natural stands. Since the soil characteristics change drastically across northern Ontario, from the Ontario Clay Belt in the northeast to heavy rock outcrops of the Canadian Shield in the northwest, comparisons were made between northwest and northeast regions of Ontario. Derived polymorphic height growth models will be validated to ensure accuracy and precision for use with confidence in the field. Accuracy and precision is important to ensure SI and total height is not over or under estimated resulting in imprecise or incorrect management practices.

This study also included preliminary soil analysis to compare characteristics in the C horizon to measures of site quality (SI and GI). Studies by Fairbanks (1988) and Carmean (1996a, 1996b) found black spruce site indices were not significantly different between forest ecosystem classification (FEC) soil types in natural stands of black spruce. The initial data used for classification were not directly related to site productivity, which may explain why FEC is such a poor tool in predicting site quality.

Due to the constraints of the project, relationships between FEC and site quality in artificially regenerated black spruce stands were examined. Multiple regression and principal component analysis (PCA) were used to explore relationships between independent soil and site variables and site quality.

Finally, this study examines the management implications on how these findings could have an impact on forest operations. Scenarios examining rotation ages and merchantable volume losses due to windthrow and disease found in black spruce plantations on high quality sites were simulated. These results are pertinent in changing the way practitioners in Ontario estimate wood volumes for young plantations of our second growth forests.

This study addresses the need for developing polymorphic height growth models that accurately describe height growth in plantation grown trees of intensively managed black spruce forest plantations (Carmean 2007). These height growth models should be a stepping stone for deriving up-to-date growth and yield curves to accurately estimate changes in stand volume over time of young black spruce plantations. These accurate estimates could increase the annual allowable cut (AAC) for forest industries and ensure sufficient timber supply to local mills to offset any foreseeable shortages in woody supply.

1.2. RESEARCH METHOD

1.2.1. Site Location

1.2.1.1. Preliminary Site Location

Before any field sampling was conducted potential sites were located from within reliable information resources of the Forest Ecosystem Science Co-operative Inc. (Forest Co-op) and the Ontario Ministry of Natural Resources (OMNR). The Forest Co-op has a database containing a collection of all permanent growth plots (PGP) established across northern Ontario. The OMNR had multiple databases to search from including: Permanent Sample Plots (PSP), System of Ontario Artificial Regeneration Surveys (SOARS), and Beckwith and Roblin (BR), all containing plots across northern Ontario. Also, before the research team went into the field, each excursion began with a meeting with the local Sustainable Forest License (SFL) holder to explain the study and gather additional maps and forest resource inventory (FRI) queries that identified additional sites not found in any of the databases mentioned above.

1.2.1.2. Site Selection Criteria

In this initial query the requirement of candidate site included: artificially regenerated stands through planting, a minimum of 40 years in age, and a minimum black spruce species composition of 70 %. In the 1960's and 70's most of the trees that were planted consisted of 2-3 year old bareroot stock. In this study trees planted up until 1969 were considered. Also, any planted 40+-year-old stands that had a black spruce species composition greater than or equal to 60 % were also considered. When these sites were visited in the field sizeable pockets deemed sufficient for sampling were found that met the 70% criterion. At all sites the criteria was verified in the field before destructive sampling occured. Figure 1.1 below shows some of the sample sites that met the selection criteria.

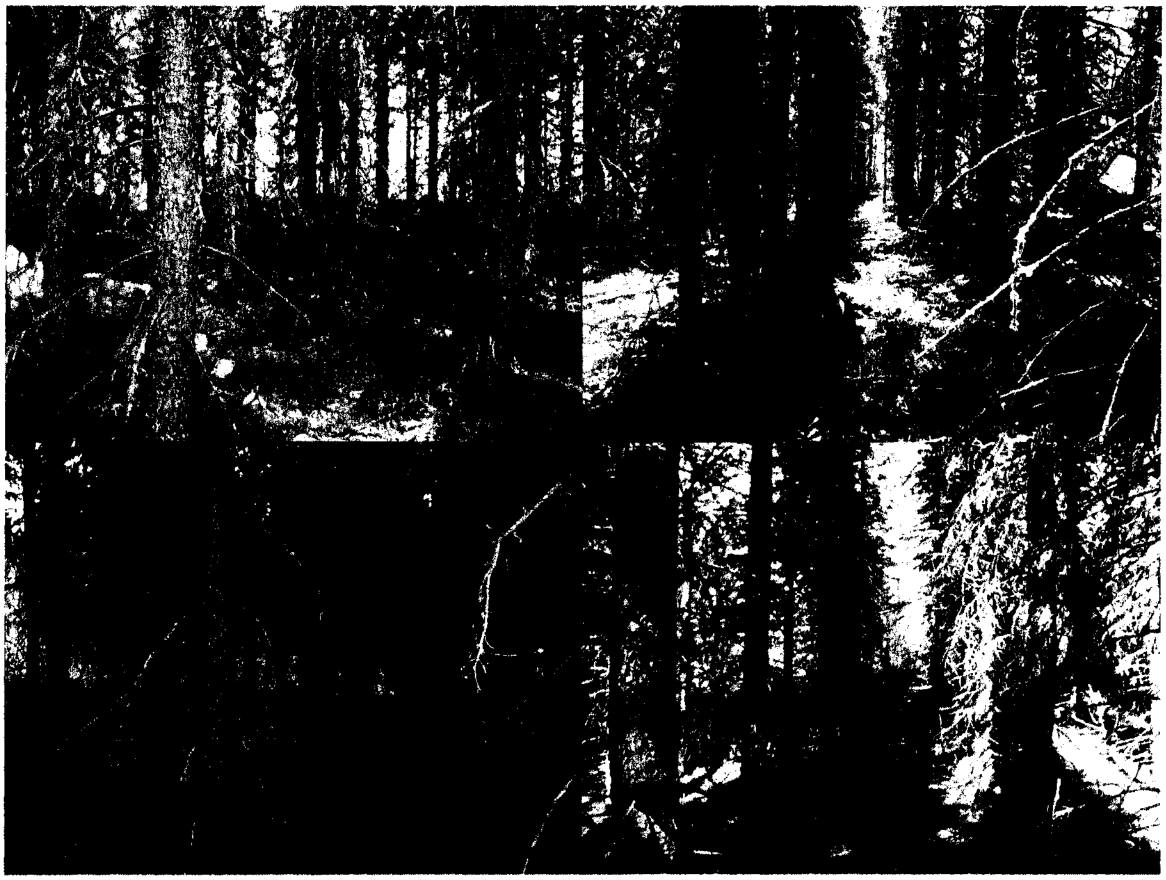


Figure 1.1. Black spruce plantations that met site selection criteria.

1.2.2. Study Area

Throughout the summer of 2006, sixty-two sample sites were located across northern Ontario, within the Boreal forest ranging from Chapleau to the south, Kirkland Lake to the east, Geraldton and Longlac to the north, and Kenora to the west. This area was split into two regions, northeast and northwest with the boundary line running along the boundary for Thunder Bay and Algoma OMNR Districts and continuing north in a straight line. This line runs just west of White River and west of the Hwy.11/Hwy.631 junction. Each region contained 31 sample plots (Figure 1.2).

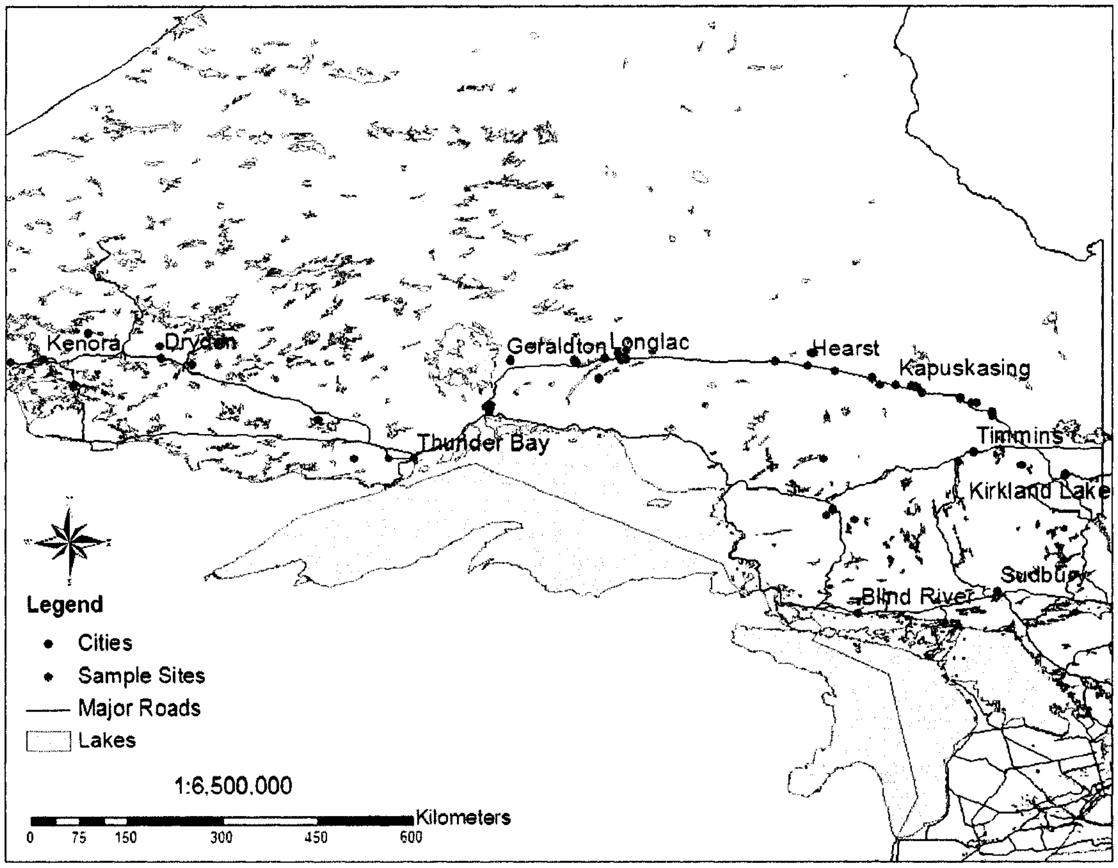


Figure 1.2. Map of northern Ontario identifying black spruce plantation sample sites.

The allocation of sites as well as the number of trees sampled (planted and natural) by town and forest management unit (FMU) is displayed in Table 1.1.

In order to meet the 40 year old criterion plantations established up to 1968 or 1969 were considered (depending on whether they were planted with 2 or 3 year old bare root stock). However, in the mid and early 1960's silviculture methods such as chemical tending did not exist thus resulting in many plantations that were out competed by trembling aspen (*Populus tremuloides* Michx.) and balsam fir (*Abies balsamea* L.) and did not survive into the 21st century. Some plantations were located down decommissioned roads as they did occur over 40 years ago (Figure 1.3), making access difficult. Using Neenah Paper's plantation records dating back to the early 1950's (the

Table 1.1. Number of sites and sampled trees by region.

Northeast			**Trees**	
Town	**FMU**	**Sites**	**Planted**	**Natural**
Smooth Rock Falls	Smooth Rock Falls Forest	4	12	1
Cochrane	Cochrane Moose River Forest	3	9	3
Timmins	Romeo-Malette Forest	1	3	3
Kapuskasing	Gordon Cosens Forest	10	30	0
Hearst	Hearst Forest	4	12	1
Chapleau	Superior Forest	5	15	1
Kirkland Lake	Timiskaming Forest	4	12	1
	Northeast Total	**31**	**93**	**10**
Northwest			**Trees**	
Town	**FMU(s)**	**Sites**	**Planted**	**Natural**
Longlac	Kenogami Forest	8	24	1
Dryden	Wabigoon & Dryden Forests	3	9	1
Kenora	Kenora Forest	3	9	1
Beardmore	Lake Nipigon Forest	3	9	0
Nipigon	Lake Nipigon Forest	8	24	1
Thunder Bay	Dog River - Matawin & Lakehead Forests	6	18	1
	Northwest Total	**31**	**93**	**5**
	Overall Total	**62**	**186**	**15**

only company with such detailed records), many plantations were established at low densities in many of the harvested stands, or planted landings at higher densities, however landings were generally small. The former was especially true on organic sites making it difficult to locate 40-year-old black spruce plantations on organic sites due to low initial planting densities and high natural ingress through natural seed dispersal and layering. As a result only 2 out of the 62 plantations sampled were from organic sites (organic soil depth > 100 cm). One was located on the Smooth Rock Falls Forest, and the other in the Gordon Cosens Forest opposite a tree nursery. A few other sites contained organic layers in the upper echelons of the soil profile but contained silt/clay C layers.

Figure 1.3. Decommissioned road on the Hearst Forest leading to possible black spruce plantations.

CHAPTER 2. GROWTH INTERCEPT AND SITE INDEX

2.1. LITERATURE REVIEW

Growth and yield modeling is an important resource tool in forest management practices. It is used extensively in timber supply models to predict future stocking and growth in regenerating forest stands. It is vital to ensure there is a sufficient and consistent wood flow in future years to supply local pulp and saw mills. To ensure height growth and volume estimations are accurate, the most up to date modeling tools should be used based on silvicultural data collected from permanent growth and yield sample plots.

Benson (1988, 1990) believes extensive forest management is best suited in Canada due to poor site quality in comparison to southern forest lands. In Ontario, due to current industrial demands of conifer and poplar fibre, analysis indicates that a wood supply shortage is imminent and approaching (OMNR 2004b). The reality is Canada's wood supplies are not inexhaustible and intensified forest management can result in enhanced forest productivity and increases in allowable cuts (Apsey *et al.* 2000). In forestry, worldwide dependence on natural forests is shifting to intensively managed forest plantations with large volume gains from relatively small areas of land as trees become a crop, as in agriculture, to be planted, tended and harvested (Sedjo and Botkin 1997, Sedjo 2001).

In a provincial report by Hearnden *et al.* (1992), it was reported that when fire origin conifer stands are harvested they typically regenerate to mixedwood stands, naturally decreasing potential conifer fibre across the landscape. Not only is intensive management pertinent to future wood supply, but the general classification that exists in

Ontario for intensive site-specific plantation management of site classes 1, 2 and 3 (good, medium, and poor sites) must be updated (Carmean 2007). The most efficient single measure to the capacity of a given site to produce wood is height growth of free growing trees of a given species (Barnes *et al.* 1988). A more detailed classification incorporating SI is required, particularly for tree species suitable for intensive plantation management (Carmean 2007). Silvicultural practices conducted in intensive forest management can influence the growth of regenerated stands compared to natural stands (Huang *et al.* 2004b). A study by Seymour and McCormack (1989) in Maine comparing unmanaged forest lands to intensively managed plantations found volume increases of three to four times over unmanaged stands. They identified three vital steps to achieve increases: greatly expanding plantations established on productive forest lands near mills; carefully timing herbicide release to obtain fully stocked, well-spaced plantations; and genetic improvement of seedlings.

Currently in northwestern Ontario polymorphic site index curves have been developed using stem analysis methods for natural stands of jack pine (Carmean and Lenthall 1989, Carmean *et al.* 2001), as well as black spruce and trembling aspen (Carmean *et al.* 2006a). These polymorphic curves are currently being used in intensively managed plantations (Carmean 2007). With the large investments that are made into intensively managed plantations, underestimating site productivity and yield by using curves developed from natural stands, could significantly underestimate potential returns on investment.

Growth intercept models have been developed in order to predict site index in plantations such as red pine (*Pinus resinosa* Ait.) in the Alleghany Plateau of Ohio

(Brown and Duncan 1990), in the northern Lake States (Bottenfield and Reed 1988, Alban 1972, 1976, and 1979), and in north central Ontario (Carmean and Thrower 1995), white spruce (*Picea glauca* [Moench] Voss) plantations in northern Ontario (Thrower 1986, 1987; Carmean *et al.* 2006b), and jack pine (*Pinus banksiana* Lamb.) plantations in northern Ontario (Guo and Wang 2006). There have also been many studies published relating site index to growth intercept for young plantations in British Columbia such as Sitka spruce (*Picea sitchensis* [Bong.] Carr.) (Nigh 1996b, 1999), western larch (*Larix occidentalis* Nutt.) (Nigh *et al.* 1999), black spruce (*Picea mariana* [Mill.] BSP) (Nigh and Klinka 2001), and ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) (Nigh 2002). Growth intercept models have been developed for jack pine natural stands in Ontario and Quebec (Carmean and Lenthall 1989, Carmean *et al.* 2001, Mailly and Gaudreault 2005), and for black spruce and balsam fir in Quebec (Mailly and Gaudreault 2005).

2.1.1. Black Spruce

Black spruce is considered a wide-ranging, abundant conifer that is found in the northern parts of North America, and the most abundant species in the Boreal forest region. Its wood is relatively light in weight, but contains the strongest fibres of any pulpwood species in Canada. This strength characteristic, unmatched by any other country, is a direct result of the species' slow growing nature and makes it the most important pulpwood species in Ontario (Viereck and Johnston 1990). In Ontario, black spruce is the most abundant working group species covering 34.4% of the total forested land area (OMNR 2002). Its annual harvest volume, including white spruce, has been increasing every year, reaching over 10.3 million m^3 or approximately 42% of the total area harvested in 2000-01 (OMNR 2004a).

Pure even-aged stands of black spruce are most commonly found in lowland swamp areas across the province. Even-aged stands are generally established after a fire disturbance, and un-even aged stands are fairly uncommon unless closed stands escape fire for more than 100 years and the layerings fill in any gaps in the canopy due to stand deterioration. In poorer, low productive, swamp stands, layering is an important means of reproduction, especially where the rapidly growing mosses cover the lower branches of the slow growing seedlings and saplings (Hatcher 1963). These trees represent advance growth on some sites, especially important where harvesting disturbances are light (Fowells 1965).

Rotation age for black spruce depends mainly on site quality in the boreal forest and ranges between 95 to 132 years, for good to poor site classes respectively. Merchantable volume ranges from 218 to 101 m^3/ha, and mean annual increment from 2.3 to 0.8 m^3/ha for good to poor site classes respectively. Ten-year-old black spruce plantations are typically between 1.5 and 4.0 m in height. Some intensive fast-growing plantation have been established on rich sites in New Brunswick producing 45-year rotations since the species is resistant to spruce budworm and has tremendous potential height growth (Viereck and Johnston 1990).

Due to the importance of black spruce as a major pulpwood species in Canada for producing high quality pulp and paper it is essential to update growth and yield potential and site productivity for intensively managed plantations across northern Ontario.

2.1.2. Growth Intercept and Site Index

Growth intercept is defined as a measure of 'average annual height growth in a period immediately above breast height'. Growth intercept models use early height growth to estimate site index. They are key and important tools in accurately estimating site index in juvenile stands and plantations that have surpassed breast height (Nigh 1998). Site index can be defined as "total height at a total age of 50 years at breast height" (Carmean *et al.* 2001), where breast height age refers to the amount of years required for a tree to attain breast height (1.3 m) (Carmean *et al.* 2001). In other words, site index is the potential productivity of a forest site (Nigh 1995a). Vanclay (1992) stated that site productivity is the potential of a certain species and site to produce timber. Sustainable forest management practices rely heavily on accurate estimation of site index since it is the most widely used measure for assessing site productivity in growth and yield modeling, timber supply analysis, silviculture, and forest inventories. There is increasing concern about the accuracy of site index estimation using models developed from mature, natural origin stands for post-harvest young plantations (Huang *et al.* 2004a).

The most commonly used method for estimating site quality in North America is by estimating side index from forest trees (Carmean and Lenthall 1989). Top height of trees represents the maximum potential height growth trajectory of the stand (Feng *et al.* 2006). Top or total height is the height of the 100 largest diameter at breast height (dbh) trees per hectare (FPCP 1999). Thus, it requires height and age measurements from several dominant and co-dominant trees in older, even-aged, fully-stocked stands, which are then related to a family of site index curves; these curves are expressed as total tree height at a specified index age (Carmean *et al.* 2001). The site trees are dominant and codominant top height trees that are undamaged and have not experienced any suppression, thus representing height growth due to site factors only (Nigh 1995a).

The growth intercept method was first proposed as an index of site productivity in 1937 (Nigh 1995b). There are two forms of growth intercept models, traditional (also known as fixed) and variable growth intercept models. Traditionally height growth intercept models predicted site index from the distance between annual branch whorls that were found on the trees and averaged over a five-year period (Nigh 1996a). The development of the growth intercept model is relatively straightforward for conifer species that possess obvious annual branch whorls such as red pine. However, for species such as jack pine and black spruce, where annual branch whorls can be missing and/or false, a modified and more variable approach is required (Nigh 1995b). This leads to the development of the variable growth intercept method. This method estimates the site index from the average height growth above breast height using variable lengths that are specified based on the sampling intensity during stem analysis data collection (Nigh 2002). Site quality is difficult to assess in black spruce and jack pine plantations since most site index curves are developed from mature trees from natural stands, old enough to have reached an index age (breast height age) of 50 years. Nigh (2002) reported that the most accurate estimates of site index were found for trees between 5 and 50 years breast height age.

Originally, there were advantages to traditional growth intercept methods as outlined by Alban (1972): (1) they could be used in stands too young to be evaluated with site index curves; (2) there was no need to measure total tree height; (3) the data is quick and easy to collect; and (4) measurement above breast height eliminated many of the establishment period variability. As well, tree age measurements are not needed avoiding unnecessary injury to trees by increment bores (Carmean 2007). The traditional method is still preferred in studying species that contain distinct annual branch whorls; however for other species the variable growth intercept method has proved to be advantageous. The variable growth intercept method has the following benefits (B.C. Ministry of Forests 1995): it can be applied to younger stands; it is suitable for species without regular annual branch whorls; and it produces more accurate site index estimation under many circumstances. These preliminary findings were further strengthened by Nigh's (1996) study that found that variable growth intercept models to have the following advantages: (1) they are developed specifically for estimating site index, not height; (2) they are intended for young stands; (3) they are not constrained to pass through the site index at index age; and (4) they are less sensitive to small deviations from the mean height when compared to height-age models.

2.1.3. Methods of Collecting Data

The two most common ways of collecting data are through permanent sample plots and stem analysis. Permanent sample plots are silvicultural surveys that are developed at a young age and require repeated height measurements throughout the growth of the stand in order to build a site index model. When available these consecutive measurements are widely considered the best basis for site index model development (Spurr 1952, Clutter *et al.* 1983, Hagglund 1981). Stem analysis reconstructs past height growth from growth rings on dissected sample trees (Dahms 1963, Curtis 1964). The advantages with stem analysis are that measurements are more precise than those for heights on standing trees in permanent sample plots, and long-term data collection is not required, however some disadvantages include the potential for serious biases due to changes in dominance, tree selections, and other reasons (Dahms 1963). Garcia (2005) compared two models derived from different data (stem analysis and permanent sample plot) and found statistical differences between models derived from the two data sets. However, it is not obvious which data set is the "correct" one or the best to use. Stem analysis is prone to the biases stated above as well as possible errors in measurement and calculation procedures. On the contrary, the permanent sample plots are more vulnerable to measurement error, and the data generally covers a narrow range in age (depending on how many re-measurements have occurred). There is also the possibility of bias associated with plot size.

Stem analysis is more appropriate for this study as the intensive sampling design for sectioning the stem will allow for accurate re-construction of early height growth which is necessary for growth intercept models (Nigh 1998). Suitable trees provide heights and ages that are required to develop growth intercept and site index models from stem analysis data. These trees must be healthy, free of breakage or damage, their height growth must not be suppressed and they should not be residuals from previous logging operations (Nigh and Martin 2001). The site trees are selected from plots in areas where a minimum of 75% stocking is required for pure even-aged stands (Guo and Wang 2006). For northern Ontario anamorphic site-class curves for black spruce have been developed using graphical methods not capable of expressing polymorphic height growth patterns (Plonski 1974, Carmean *et al.* 2006a).

Traditionally trees are sectioned at the stump, 0.5, 1.3, and 2.0 m, at 1-m intervals up to 13.0 m and at 0.50-m intervals thereafter (Carmean and Lenthall 1989). However, there is a problem with sectioning the stem at 1 m intervals because you cannot distinguish where internodes end and where new growth begins (Nigh 1996a). Therefore, for a 1-meter section that has grown 3 years it is incorrect to assume that each year's growth was attained in equal 0.33 m segments. Perhaps two of the years the tree grew 0.25 m and 0.50 m in the final year of the three years even without being subject to stressful environmental conditions. Therefore, the accuracy of distinguishing where internodes end and new growth begins will increase by sectioning the stem at 0.5 m intervals after the 2.0 m disc. Age at each height is then determined by cutting and sanding the discs in the laboratory and counting the rings (Carmean and Lenthall 1989). However, the rings no longer have to be counted manually with the development of powerful tree-ring analyzing software such as WinDENDRO that scan the disc image into the computer and provide all the information (age, radius and diameter of the disc, ring width etc.) directly to the user.

Testing and verifying the site index curves that are obtained from the data using control plots are important. Sites from the original collected data set are selected randomly as independently selected verification plots and are used to verify the precision for fitting the site index curves (Carmean *et al.* 2001). In some cases the optimism principle applies. This principle states that a model tested with the model development data will almost certainly indicate better performance than would be expected in practice (Nigh 1996a).

2.1.4. Model Development

Typically individual tree height-age curves are plotted and inspected for any abnormal tree height-growth patterns that are commonly caused by early suppression or by top damage or breakage (Carmean *et al.* 2001). A small bias, that occurs as height at the sectioning point underestimates the actual height attained for that particular year. The bias is corrected since growth for that year does not occur exactly where the stem is sectioned, but between two sections (Carmean 1972, Dyer and Bailey 1987, Carmean and Lenthal 1989).

Nigh's (1996c) method can be used to determine the number of years it takes a tree to grow to breast height, enabling the calculation of breast height age (BHA) for each tree, and the average for each site. BHA is used since it eliminates variation in height growth caused by nonsite factors (Monserud 1984) including early competition, mammal and insect damage, frost damage, quality of planting, quality of planting stock, allelopathic compounds, and small microsite differences (Carmean *et al.* 2006b). Nigh's (2002) method can be used to convert average annual height growth (cm/yr) of the measured dominant and co-dominant trees into growth intercept form. The growth intercept is then related to site index using a power function, and providing growth intercept models for specified BHAs (Nigh 1998).

Outliers are examined and standard regression assumptions are met by testing residuals for normality, homoscedasticity and bias. Any plots that seem highly influential on the data are deleted from the data set (Guo and Wang 2006). Finally, Newnham's (1998) non linear regression model, which forces curves to pass exactly through tree height at specified index age, is used to fit the site index curves with higher precision (Carmean *et al.* 2006a).

2.1.5. Model Validation

Validation is defined by Reynolds *et al.* (1981) as "the testing and comparing of the model output with what is observed in the real world." Validation consists of checking for bias in the estimated height and/or site index and determining the precision of the models (Nigh and Sit 1996). The final validation of a model relates to the potential applications, uses, and long term acceptance by practitioners of the model (McCarl 1984; Nigh and Sit 1996).

Of the available methods for model validation often the simple ones are both adequate and preferable (Mayer and Butler 1993). Accuracy assessment techniques used in Chen *et al.* (1998) and Buda and Wang (2006) are adequate in validating and checking for accuracy and bias in height growth models. The accuracy of a model is the proximity of predicted value to its actual value, which is a combined measure precision and lack of bias (Sokal and Rohfl 1981; Nigh and Sit 1996). Root mean square error (RMSE) is recommended as a more stable statistics for measuring deviance among the data (Mayer and Butler 1993). Plots of predicted versus observed total heights are tested against regression $y = x$ (Chen *et al.* 1998, Buda and Wang 2006). This plot directly presents goodness of fit as vertical deviations from the 'perfect' line, and indicated any biases present (Mayer and Butler 1993). The test is a simple t-test as described in Zar (1996) in comparing slopes of regression lines. Regression analysis of observed versus predicted total heights is also a useful tool for model testing (Mayer and Butler 1993), thus the same test can be used to test two models to see if they are significantly different from one another. An analysis of variance (ANOVA) examining predicted heights between height growth models is another simple method in comparing models. However, sometimes the ANOVA assumptions, homogeneity of variance and randomly selected samples, may be violated.

Chen *et al.* (1998) identified two causes of bias in height growth and site index models: the lack of flexibility of selected model functional forms describing biological pattern (Hunt 1982; Nigh and Sit 1996); and poor representation of the samples used to construct models for a given population (Neter *et al.* 1996; Nigh and Sit 1996). Although model validation is a useful procedure that gives analysts confidence in their models the results need to be interpreted carefully when testing for bias and precision. Many problems may be a result of poor sampling (Nigh and Sit 1996).

2.1.6. Growth and Yield

Growth and yield models describe forest dynamics (i.e., the growth, mortality, reproduction, and associated changes in the stand) over time (Peng 2000). This information is essential to successful forest management. Growth and yield is widely used in long-term strategic planning, updating forest inventory data, projecting future yield, providing input for annual allowable cut determination in timber supply analysis, and evaluating stand performance and silvicultural alternatives (Huang *et al.* 2004a). Therefore, predicting future forest growth and yield under different management scenarios is a key element of sustainable forest management (Peng 2000). However, growth and yield data are often based on historical stand performance resulting in inaccurate estimates of future stand conditions (Huang *et al.* 2004a).

Growth and yield models date as far back as the early 1850's where central European foresters used graphical methods to model the growth and production of forests. For important tree species in Europe yield tables were constructed based on complete observations throughout the entire rotation of the stand (Vuokila 1965). Growth and yield modeling has moved forward significantly in the last 20 years thanks, in part, to advanced mathematical statistics and computing technology. These advancements have occurred at increasing rates enabling the production of many computer based growth and yield models (Peng 2000).

In Ontario the need for forest growth and yield data has been well documented. Forest structure and composition has been a significant missing component of growth and yield that can be acquired from established plots in the forest over the past 40 to 80 years. Millions of dollars have been invested by government and industry to establish these plots in the past. These plots were re-established by the Forest Co-op to complete the final missing component of growth and yield in Ontario. The focus was for a large return on a previous investment since the cost of re-creating these historic plots in today's dollars was estimated at over $3 million. There is a growing uncertainty concerning wood supply and its impact on Ontario's forest industry sector. This need requires increased precision and accuracy of projected harvest levels and wood supply based on completing the analysis of historical data that has been collected (Forest Co-Op 2004).

2.1.7. Notable Findings

2.1.7.1. Natural Stands

Early work with site index curves in north central Ontario occurred in jack pine stands. Carmean and Lenthall (1989) showed that for jack pine: (1) site index curves based on breast-height age were more precise than curves based on total age; (2) height-growth patterns were polymorphic, with height growth becoming more curvilinear as site index increased; (3) even though site index varied greatly polymorphic patterns of height growth were similar for trees growing on mineral soils developed from four major upland landforms; and (4) height-growth patterns for trees aged less than 50 years were similar to the commonly used Plonski (1974) anamorphic site class curves for Ontario, but after 50 years, height growth was better than predicted by the Plonski curves.

Variable growth intercepts were developed as they are suitable for species without distinct annual branch whorls. Nigh's (1995b) first study incorporating variable growth intercept models found that: (1) the models can be used as soon as one year after the trees reach breast height; and (2) for stands over 5 years BHA, site index should be estimated from all available growth, resulting in more accurate estimates. However, several disadvantages were discovered. The models require height and age measurements that, on small trees, are subject to large relative measurement errors. These techniques are more difficult to use in stands older than 30 years breast height age. Variable growth intercept models may lose some precision when compared to the fixed growth intercept models. Thirty sub models are required, which can be unwieldy unless data are presented in a tabular, computer, or single equation form. And finally, calculation of breast height age from the ring count can be problematic because an internode does not always begin at breast height.

The assumption that breast height occurs midway between two annual nodes may violate the variable growth intercept model method (Nigh 1996a). This error can be reduced by increasing the number of sample trees, or to accurately identifying and measuring the first (A – 0.5) year of growth above breast height from the annual whorls. This measured growth is divided by (A – 0.5) to get the average annual height growth (GI_A). Site index is then determined from the sub-model corresponding to breast height age A. Although it is more difficult to implement, this method gives a more accurate growth intercept because it does not assume that breast height lies midway between annual nodes. Nigh (1998) recommends that growth intercept models should be used for stands between 14 and 50 years breast height age, although their precision is only marginally better than the height-breast height age model's precision.

Continuing with their work dealing with polymorphic site index curves for jack pine in Northern Ontario, Carmean *et al.* (2001) found that the four separate and independent regional equations that predicted similar polymorphic height growth. This justified the conclusion, that data from all four regions could be combined for the computation of a single final equation and a single set of site index curves that would become applicable to all the mineral soils found across northern Ontario. In a study published a year later by Zhang *et al.* (2002) concluded that local environmental conditions, such as climate, soil, and vegetation type, play a significant role in affecting the ecoregion-based height-diameter relationships. There are distinct variations in height-diameter relationships for jack pine among the seven ecoregions in the Boreal and Central forest regions of Ontario (Zhang *et al.* 2002).

Polymorphic height growth curves using BHA are more precise than models using total age. Nigh (2002) found that the height growth of trees varies considerably below breast height, which is reflected in the root mean squared error (or the standard deviation in this case) associated with years to breast height models in general. These findings further support the findings of Carmean and Lenthall (1989) that height growth curves based on BHA are more precise than curves based on total age due to the slow and erratic early height growth before reaching breast height.

Growth intercept models were developed for black spruce, jack pine, and balsam fir (*Abies balsamea* [L.] Mill.) in Quebec (Mailly and Gaudreault 2005). They concluded that the models for black spruce were the most precise, followed by those for jack pine and finally those for balsam fir. Overall the growth intercept models were equal if not superior in accuracy when compared to models that have been developed in British Columbia. As is typical for growth intercept models, the accuracy of the model increased as the tree age increased. This study showed that the variable growth model proposed by Nigh (1997) as applicable in Quebec to black spruce, jack pine and balsam fir. The relationship between site index and the growth intercept lengths is slightly curvilinear, which indicated that as growth intercept length increased the increase in site index was progressively smaller. This also suggested that trees growing on good sites reached the maximum rate of height growth earlier than trees that grew on poor sites.

Biases that may occur in overestimating site index in juvenile stands should be corrected. Feng *et al.* (2006) found that new height age equations developed from an additional juvenile performance survey (10 to 15 years) corrected these biases. They found that site index (at BHA 50) would have been 3.3 m higher on average if this correction was not applied. The average height bias in five white spruce stands was 14%, which was linked to dominance switching if the stand is not sampled when top height trees are at index age (Dahms 1963, Magnussen and Penner 1996). However, the authors caution users about the application of this method as it is unclear how these results will apply to more intensively managed stands. Rapid juvenile growth following mechanical site preparation in lodgepole pine produced high early growth rates, but did not continue and stabilized once stands reached crown closure (Bedford and Sutton 2000), which contradicts the findings by Huang *et al.* (2004b).

Polymorphic site index curves were developed for natural black spruce stands for both upland mineral soils and organic soils across northwestern Ontario (Carmean *et al.* 2006a). By accepting the critical windthrow height of 20 m for black spruce (Smith *et al.* 1987), then these curves can be used to estimate BHA when dominant and co-dominant black spruce reach 20 m. Thus rotation age should decrease as site index increases; black spruce trees on sites with site index (BHA 50) of 20, 18, 16, and 14 m are predicted to reach 20 m height at 50, 62, 76, and 96 years BHA respectively.

2.1.7.2. Planted Stands

Carmean *et al.* (2006b) observed that height growth is still somewhat erratic for the first five years above BHA. Comparing the height growth data to Berry's (1978) curves for southeastern Ontario it is recommended that Berry's (1978) yield tables for white spruce plantations in southeastern Ontario be used in north central Ontario until local yield tables are developed in the area.

2.1.7.3. Silvicultural Effects on Site Index

Recently, silviculture activities have been found to have positive effects on site index. Farnden and Herring (2002) found, through combinations of thinning and fertilization, the best treatment increased top height by 3 m and site index (at BHA 50) increased almost 8 m in repressed lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) stands. Some practitioners define site index as the maximum site potential, thus suggesting that site potential was increased by almost 8 meters, however stem analysis of two remaining old growth trees suggested the site index of 22 m at BHA 50. Thus, the potential of the site did not increase; the stand was released and increased in height growth to attain the historic site index for that stand. A study by Huang *et al.* (2004b) addressed the concern of whether or not the site index obtained from early height growth of post-harvest stands is maintained through to maturity. Their findings for lodgepole pine recorded overall post-harvest mean site index to be 27 to 35 % higher than fire-origin stands by simply logging the stand, performing some site treatment (scarification), and successful natural regeneration. The results imply that previously unproductive fire-origin lodgepole pine sites can be turned into productive sites once they are harvested, treated, and regenerated. Suggestions for increased post-harvest growth and site index also include global warming or climate change since biogeoclimatic attributes such as climate that control the environment of a site may change, it is possible that site index can also be changed. However, the sample size in this study is still considered small and should be expanded to help determine if site index gain of post-harvest stand is consistent on a broader land base (Hunag *et al.* 2004b). Thus far studies relating silviculture to site index show that site treatments can improve site index on a repressed or overstocked site, however in terms of increasing the site index of a site that was not repressed remains unknown.

2.1.7.4. Comparison of Natural Versus Planted Stands

Site index curves for natural jack pine stands in northern Ontario have been published (Carmean and Lenthall 1989, Carmean *et al.* 2001), however we do not know if these site index curves are applicable for young jack pine plantations (Guo and Wang

2006). Site index models for different plantation species have only been developed in British Columbia. However, very few studies exist comparing natural stands to young plantations to determine whether site indices based on natural stands are sufficient for predicting future stand characteristics of plantations. It is important for forest managers to determine whether the increase in site index, if any, is adequate to recover the investment being made in intensive silvicultural practices. Nigh and Love (1997) compared site indices that were determined for old growth stands to those simulated for young managed stands. They found that the average site index at breast height age to be 13.7 and 24.9 m respectively, and that the average difference between managed stand site indices and old-growth site indices was 11.2 m.

The findings above were consistent with those found in a study by Guo and Wang (2006) that compared height growth and growth intercept models of jack pine plantations and natural stands in northern Ontario. The results from the study indicated significant differences between growth intercept models derived from jack pine plantations and natural stands. The difference is believed to be due to the different height growth patterns in plantations and natural stands. It is too early to conclude that these differences are only due to management, but a combination of factors including site conditions influenced by climate, soil, and topography should be explored. To illustrate all the possible reasons a study that contains more plots in plantations that are over 50 years of age are required.

Finally, a study conducted in north-western Spain by Dieguez-Aranda *et al.* (2005) modeled dominant height growth of radiata pine (*Pinus radiata* D. Don) plantations. They collected 161 trees that were sectioned for stem analysis and the data was used to construct the model. The model was then tested and compared to the current model being used in the plantation (Sanchez *et al.* 2003). The new model was more realistic than the current model, derived from natural stands, that was recommended for height growth estimation and site classification for radiata pine plantations in Galicia (north-western Spain).

Although limited, these three studies indicate that there are differences in height growth patterns between natural stands and young plantations that must be affected by silvicultural practices, such as site preparation and herbicide control, during intensive forest management. However, more studies that compare natural stands and young plantations need to be conducted in similar site and environmental conditions to strengthen the argument. I expect there is a difference in site productivity and height growth patterns between black spruce natural stands and plantations in northern Ontario. These differences should be more pronounced in early years above BHA where silvicultural activities would decrease competition with less desirable species resulting in increased height growth of black spruce. This hypothesis will be tested by examining growth intercept and site index models generated from stem analysis of dominant and co-dominant trees sampled from black spruce plantations across common soil types in the boreal regions of Ontario.

2.2. METHODS

2.2.1. Data Collection and Sampling

In the field, site selection parameters such as artificial regeneration, at least 70% black spruce species composition and a minimum total age of 40 years old were verified using an increment borer (Figure 2.1) and a temporary sample plot. Sample trees were healthy, free-growing, undamaged, and unsuppressed due to competition or disease. Natural sample trees met the above criteria as well as being in close proximity to the plantation on an equally productive site and at least 50 years at breast height.

2.2.1.1. Plot Establishment

At each site a 200 m^2 circular temporary sample plot with a radius of 7.98 m was established. The number of standing trees as well as the diameter at breast height (dbh) was recorded by 2 cm dbh classes using a dot dash tally within the plot. Elevation (m), latitude, and longitude were measured using a Garmin eTrex Legend Global Positioning System (GPS). The site position (crest, upper slope, middle slope, lower slope, toe depression, or level), degree of slope, and aspect were recorded. In addition vegetation information such as associated cover species (in and outside of the temporary sample plot) and list of shrub and herb species were also recorded.

2.2.1.2. Stem Analysis Sampling

Three black spruce sample trees that fell into the largest dbh class(es), also termed site trees, were destructively sampled. Precise dbh measurements were recorded, and 0.3 and 1.0 m sections were marked on each sample tree before they were felled. Once each tree was felled and limbed (Figure 2.1) the total height of the tree was recorded. Next 1.3, 2.0 and at 0.5 m interval sections were marked on the tree. These sections were cut into discs (Figure 2.1), including a disc at 0 m or close to the ground as possible, and marked accordingly before being packed into burlap sacks by respective sample tree and transported out of the forest.

Figure 2.1. From left to right, boring, limbing and cutting sample trees into discs.

2.2.2. Stem Analysis Sample Preparation

Each burlap bag containing tree discs was opened and tree discs were shuffled around to air dry in order to prevent heavy mould and mildew from forming on the samples. Once the field season was complete and all the samples had been collected and air-dried they were sanded in the Lakehead University Wood Science facility using a belt sander. After sanding, the discs were blotted with water to increase the distinct color difference between earlywood and latewood to improve accuracy in identifying growth rings. The time between sanding and scanning was minimized to ensure no mould or mildew stains would reoccur on the scanning surface. Discs were scanned on an EPSON scanner, and the resulting images were analyzed using WinDendro software. The ring counts are verified by the user as the program sometimes misses or counts additional rings. Some natural samples required growth ring analysis using a handheld lens and manual counting, as the rings were too thin to be analyzed by the software. There are some limitations of the software when dealing with slow growing species such as black spruce. The discs are sanded very smoothly and scanned in at higher resolutions. However, when dealing with a project of this magnitude time, in sanding and scanning, as well as file storage space for the images become an issue. A compromise is met, which results in the user spending more time in verifying the accuracy of the software, as lower resolution images are used.

2.2.3. Data Analysis

For natural black spruce stands site index was defined as the average height of dominant and co-dominant, unsuppressed, injury and disease free trees at 50 years breast height (1.3 m) age (SI_{50}). For black spruce plantations, since stands over 40 years total age were sampled, the site index age was determined at 30 years breast height age (SI_{30}). The corrected total tree height of planted and natural black spruce at 30 and 50 years breast height age respectively was used to estimate site index. Due to the small dataset of naturally regenerated trees collected in this study, data from natural stands collected by Carmean (2006a) were used for comparison with the plantation dataset. The dataset included the site index and corrected total height at breast height age starting from 0 to 50 in 5 year intervals.

2.2.3.1. Stem Analysis Data Preparation

Since internodes of tree height growth do not occur exactly where stem discs are sampled, at the specified 0.5 m intervals, the true height for that particular growth year occurs between disc sections and thus must be estimated. I used Carmean's (1972) method (as stated by Dyer and Bailey 1987) to estimate the true height of each tree at each year of growth using the formula below:

Eq. 1 $$H_{ij} = h_i + \frac{(h_{i+1} - h_i)}{2(r_i - r_{i+1})} + \frac{(j-1)(h_{i+1} - h_i)}{(r_i - r_{i+1})}$$

where,

H_{ij} = estimated total tree height at age t_{ij},

t_{ij} = age of the tree associated with the jth inner ring at the ith crosscut, $n - r_i + j$,

h_i = height at the ith crosscut (i.e., the sum of all bolt lengths below the ith crosscut),

r_i = the number of growth rings at the ith crosscut,

n = total tree age.

Using these estimated true heights; tree height was plotted against total tree age. Based on these plots, 4 trees were removed from the dataset as they exhibited suppressed height growth patterns; two trees from the Superior Lake Forest, one from the Hearst Forest, and one from the Kenora Forest.

2.2.3.2. Years To Breast Height (YTBH)

Years to breast height is defined as the number of years it takes an individual site tree to reach breast height, and was calculated using the equation below (Nigh 1996c):

Eq. 2 $$YTBH = A_0 + \frac{1.3 - H_0}{H_1 - H_0}$$

where,

A_0 = total age (years) of the tree below breast height,

H_0 = height (m) of the tree at A_0 year,

H_1 = height (m) of the tree at breast height age (BHA) 1.

Many studies (Thrower 1986; Carmean and Lenthall 1989; Carmean et al. 1989; Carmean 1996; Nigh 2002; Guo and Wang 2006; Carmean *et al.* 2006b) concluded that height growth models should be derived using breast height age (BHA) to avoid early erratic height growth that takes place below breast height. The relationship between YTBH and site index was examined to distinguish whether slow and erratic height growth below breast height is related to site quality. Nigh's (2002) equation was used to fit the relationship between YTBH and site index:

Eq. 3 $YTBH = b_1 \times b_2{}^{SI}$

where,

SI = site index (m at breast height age 30 for plantations and breast height age 50 for natural stands),

b_i = model parameters.

2.2.3.3. Growth Intercept Model

The height and breast height age data needs to be converted into growth intercept form in order to relate it to site index. Since the growth after attaining breast height is a part of the total growth for that year's height growth, an adjustment for BHA is required to ensure the accuracy and precision of the growth intercept. The growth intercept is calculated using the equation below (Nigh 2002):

Eq. 4 $$GI_{BHA} = \frac{(HT - 1.3) \times 100}{BHA - \dfrac{1.3 - H_0}{H_1 - H_0}}$$

where,

GI_{BHA} = growth intercept (cm/yr) corresponding to breast height age (BHA) in years,

HT = averaged total height of 3 site trees (m),

BHA = breast height age, total age minus years to reach breast height (1.3 m).

A non linear power function was used to model the relationship between growth intercept and site index for the sampled site trees (Nigh 1996c):

Eq. 5 $SI = 1.3 + b_1 GI_{BHA}^{\ \ b_2} + \varepsilon$

where,

SI = site index,

GI_{BHA} = growth intercept at breast height age,

b_i = model parameters,

ε = random error.

Nonlinear least squares regression was used to fit the dataset to Eq. 5 using SYSTAT (SPSS Inc. 2000). Models were developed for breast height ages 1 to 30 for black spruce plantations, and 5 to 50 (at 5 year intervals) for black spruce natural stands. To ensure standard regression assumptions were met, and to detect outliers, residuals were tested for normality, homoscedasticity and bias. Outlier analysis was conducted; however the few that were detected did not prove to be highly influential on the final models and were not removed from the dataset.

2.2.3.4. Site Index Model

To predict site index of natural or planted stands that are younger than index age requires the use of growth intercept models. However, when the stands are older than index age, site index curves can be developed. A polymorphic height growth model is required to fit a site index curve that has the ability to constrain the curves to pass exactly through the tree height specified at index age. The Newnham (1988) model, derived from adaptations of Ek (1971) and Monserud (1984) models, possesses flexibility and the constraining abilities without sacrificing excellent precision. Thus, site index curves were fitted using the Newnham (1988) constrained version of the Ek (1971) nonlinear regression equation below:

Eq. 6 $$\hat{H} = 1.3 + b_1(SI - 1.3)^{b_2}\left[1 - K^{\frac{BHA}{30}}\right]^{b_3(SI-1.3)^{b_4}}$$

where $$K = 1 - \left[\frac{SI - 1.3}{b_1(SI - 1.3)^{b_2}}\right]^{\frac{1}{b_3(SI-1.3)^{b_4}}}$$

$\hat{H}$ = predicted height (m) of dominant and codominant tree;

SI = site index (average height (m) of dominant and codominant tree at 30 years breast height age;

BHA = breast height age (years);

b_i = regression coefficients to be estimated; i = 1, ..., 4.

Site index curves allow the graphical estimation of site index by locating the breast height age and corresponding measured tree height on the curves and interpolating between the curves for the estimated site index. Some disadvantages with this method are that it is relatively slow, inefficient and introduces small bias when interpolating between the curves. This can be avoided by using a site estimation model to directly calculate site index from total height and breast height age. Carmean et al. (2001) suggested that this kind of model can be developed separately as opposed to solving it backwards from the site index curve model. Thus site index measurements were estimated using the following equation:

Eq. 7 $$SI = b_0 + b_1(HT - 1.3) + b_2LN(HT - 1.3) + b_3LN(BHA) + b_4LN(BHA)^2 + b_5\left(\frac{HT - 1.3}{BHA}\right) + b_6(BHA)LN(HT - 1.3)$$

where,

HT = average total height of site trees;

SI = site index;

BHA = breast height age (years);

b_i = regression coefficients to be estimated; i = 1, …, 6.

2.2.3.5. Model Testing

Residuals from polymorphic height growth models were inspected for bias, heteroscedasticity, and normal distribution using the RMSE. Models were further tested for precision and accuracy using methods described in Chen et al. (1998), and Buda and Wang (2006). Regression of predicted versus observed total heights were tested against a y = x regression (line of best fit) using a two-tailed t-test as described in Zar (1996). The regression models were forced through the origin to keep the intercept constant and focus on the slopes. The polymorphic height growth models were plotted against observed data stem analysis data clouds to further examine the goodness of fit between the model and the observed data.

2.2.3.6. Model Comparison

Polymorhpic height growth models (SI_{30}) between black spruce plantations and natural stands in northern Ontario were compared by evaluating respective R^2 and MSE values from each model. This was also done for SI_{30} models between black spruce plantations for northeastern and northwestern Ontario. The SI_{30} curves of each model were plotted against one another for a direct graphical comparison. An analysis of variance (ANOVA) tested predicted heights from each derived height growth model to see if total height predictions differ between the models being tested. Total heights of predicted versus observed values were plotted and a regression was fit to the data. The slopes of the regression were tested statistically using a two-tailed t-test as explained in Zar (1996).

2.3. RESULTS

The stem analysis data collected from northern Ontario black spruce plantations were prepared for growth intercept and site index analysis. The heights at each section (0.5 m increment) were adjusted since internodes of tree height growth do not occur at the exact point of sectioning of the stem instead it occurs between disc sections and must be estimated to acquire the true height. Once the years to breast height (YTBH) were calculated and total ages were adjusted to breast height ages (BHA) it was possible to derive the site index at index age 30 for all sampled trees from black spruce plantations. Black spruce trees were sampled from nearby natural stands attempting to capture similar site and soil conditions to the black spruce plantations for a direct comparison of height growth. The heights were also adjusted for these sampled black spruce trees from natural stands to compile a site index at index age 50, the standard index age for site index models, and at index age 30 to create a direct comparison between natural and planted site indices.

Black spruce plantations in northwestern Ontario on average had a higher site index (m) at breast height age 30 than black spruce plantations in northeastern Ontario (Table 2.1 & 2.2). The difference of 1.37 m is directly correlated to the difference in average total heights between the two regions. Average total height for black spruce plantations in northwestern Ontario is 14.88 m in comparison to only 13.03 m for black spruce plantations in northeastern Ontario. However, the average density of the black spruce plantations was higher in northeastern Ontario when compared to northwestern Ontario by almost 400 stems/ha, 2410 stems/ha compared to 2039 stems/ha respectively (Tables 2.1 & 2.2). These densities include all species found within the sample plot, including jack pine (*Pinus banksiana* Lamb.), white spruce (*Picea glauca* (Moench)

Table 2.1. Average total height, site index, density and locations of all sample plots in northeastern Ontario for black spruce plantations.

Site	**Average Total Height (m)**	**SI$_{30}$ (m)**	**Density (stems/ha)**	**Latitude**	**Longitude**
A2	10.07	9.31	3100	N 49^0 13' 34.1"	W 81^{0}31' 21.6"
A3	11.84	10.51	3700	N 49^0 10' 00.3"	W 81^{0}31' 53.7"
A4	10.73	9.70	3100	N 49^0 10' 04.8"	W 81^0 17' 31.0"
A5	11.74	10.68	2300	N 49^0 10' 01.2"	W 81^0 16' 52.5"
B2	9.60	8.77	1100	N 48^0 59' 55.9"	W 81^{0}04' 25.3"
B3	13.47	10.98	1600	N 49^0 00' 36.2"	W 81^{0}04' 25.2"
B4	10.25	9.33	1100	N 49^0 02' 17.9"	W 81^{0}04' 16.4"
C2	10.86	9.91	2000	N 48^0 20' 24.4"	W 81^{0}33' 19.6"
D1	12.33	9.82	2550	N 49^0 36' 05.2"	W 83^0 17' 07.2"
D2	15.03	12.67	1950	N 49^0 23' 03.4"	W 82^{0}07' 13.1"
D3	14.66	11.84	2500	N 49^0 36' 33.5"	W 83^0 16' 31.5"
D4	12.49	10.72	2150	N 49^0 36' 17.6"	W 83^0 16' 49.4"
D5	12.91	10.18	2900	N 49^0 25' 13.3"	W 82^0 39' 00.4"
D6	14.03	12.51	3200	N 49^0 25' 22.5"	W 82^0 38' 50.1"
D7	15.14	11.48	4350	N 49^0 30' 34.3"	W 82^0 45' 08.1"
D8	13.28	10.98	2750	N 49^0 18' 31.4"	W 82^{0}03' 01.9"
D9	12.76	11.57	2900	N 49^0 18' 23.9"	W 82^{0}03' 03.7"
D10	12.21	10.50	2450	N 49^0 24' 25.4"	W 82^0 12' 49.7"
E1	12.98	12.44	3150	N 49^0 52' 13.6"	W 83^{0}36' 14.0"
E2	12.31	11.50	3200	N 49^0 51' 58.2"	W 83^{0}36' 41.7"
E3	13.16	12.50	2600	N 49^0 51' 39.8"	W 83^{0}34' 46.1"
E4	13.92	11.02	3000	N 49^0 44' 36.8"	W 84^{0}07' 22.3"
F1	11.86	10.52	2450	N 47^0 31' 02.3"	W 83^{0}00' 18.7"
F2	14.61	10.55	2100	N 47^0 34' 27.6"	W 83^{0}24' 08.9"
F3	11.73	9.26	1700	N 47^0 34' 33.4"	W 83^{0}24' 08.2"
F4	14.81	10.92	1800	N 47^0 39' 32.2"	W 83^0 18' 50.4"
F5	14.14	12.12	2650	N 48^0 22' 25.8"	W 83^{0}25' 51.0"
H1	15.81	13.18	1750	N 48^0 17' 41.7"	W 80^{0}38' 31.6"
H2	15.43	13.30	1600	N 48^0 17' 23.3"	W 80^{0}39' 24.4"
H3	16.23	13.56	1500	N 48^0 17' 43.5"	W 80^{0}38' 22.8"
H4	13.55	12.26	1500	N 48^0 17' 20.7"	W 80^{0}38' 58.0"
Average	**13.03**	**11.12 ± 1.29**[a]	**2410**	-	-

* A = Smooth Rock Falls; B = Cochrane; C = Timmins; D = Kapuskasing; E = Hearst; F = Chapleau; H = Kirkland Lake

[a] Standard Deviation of SI$_{30}$

Table 2.2. Average total height, site index, density and locations of all sample plots in northwestern Ontario for black spruce plantations.

Site	Average Total Height (m)	SI$_{30}$ (m)	Density (stems/ha)	Latitude	Longitude
G1	12.77	10.62	1900	N 49^{0}30' 56.4"	W 86^{0}36' 53.8"
G2	17.34	13.76	2150	N 49^{0}45' 33.0"	W 86^{0}58' 31.6"
G3	16.01	12.78	2250	N 49^{0}54' 09.7"	W 86^{0}13' 25.4"
G4	15.53	12.51	1600	N 49^{0}51' 00.1"	W 86^{0}20' 52.8"
G5	13.68	10.55	2050	N 49^{0}46' 29.1"	W 86^{0}18' 01.4"
G6	12.38	9.32	2000	N 49^{0}46' 21.6"	W 86^{0}17' 53.8"
G7	15.23	11.96	1450	N 49^{0}46' 45.7"	W 86^{0}13' 40.9"
G8	17.49	13.15	1250	N 49^{0}47' 16.5"	W 86^{0}17' 33.7"
I1	14.22	12.68	1950	N 49^{0}41' 21.9"	W 92^{0}23' 07.1"
I2	14.70	13.09	1800	N 49^{0}41' 24.8"	W 92^{0}23' 38.5"
I3	15.23	13.51	2000	N 49^{0}57' 33.2"	W 92^{0}50' 46.5"
J1	16.06	13.43	1450	N 49^{0}23' 49.9"	W 94^{0}03' 52.5"
J2	15.56	14.40	1250	N 50^{0}08' 27.0"	W 93^{0}51' 23.7"
J3	16.18	13.63	1250	N 49^{0}43' 26.5"	W 94^{0}57' 08.8"
K1	12.85	11.63	1450	N 49^{0}45' 51.3"	W 87^{0}51' 48.3"
K2	14.01	12.50	2100	N 49^{0}45' 52.3"	W 87^{0}52' 32.6"
K3	15.59	13.06	2000	N 49^{0}45' 41.9"	W 87^{0}53' 05.6"
L1	16.00	12.93	1800	N 49^{0}08' 10.0"	W 88^{0}09' 09.9"
L2	15.78	13.09	2450	N 49^{0}07' 45.9"	W 88^{0}09' 46.1"
L3	13.85	12.45	2300	N 49^{0}08' 04.7"	W 88^{0}11' 09.3"
L4	11.84	10.62	2000	N 49^{0}08' 10.8"	W 88^{0}10' 50.8"
L5	13.37	12.26	2350	N 49^{0}05' 55.4"	W 88^{0}10' 02.4"
L6	13.16	12.04	2900	N 49^{0}04' 47.9"	W 88^{0}09' 28.8"
L7	13.65	12.28	2650	N 49^{0}04' 57.5"	W 88^{0}09' 38.2"
L8	13.55	12.65	2200	N 49^{0}05' 12.2"	W 88^{0}09' 59.8"
M1	13.57	12.37	3150	N 48^{0}23' 08.7"	W 90^{0}04' 34.7"
M2	13.68	11.42	3300	N 48^{0}23' 02.3"	W 90^{0}04' 30.8"
M3	14.38	12.31	2200	N 48^{0}56' 06.3"	W 90^{0}35' 50.5"
M4	15.87	12.80	2600	N 48^{0}56' 13.6"	W 90^{0}35' 47.4"
M5	19.19	13.92	1850	N 48^{0}22' 29.7"	W 89^{0}36' 12.7"
M6	18.57	13.61	1550	N 48^{0}22' 31.2"	W 89^{0}36' 11.1"
Average	**14.88**	**12.49 ± 1.11[a]**	**2039**	-	-

* G = Longlac; I = Dryden; J = Kenora; K = Beardmore; L = Nipigon; M = Thunder Bay

[a] Standard Deviation of SI$_{30}$

Voss), balsam fir (*Abies balsamea* (L.) Mill.), white birch (*Betula papyrifera* Marsh.), and trembling aspen (*Populus tremuloides* Michx.).

Seven sites in northeastern Ontario exhibited a site index of less than 10.00 m compared to only one site in northwestern Ontario. The reverse is true for higher quality sites, when looking at a site index of at least 13.00 m only three sites are found in the northeast while eleven sites are present in the northwest region. This trend of lower quality sites in northeastern Ontario and higher quality sites in northwestern Ontario is strikingly more evident when looking at the distribution of the sample trees across ranges of site index (Figure 2.2).

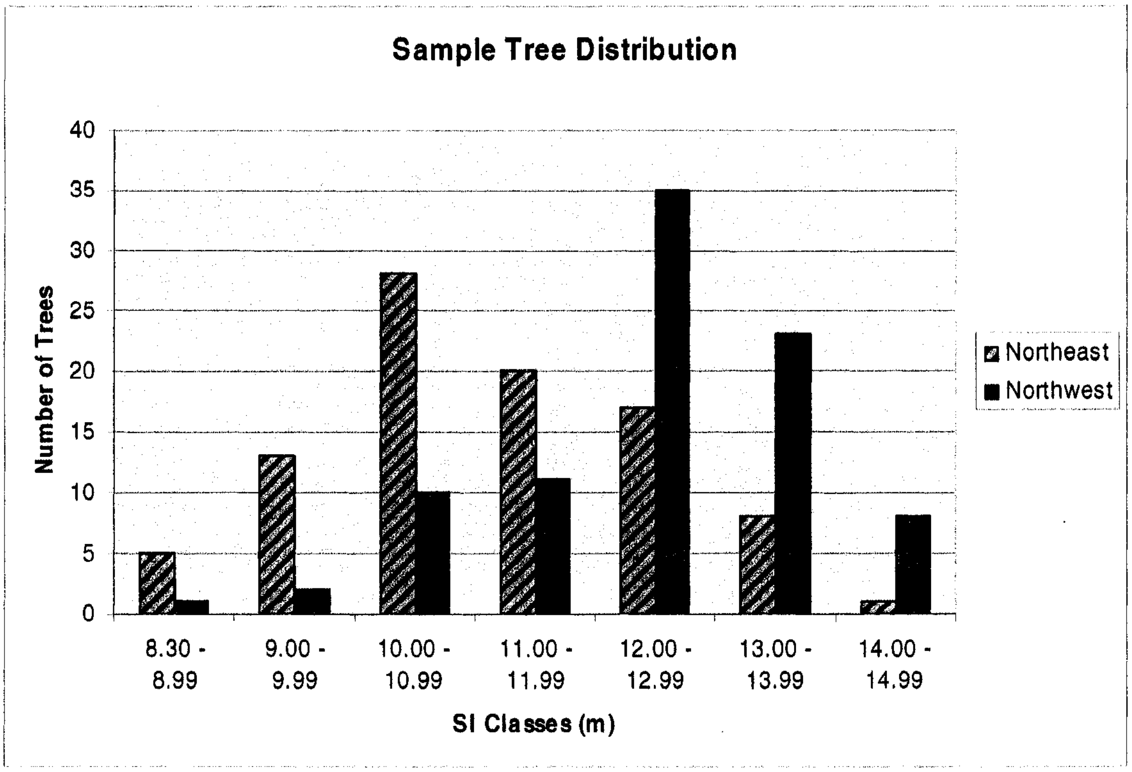


Figure 2.2. Sample tree distribution between northeastern and northwestern Ontario by site index classes at BHA 30 for black spruce plantations.

An analysis of variance (ANOVA) was conducted to compare the distributions of site index at breast height age 30 for black spruce plantations between northwestern and northeastern Ontario (Table 2.3).

Table 2.3. ANOVA results for SI_{30} between northwestern and northeastern Ontario black spruce plantations.

Source	df	Sums of Squares	Mean Square	F-ratio	*p*-value
Region	1	84.202	84.202	49.292	0.0001
Error	180	307.483	1.7082		
Total	181	391.685			

A significant difference between site quality in northeastern and northwestern Ontario does exist as suggested by the ANOVA with an F-ratio of 49.292, which is well above the allotted value as suggested by a *p*-value of 0.0001.

2.3.1. Years to Breast Height (YTBH)

Stem analysis data was used to determine the number of years it took planted black spruce trees to reach breast height at 1.3 m (Table 2.4). YTBH for planted black spruce ranged from 4.68 to 6.41 years across the different regions and forest management units in northern Ontario. Black spruce plantations in northwestern Ontario reached breast height 0.28 years earlier than black spruce plantations in northeastern Ontario. The average across northern Ontario was 5.19 years to reach breast height. Based on all sites sampled the YTBH ranged from 3.49 to 7.38 years.

Since the dataset from Carmean (2006a) does not contain years to breast height age information for natural black spruce, the naturally regenerated trees that were sampled and collected in this study from nearby black spruce natural stands were used. The years to breast height for naturally regenerated trees ranged from 6.68 years on the Wabigoon Forest to 29.42 years (an extreme case) on a poor organic site in Smooth

Table 2.4. Average years to breast height age for planted black spruce by town and forest management unit.

Northeast Town	FMU	YTBH
Smooth Rock Falls	Smooth Rock Falls Forest	5.72
Cochrane	Cochrane Moose River Forest	5.57
Timmins	Romeo-Malette Forest	5.61
Kapuskasing	Gordon Cosens Forest	4.74
Hearst	Hearst Forest	6.41
Chapleau	Superior Forest	5.41
Kirkland Lake	Timiskaming Forest	5.11
	Northeast Average	**5.33**
Northwest **Town**	**FMU(s)**	**YTBH**
Longlac	Kenogami Forest	4.86
Dryden	Wabigoon & Dryden Forests	4.68
Kenora	Kenora Forest	5.15
Beardmore	Lake Nipigon Forest	5.84
Nipigon	Lake Nipigon Forest	5.07
Thunder Bay	Dog River - Matawin & Lakehead Forests	5.04
	Northwest Average	**5.05**
	Overall Average	**5.19**

Rock Falls. The slowest tree to reach breast height on mineral soil was 17.26 years in Chapleau. The average for natural trees was 11.7 years to reach breast height age or more than double that of planted black spruce. The years to breast height data is summarized by different site index classes in black spruce plantations (Table 2.5).

Table 2.5. Average YTBH between different site index (m) classes, for black spruce plantations across northern Ontario.

SI Classes (m)*	Average SI (m)	Average YTBH (yrs)	Number of Trees
8.30 - 8.99	8.67	7.02	6
9.00 - 9.99	9.50	6.00	15
10.00 - 10.99	10.52	5.24	38
11.00 - 11.99	11.56	4.95	31
12.00 - 12.99	12.49	5.17	52
13.00 - 13.99	13.50	4.79	31
14.00 - 14.99	14.36	4.75	9
Total	**11.81**	**5.19**	**182**

* Site index is the average height (m) of dominant trees at 30 yr breast height age.

Generally, as site index increases the number of years to reach breast height decreases. There was a significant relationship (p = 0.001) between YTBH and site index in plantation grown black spruce when the plantation site tree data was fit to Nigh's (2002) equation (Eq. 3):

Eq. 8 $YTBH = 9.449275 \times 0.950367^{SI_{30}}$ $R^2 = 0.159758$; MSE = 0.700694

The number of years to reach breast height age is negatively related to site quality (Figure 2.3), but the relationship is relatively weak based on a high MSE and a low R^2.

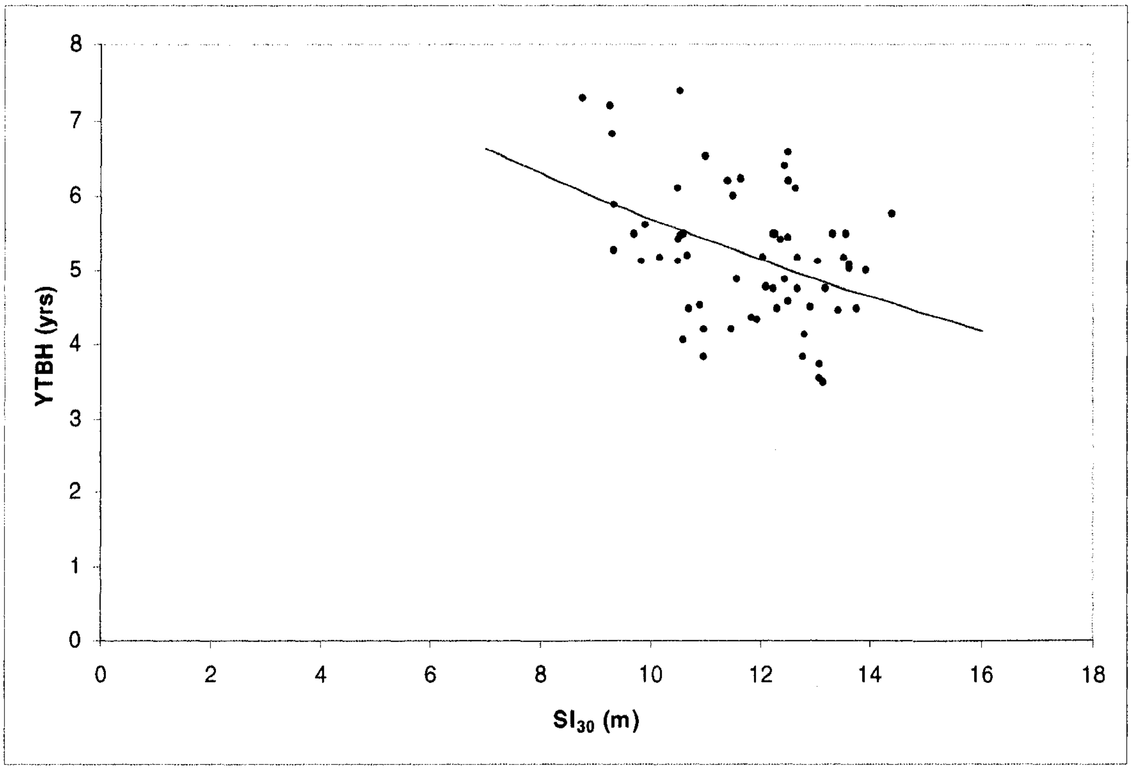


Figure 2.3. Relationship between years to reach breast height and SI_{30} for black spruce plantations.

2.3.2 Growth Intercept Models

The corrected height and YTBH data was converted into growth intercept form (Table 2.6) in order to relate it to site index and develop growth intercept models for black spruce plantations (Eq. 5). An adjustment for BHA is required to ensure accuracy and precision of the growth intercept since the height growth after attaining breast height is a part of the total growth for that year's height growth. The average growth intercept at BHA for all sampled tress was 33.0 cm/yr. The growth intercept at BHA ranged from 27.1 cm/yr on the Cochrane Moose River Forest to 39.2 cm/yr on the Kenora Forest.

Table 2.6. Average growth intercept at breast height age (GI_{BHA}), breast height age (BHA), and BHA adjustment values by town and forest management unit.

Northeast **Town**	**FMU**	**BHA** **Adjustment (yrs)**	**BHA*** **(yrs)**	**GI_{BHA}** **(cm/yr)**
Smooth Rock Falls	Smooth Rock Falls Forest	0.47	34.28	29.0
Cochrane	Cochrane Moose River Forest	0.57	36.54	27.1
Timmins	Romeo-Malette Forest	0.61	34.39	28.3
Kapuskasing	Gordon Cosens Forest	0.47	39.49	31.3
Hearst	Hearst Forest	0.50	35.59	34.0
Chapleau	Superior Forest	0.48	40.52	29.9
Kirkland Lake	Timiskaming Forest	0.45	38.89	36.3
	Northeast Average	**0.49**	**37.92**	**31.2**
Northwest **Town**	**FMU**	**BHA** **Adjustment (yrs)**	**BHA*** **(yrs)**	**GI_{BHA}** **(cm/yr)**
Longlac	Kenogami Forest	0.44	45.14	30.9
Dryden	Wabigoon & Dryden Forests	0.45	35.99	37.8
Kenora	Kenora Forest	0.40	37.93	39.2
Beardmore	Lake Nipigon Forest	0.51	36.83	35.4
Nipigon	Lake Nipigon Forest	0.49	36.22	35.3
Thunder Bay	Dog River - Matawin & Lakehead Forests	0.43	41.35	35.5
	Northwest Average	**0.45**	**39.70**	**34.8**
	Overall Average	**0.47**	**38.82**	**33.0**

* Does not include the BHA adjustment

On average trees from the northwest showed faster growth by 3.6 cm/yr without any forest management units falling below 30.0 cm/yr. However, in the northeast region the

Cochrane Moose River Forest, the Smooth Rock Falls Forest, Romeo-Malette Forest, and Superior Forest all displayed average values that fell below 30.0 cm/yr.

The average BHA of all sampled planted black spruce trees was 38.82 years, with less than two years separating northwestern and northeastern regions. The oldest plantations on average were found on the Kenogami Forest in terms of BHA at 45.14 years and the youngest plantations were found on the Smooth Rocks Falls Forest with an average BHA of 34.28 years. On average the BHA adjustment of 0.47 years is consistent with Nigh (1995) of simply using 0.50 years as the breast height adjustement when calculating growth intercepts. Once the growth intercepts were calculated they were related to site index to form a growth intercept model for black spruce plantations for breast height ages 1 thru 30 years (Table 2.7). As BHA increases the R^2 value increases while the RMSE decreases presenting a better fit for the growth intercept model. At the same time, as BHA increases, the relationship between site index and growth intercept becomes less curvilinear and more linear as the data deviates less from the derived model (Figure 2.4).

Carmean's data was used to create growth intercept models for natural black spruce stands (Table 2.8) with site index at BHA 30 to allow for direct comparison with the black spruce plantation models. The data from natural regenerated trees that were felled nearby the sample black spruce plantations were converted into growth intercepts and derived separate black spruce growth intercept models for black spruce natural stands at index age 30 (Table 2.8).

Table 2.7. Growth Intercept model parameters, R^2, and root mean square error (RMSE) for black spruce plantations from BHA 1 to 30.

BHA	b_1	b_2	R^2	**RMSE**
1	3.333097	0.336887	0.220078	1.228517
2	3.604466	0.312769	0.292209	1.170329
3	3.274097	0.340158	0.365315	1.108241
4	3.021276	0.360315	0.460466	1.021797
5	2.862173	0.373265	0.530366	0.953312
6	2.750966	0.382785	0.568496	0.913796
7	2.672494	0.389470	0.586560	0.894462
8	2.562594	0.400086	0.601685	0.877948
9	2.396004	0.417610	0.630929	0.845104
10	2.196873	0.440531	0.667903	0.801656
11	1.997466	0.466280	0.708054	0.751634
12	1.812692	0.493331	0.754146	0.689754
13	1.650808	0.519527	0.790013	0.637458
14	1.507859	0.544466	0.816313	0.596205
15	1.388994	0.567054	0.839886	0.556634
16	1.256863	0.594811	0.863385	0.514166
17	1.142866	0.621286	0.879254	0.483384
18	1.060552	0.642041	0.887479	0.466629
19	1.001696	0.657768	0.893605	0.453749
20	0.937405	0.676249	0.902870	0.433542
21	0.825971	0.711563	0.922141	0.388158
22	0.735670	0.744113	0.938762	0.344244
23	0.670788	0.770665	0.949390	0.312947
24	0.623165	0.791905	0.956147	0.291309
25	0.585551	0.809730	0.961673	0.272338
26	0.519965	0.842948	0.967339	0.251414
27	0.453026	0.881727	0.975515	0.217674
28	0.394876	0.921101	0.985591	0.166985
29	0.346549	0.958455	0.994251	0.105475
30	0.311767	0.988805	0.999326	0.036125

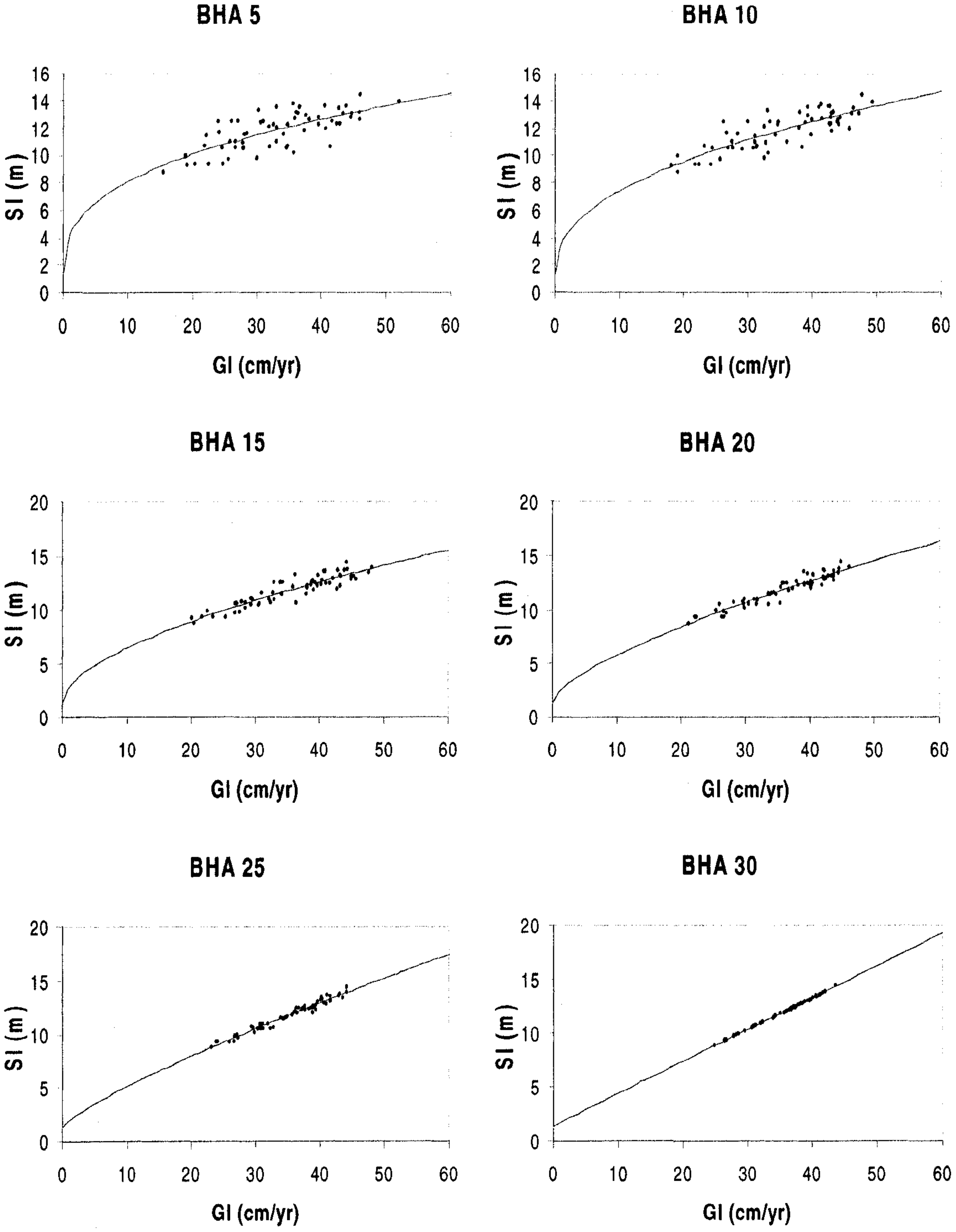


Figure 2.4. Relationship between SI_{30} and growth intercept (cm/yr) at BHAs 5, 10, 15, 20, 25, and 30.

Table 2.8. Natural growth intercept models using Carmean's data and collected data from naturally regenerated trees using SI_{30}.

Carmean's Data					**Collected Data**				
BHA	b_1	b_2	R^2	**RMSE**	**BHA**	b_1	b_2	R^2	**RMSE**
5	0.818537	0.658105	0.723868	1.244626	**5**	1.171880	0.629441	0.508825	1.868247
10	0.589564	0.769072	0.840730	0.945251	**10**	0.779517	0.742649	0.796406	1.202813
15	0.483217	0.835315	0.912581	0.700298	**15**	0.785840	0.716948	0.863773	0.983895
20	0.381866	0.911674	0.962192	0.460548	**20**	0.609837	0.786139	0.935485	0.677092
25	0.329559	0.961377	0.988127	0.258081	**25**	0.423303	0.899354	0.965436	0.495595
30	0.298056	0.997539	0.999271	0.063930	**30**	0.298708	1.001889	0.999722	0.044418

Carmean's data provided more accurate growth intercept models in terms of a lower root mean square error (RMSE) for BHA 5 to 25; at BHA 30 the collected data appears has a higher R^2 and a lower RMSE than Carmean's data. The difficulty in comparing these two datasets is the number of observations in each; the Carmean data contains 211 samples while the collected data only contains 15 samples.

There are differences between the growth intercept models for black spruce plantations and the growth intercept models for black spruce natural stands from using Carmean's data in early breast height ages (Figure 2.5). At BHA 5 there is a large difference between planted and natural growth intercept models and their predictions of site index. As BHA increases the two sets of growth intercept models slowly converge until at BHA 30 they are almost identical and become linear. The black spruce plantation growth intercept models also appear to be more curvilinear than the natural stand models.

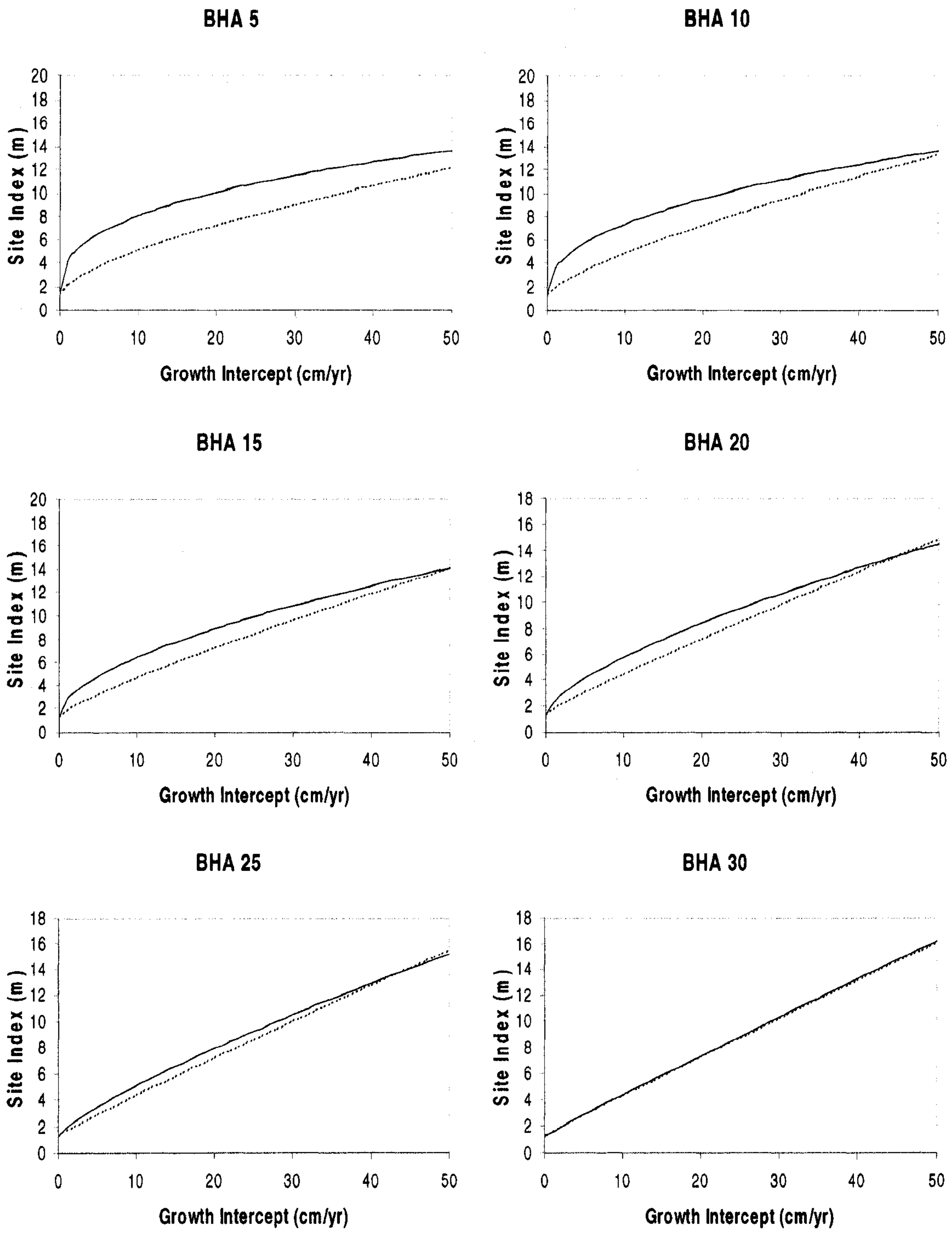


Figure 2.5. Black spruce natural stand (solid) growth intercept models versus black spruce plantation (dashed) growth intercept models across different BHAs using SI_{30}.

2.3.3. Site Index Models

The site index information from the stem analysis enabled the construction of height growth and estimation models for both black spruce plantations and natural stands at a reference age of BHA 30. Since there was a significant difference between northeastern and northwestern Ontario in terms of site index (SI_{30}), separate height growth models for each region were developed and compared.

2.3.3.1. Height Growth Model for Black Spruce Plantations

The collected stem analysis data from black spruce plantations across northern Ontario were used to develop a polymorphic height growth model based on site index at BHA 30. The polymorphic height growth model for black spruce plantations in northern Ontario is:

$$\text{Eq. 9} \quad \hat{H} = 1.3 + 0.218185(SI - 1.3)^{2.115432}\left[1 - K^{\frac{BHA}{30}}\right]^{12.068081(SI-1.3)^{-1.096969}}$$

$$R^2 = 0.976817; MSE = 0.094886$$

$$\text{where} \quad K = 1 - \left[\frac{SI - 1.3}{0.218185(SI - 1.3)^{2.115432}}\right]^{\frac{1}{12.068081(SI-1.3)^{-1.096969}}}$$

All parameters are as defined previously in Eq. 6

The height growth model for black spruce plantations has a very high R^2 value of 0.98, thus 98 % of the variance in the data set is accounted for by the model and its parameters. As a result the model has also yielded a low mean square error (*MSE*) value of 0.094886 m. The low MSE value is evident in the scatterplot (Figure 2.6) of predicted (estimate) versus residual values, which compares the observed heights with the predicted heights generated by the height growth model. The spread of the residuals across the predicted (estimate) values is very minimal and within a range of +/- 1.0 m of the observed heights (Figure 2.6).

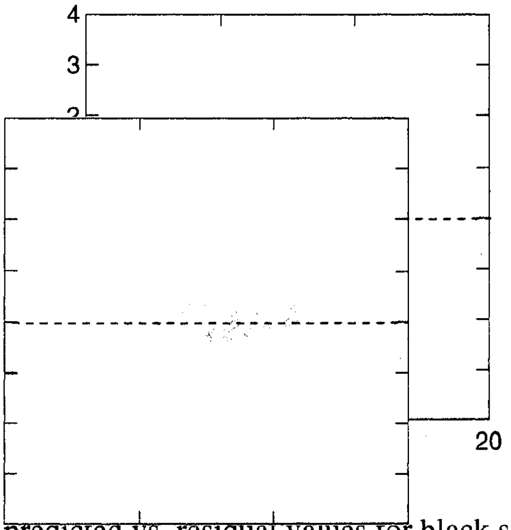


Figure 2.6. Scatterplot of predicted vs. residual values for black spruce plantations from a polymorphic height growth model using SI_{30}.

Using the height growth model, site index curves for planted black spruce in northern Ontario were developed ranging from observed site index values between 8 and 15 m at BHA 30 (Figure 2.7).

It was difficult to find black spruce plantations on poor sites since most of the plantations were established in upland sites, and organic sites were planted at low densities with substantial natural ingress. This made it difficult to distinguish between planted and natural trees on organic sites, and increased the site index range of the site index curves that were generated.

A site index prediction model was developed to estimate SI_{30} by measuring total height and BHA for black spruce plantations across northern Ontario:

$$\text{Eq.10}\quad SI = -145.585592 - 0.943564(HT - 1.3) - 10.301407LN(HT - 1.3)$$

$$+ 97.239622LN(BHA) - 15.879589LN(BHA)^2 + 63.712791\left(\frac{HT - 1.3}{BHA}\right)$$

$$+ 0.319242(BHA)LN(HT - 1.3)$$

$$R^2 = 0.969814;\ MSE = 0.063725$$

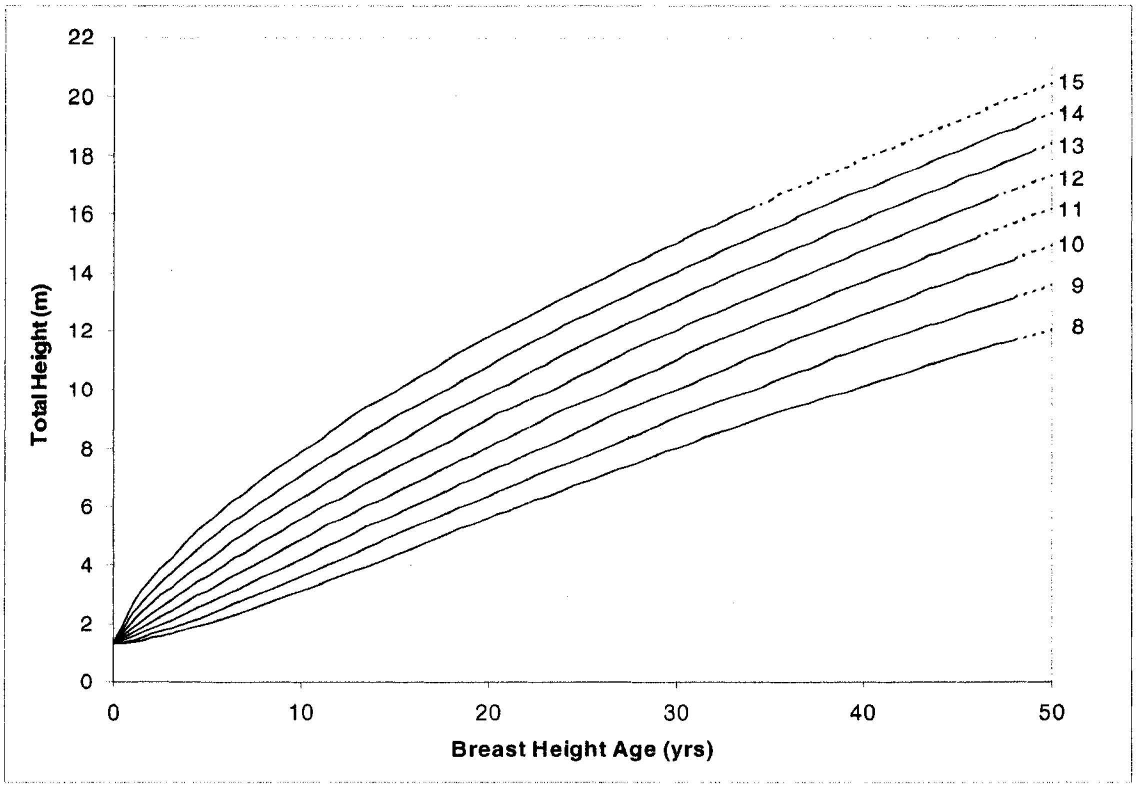


Figure 2.7. SI_{30} curves for black spruce plantations in northern Ontario; dashed lines indicate extrapolations beyond stem-analysis data.

2.3.3.2. Height Growth Model for Black Spruce Natural Stands

Two polymorphic height growth models were developed for black spruce natural stands, one using Carmean's data from black spruce natural stands across northwestern Ontario and the other using the data that was collected from black spruce natural stands located nearby black spruce plantations that were sampled. Carmean's data produced a height growth model at SI_{30}:

Eq. 11 $$\hat{H} = 1.3 + 11.847173(SI - 1.3)^{0.267023}\left[1 - K^{\frac{BHA}{30}}\right]^{2.115862(SI-1.3)^{-0.136182}}$$

$R^2 = 0.743811$; $MSE = 2.705359$

where $$K = 1 - \left[\frac{SI - 1.3}{11.847173(SI - 1.3)^{0.267023}}\right]^{\frac{1}{2.115862(SI-1.3)^{-0.136182}}}$$

The *MSE* for this height growth model is high (28.5 times higher) in comparison to the model derived for black spruce plantations. The R^2 value is lower than the model for black spruce plantations accounting for less variance amongst the black spruce natural stand dataset. This is evident when comparing predicted (estimated) versus residual values generated from the height growth model for black spruce natural stands (Figure 2.8).

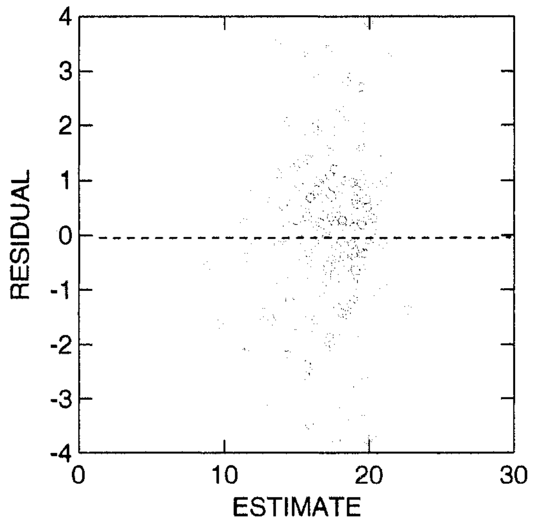


Figure 2.8. Scatterplot of predicted vs. residual values for black spruce natural stands from a polymorphic height growth model using SI_{30}.

The wide dispersion of the residuals is expected when the MSE is as high as 2.71 m. There are 3 data points that contained residuals exceeding the bounds of +/- 4.0 m, meaning that the height growth model's prediction of total height based on site index was greater than 4.0 m in relation to the observed total height of the tree. The height growth model for black spruce plantations (Figure 2.6) showed greater accuracy in predicting total height using SI_{30} than the model for natural black spruce. Using the height growth model for natural black spruce, site index curves for black spruce natural stands in northern Ontario were developed ranging in site index values between 4 and 14 m at BHA 30 (Figure 2.9).

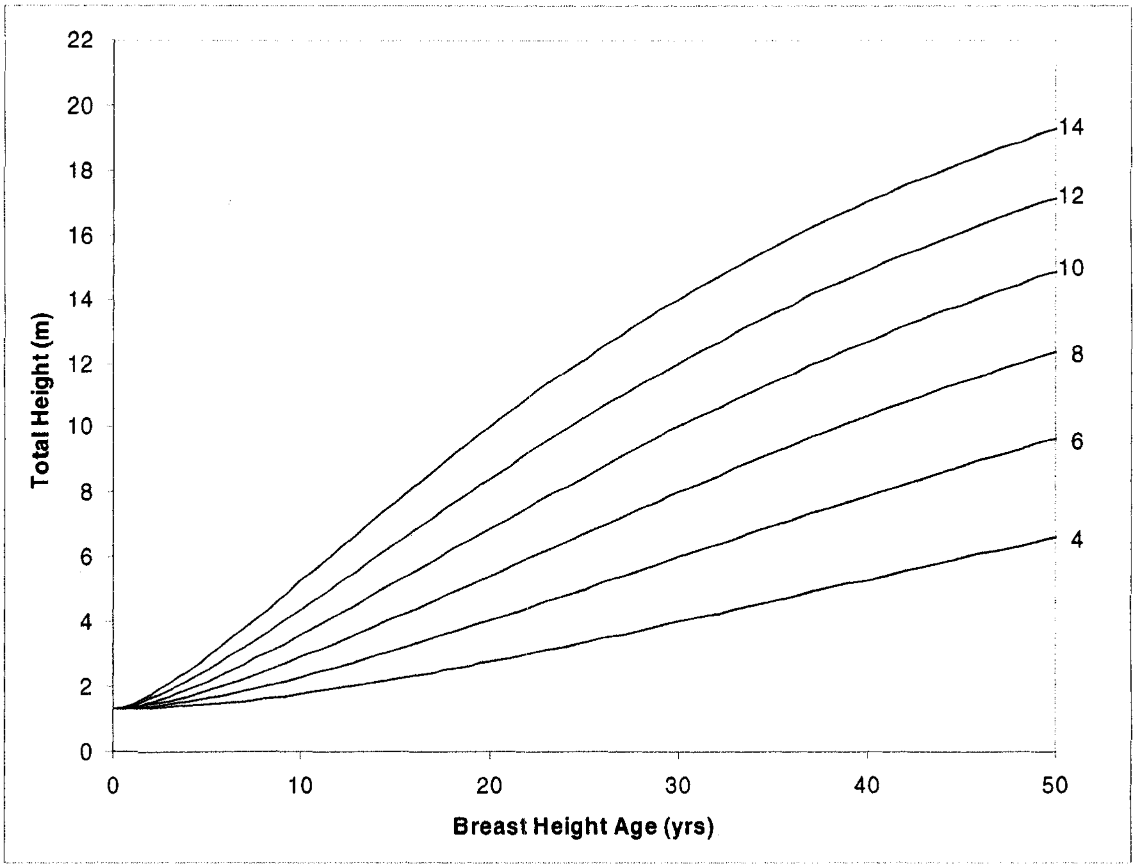


Figure 2.9. SI_{30} curves for black spruce natural stands in northern Ontario from Carmean's data.

The black spruce natural stand data contains an increased number of low quality sites that are not present in the black spruce plantation data resulting in a wider range of site index. The observed site index range for black spruce natural stands was 2.36 to 14.24 m at BHA 30 compared with 8.30 to 14.98 m for black spruce plantations.

To conveniently estimate site index at breast height age 30 by measuring total height and breast height age, a site index prediction model was developed for black spruce natural stands in northern Ontario:

Eq. 12 $$SI = -171.850411 - 0.135540(HT-1.3) - 7.835155LN(HT-1.3)$$

$$+89.755385LN(BHA) - 11.333779LN(BHA)^2 + 63.278778\left(\frac{HT-1.3}{BHA}\right)$$

$$+0.072380(BHA)LN(HT-1.3)$$

$$R^2 = 0.828115; MSE = 0.987903$$

The site index prediction model for black spruce natural stands has a lower R^2 value than the model for black spruce plantations as well as higher *MSE* value indicating that the site index prediction model for black spruce plantations is superior and more accurate in estimating site index in black spruce plantations.

2.3.3.3. Comparison of Height Growth Models for Black Spruce Plantations

The stem analysis data collected from black spruce plantations was divided into northeastern and northwestern Ontario to develop separate polymorphic height growth models for each region. An ANOVA between the two regions when comparing site index (Table 2.3) displayed a significant difference between site index in black spruce plantations from northeastern and northwestern Ontario. The height growth model for black spruce plantations in northwestern Ontario using site index at BHA 30 is:

Eq. 13 $$\hat{H} = 1.3 + 1.266302(SI-1.3)^{1.185453}\left[1-K^{\frac{BHA}{30}}\right]^{2.038415(SI-1.3)^{-0.225645}}$$

$$R^2 = 0.974461; MSE = 0.088733$$

where $$K = 1-\left[\frac{SI-1.3}{1.266302(SI-1.3)^{1.185453}}\right]^{\frac{1}{2.038415(SI-1.3)^{-0.225645}}}$$

High R^2 and low MSE values are encouraging for an adequately fitting model to the black spruce plantation data in northwestern Ontario.

The height growth model for black spruce plantations in northeastern Ontario using site index at BHA 30 is:

$$\text{Eq. 14} \quad \hat{H} = 1.3 + 3.818123(SI - 1.3)^{2.256424}\left[1 - K^{\frac{BHA}{30}}\right]^{4.442599(SI-1.3)^{-0.763883}}$$

$R^2 = 0.980157$; $MSE = 0.060616$

$$\text{where} \quad K = 1 - \left[\frac{SI - 1.3}{3.818123(SI - 1.3)^{2.256424}}\right]^{\frac{1}{4.442599(SI-1.3)^{-0.763883}}}$$

The R^2 and MSE values from the polymorphic height growth model for black spruce plantations in northeastern Ontario is very similar to the values generated from the height growth model for black spruce plantations in northwestern Ontario. The developed polymorphic height growth models were converted into site index curves for observed site index ranges between 8 and 15 m at BHA 30 (Figure 2.10). Despite the similar R^2 and MSE values suggesting height growth models with adequate fit, the shapes of the curves differ between black spruce plantations in northwestern and northeastern Ontario. As site index increases the difference between predicted total heights at a specified BHA from both respective models increases at early BHA (up to 20 years), with the height growth model for black spruce plantations in northeastern Ontario predicting higher total heights. However, after index age, BHA 30, height growth models developed for black spruce plantations in northwestern Ontario predict larger total heights at site index 14 and 16 m. This trend, after BHA 30, reverses for lower site index ranges where the height growth model for black spruce plantations in northeastern Ontario predicts larger total heights. Since older black spruce plantation sites were found in northwestern Ontario the range of stem-analysis data required less extrapolation in comparison to the site index curves for black spruce plantations in northeastern Ontario.

Figure 2.10. Comparison of SI_{30} curves for black spruce plantations between northeastern (red) and northwestern (black) Ontario; dashed lines indicate extrapolations beyond stem-analysis data.

The polymorphic height growth models for black spruce plantations in northeastern and northwestern Ontario were compared statistically using two methods. An ANOVA was conducted to compare predicted total heights between black spruce plantations in northeastern and northwestern Ontario, and the second consisted of fitting a simple linear regression to each observed total height versus predicted total height scatterplot to compare the slopes (Zar 1996). The ANOVA resulted in a significant difference between predicted total heights of height growth models for black spruce plantations in northeastern and northwestern Ontario (Table 2.9).

Table 2.9. ANOVA results between predicted total heights of polymorphic height growth models for black spruce plantations in northeastern and northwestern Ontario.

Source	**df**	**Sums of Squares**	**Mean Square**	**F-ratio**	***p*-value**
Region	1	50.2552	50.2552	17.245	0.0001
Error	60	174.848	2.91414		
Total	61	255.103			

The comparison of slope between regression lines fitted to the data (observed total height versus predicted total height) found the lines to contain significantly different slopes using a two tailed t-test (Figure 2.11).

The two tailed t-test produced a value of 5.147, which translates into a *p*-value of less than 0.0001. The regression lines in Figure 2.11 appear to be identical, however the t-test still produced a significant result due to the low MSE (Equations 13 & 14). The models for both regions contain very small residuals meaning the slightest change in slope of the regression lines (Figure 2.11) will result in a significant difference using the t-test. Due to this fact, the significant difference is not accepted.

The separate polymorphic height growth models were further assessed using methods presented by Chen *et al.* (1998) by plotting predicted versus observed heights (as in Figure 2.11) and tested against the regression $y = x$. The y-intercept must remain constant, thus the data must be forced through the origin. Once slopes of the regression for each height growth model have been developed they are tested using a two tailed t-test. The t-test values were not significant ($p > 0.05$) showing that regressions for both models were not different from y = x (Figure 2.12). The height growth models were

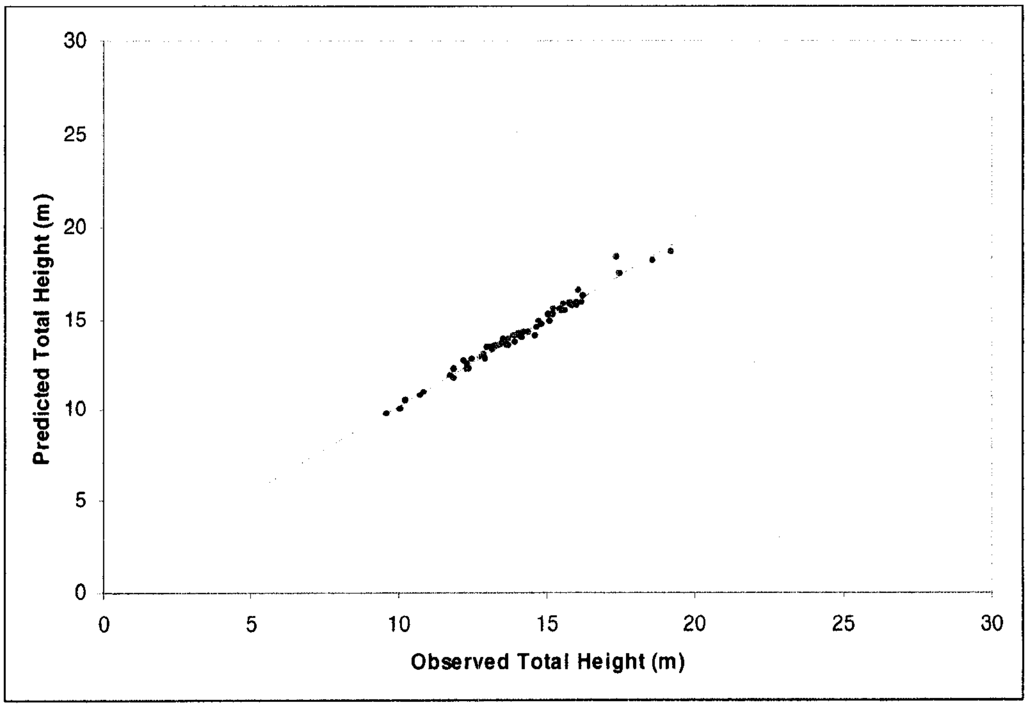


Figure 2.11. Comparison of linear regression between height growth models for black spruce plantations in northeastern (black) and northwestern (red) Ontario in terms of observed versus predicted total height values.

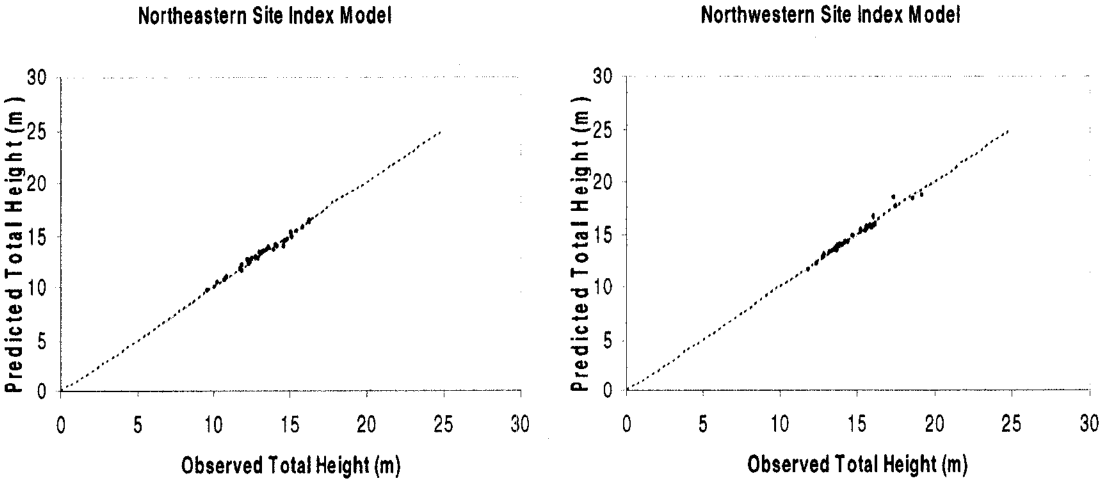


Figure 2.12. Comparison of regression results between separate height growth models for black spruce plantations in northeastern and northwestern Ontario (solid line) versus y = x (dashed line) assessing model accuracy.

plotted against the observed data to ensure a satisfactory level of fit. Both models exhibited exceptional fit to support model accuracy and precision (Figure 2.13).

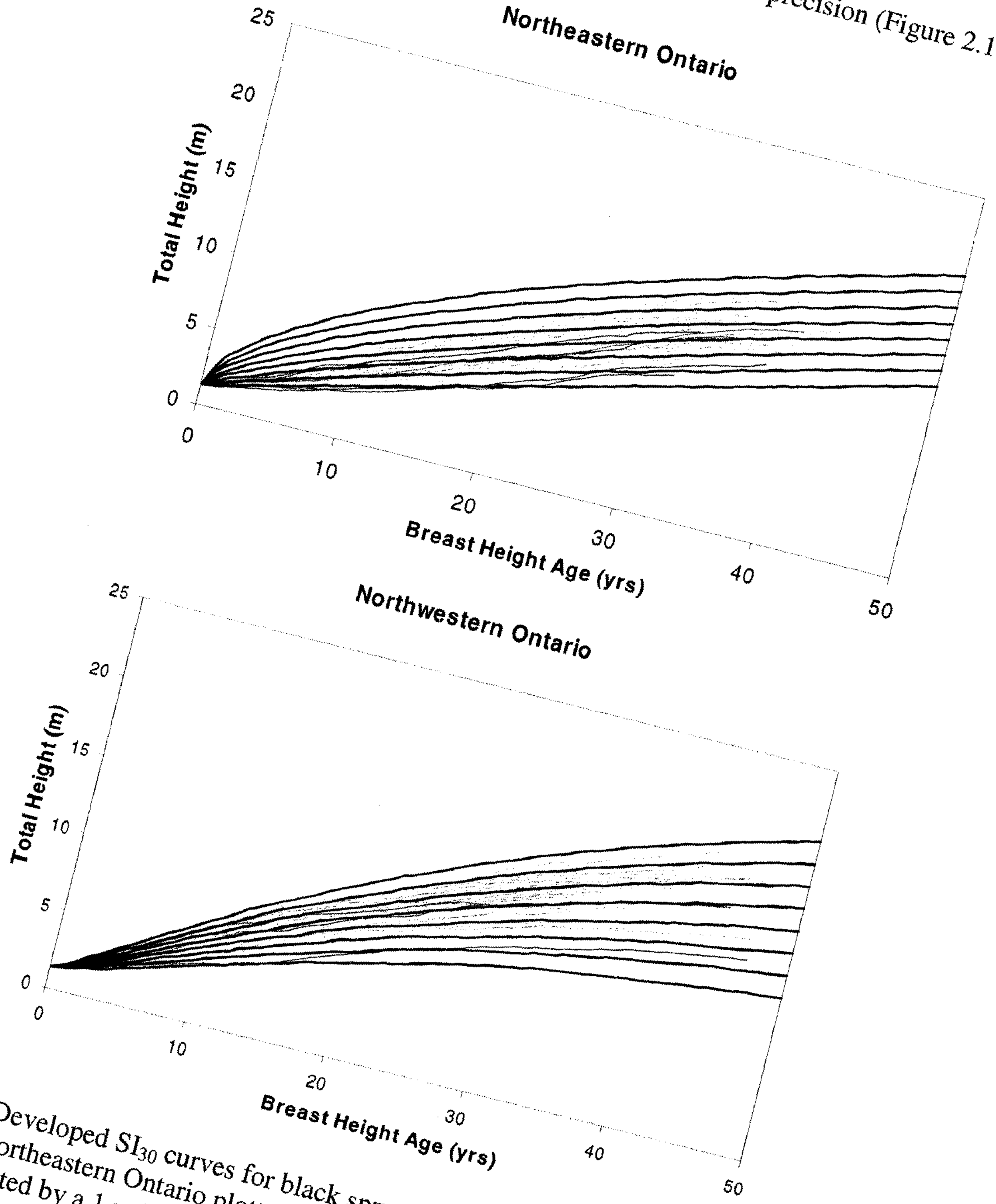


Figure 2.13. Developed SI_{30} curves for black spruce plantations in northwestern and northeastern Ontario plotted versus observed data. Height growth curves fitted by a 1 m interval of site index from 8 to 15 m.

2.3.3.4. Comparison of Height Growth Models for Black Spruce Plantations Versus Black Spruce Natural Stands

The developed polymorphic height growth models for black spruce plantations and black spruce natural stands at BHA 30 were compared by plotting the site index curves derived from each model (Figure 2.14). As the site index class increases the difference between height growth models in predicting total height increases with the height growth model for black spruce plantations predicting larger total heights until BHA 25. After BHA 25 both curves seem to level out predicting relatively equal total heights (m) until the curves approach BHA 50 where the height growth model for black spruce plantations begins predicting larger total heights for site index 12 and 14 m.

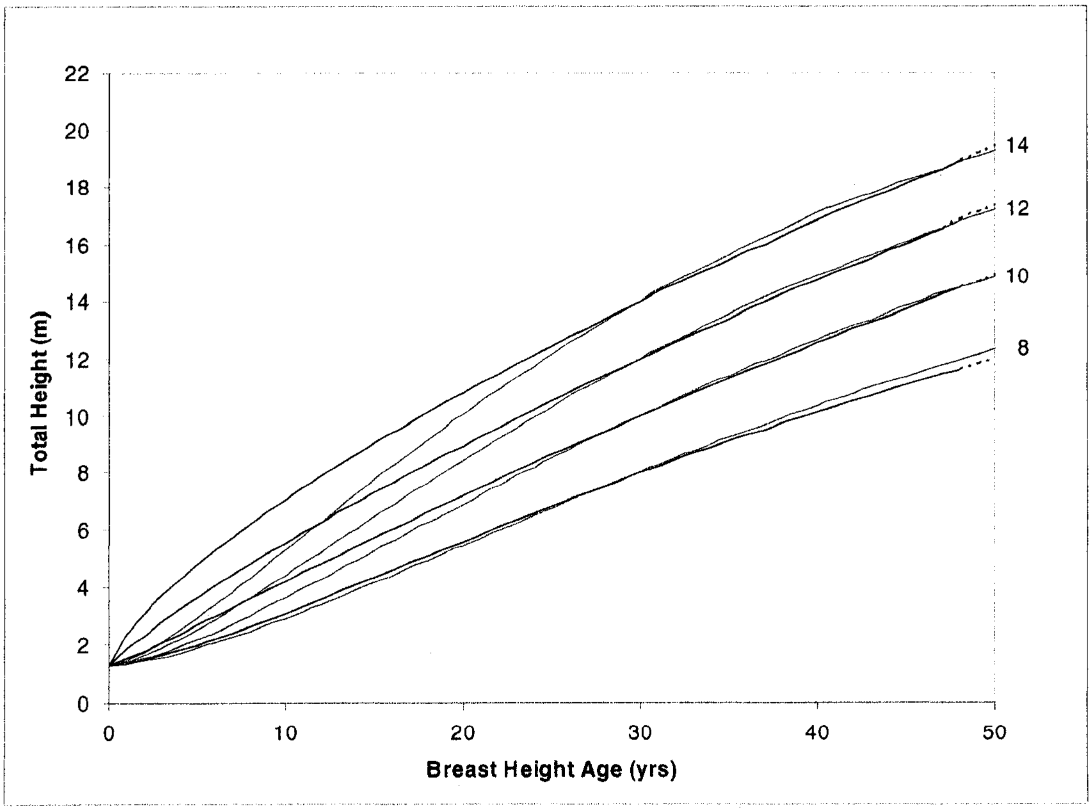


Figure 2.14. Comparison of SI_{30} curves between black spruce plantations (black) and black spruce natural stands (red) in northern Ontario; dashed lines indicate extrapolations beyond stem analysis data.

The same two statistical methods that were previously used in comparing height growth models for black spruce plantations between northeastern and northwestern Ontario are used here in comparing the height growth models between black spruce plantations and natural stands. The ANOVA resulted in significant differences for predicted heights of height growth models between black spruce plantations and natural stands (Table 2.10).

Table 2.10. ANOVA results between predicted total heights of polymorphic height growth models for black spruce plantations and natural stands in northern Ontario.

Source	**df**	**Sums of Squares**	**Mean Square**	**F-ratio**	***p*-value**
Region	1	452.37	452.37	70.09	0.0001
Error	271	1749.15	6.45		
Total	272	2201.52			

The regression lines fitted to each dataset, in terms of observed versus predicted total height, were compared statistically using the slope of each line (Zar 1996). Using a two tailed t-test the comparison showed that the slopes between the two datasets are statistically significant (Figure 2.15). The two tailed t-test produced a value of 17.865, which translates into a *p*-value of less than 0.0001 verifying that there is a significant difference in the height growth models between black spruce plantations and natural stands.

As in the previous section methods by Chen *et al.* (1998) were used to further assess and validate the current polymorphic height growth models developed for black spruce plantations and natural stands at site index index age 30. Observed versus predicted total heights were plotted and the regression line was tested against a $y = x$ regression (Figure 2.16). The regression lines for the two datasets were forced through the origin to compare against the $y = x$ regression in keeping the intercept constant and

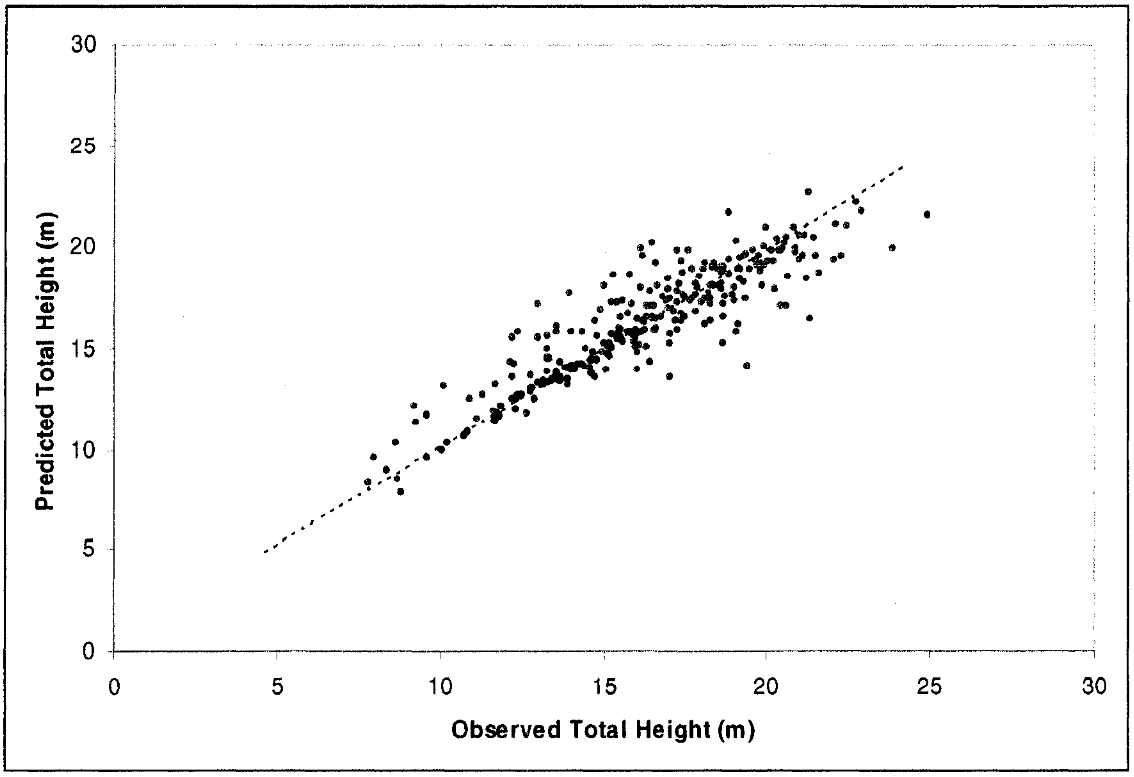


Figure 2.15. Comparison of linear regression between height growth models for black spruce plantations (black) and natural stands (red) in northern Ontario in terms of observed versus predicted total height values.

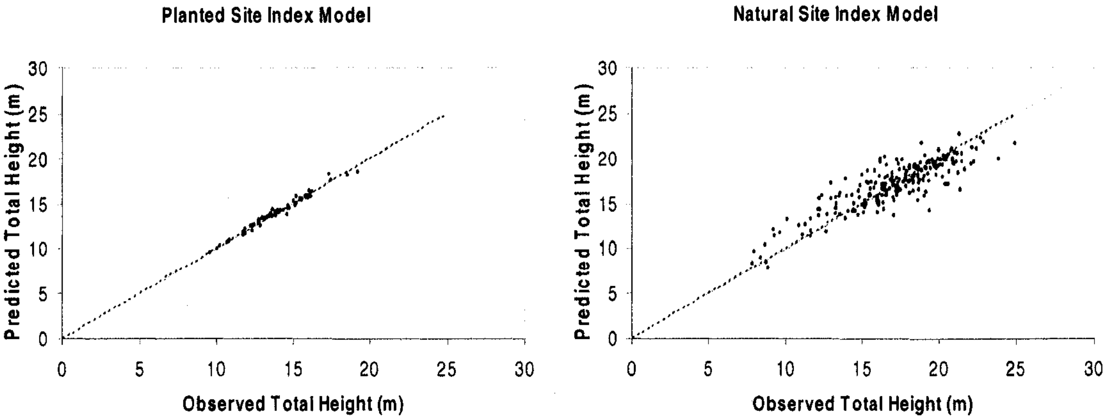
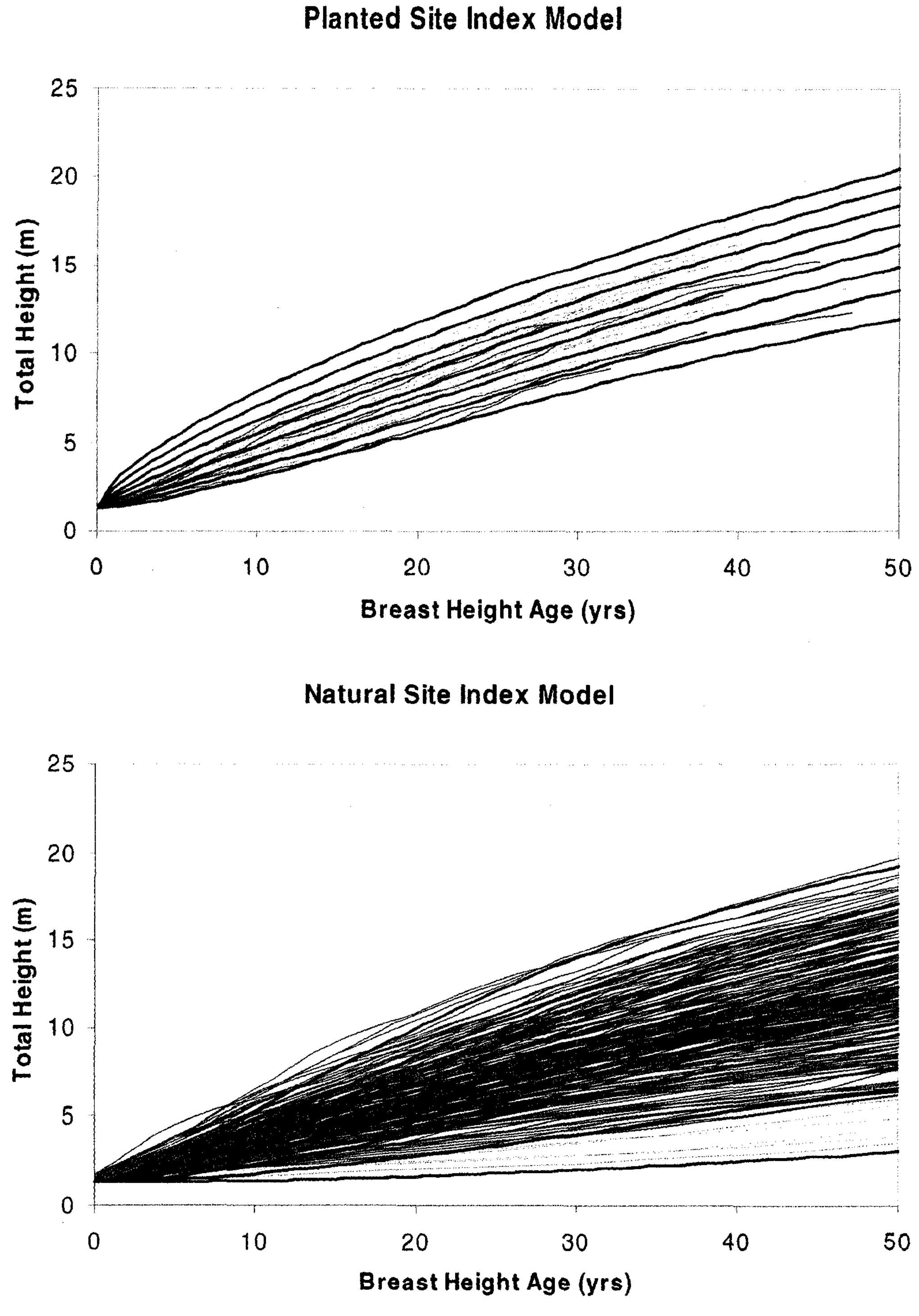


Figure 2.16. Comparison of regression results between separate height growth models for black spruce plantations and natural stands in northern Ontario (solid line) versus y = x (dashed line) assessing model accuracy.

focusing only on the slope. The two tailed t-test for both polymorphic height growth models resulted in no significant differences ($p > 0.05$) showing that the derived height growth models provide a satisfactory fit to the data.

The height growth models were plotted against the observed data to ensure a satisfactory level of fit. The height growth model for black spruce plantations displayed exceptional fit (Figure 2.17). The height growth model for black spruce natural stands showed good fit to the observed data except for the first 10 years of BHA (Figure 2.17).


Planted Site Index Model

Natural Site Index Model

Figure 2.17. Developed site index curves for black spruce plantations and natural stands in northern Ontario plotted against observed data. Height growth curves fitted by a 1 m interval of site index from 8 to 15 m for black spruce plantations and a 2 m interval of site index from 2 to 14 m for black spruce natural stands.

2.4. DISCUSSION

I observed a significant difference in SI30 between black spruce plantations in the two regions I studied, with SI30 being approximately 12 % high in northwestern Ontario. Lower site index in northeastern black spruce plantations could be related to a lack of surface horizons covering the rich Ontario Clay Belt in sampled sites. A study by Thrower (1984) for white spruce plantations found drastic reductions in site quality on sites with little or no surface horizons on lacustrine clay sites near Thunder Bay. Strong and La Roi (1983) and Steele *et al.* (1997) state that a large proportion of the total root biomass for black spruce is located in the first 15 cm of soil, making these top soil horizons, especially L, F, and H horizons, vital to successful tree growth. Foster *et al.* (1995) also found that humus layers are vital for the release of N vital for adequate tree growth and development. With a lack of surface horizons N shortages could help explain the significant differences in black spruce plantation site qualities between northwestern and northeastern Ontario.

Years to breast height were not closely related to site index ($R^2 = 0.16$) for black spruce plantations in northern Ontario. This result supports findings from other studies (Thrower 1986; Nigh 2002; Guo and Wang 2006; Carmean *et al.* 2006b) that growth intercept (GI) and SI models should be derived using BHA to avoid the early erratic height growth that takes place below breast height. Trees on poorer sites require more time to reach breast height with the average being 5.2 years across northern Ontario for black spruce plantations. This was significantly faster than the average of 17.6 years it took black spruce to reach breast height after fire (Vasiliauskas and Chen 2002), and the average of 11.7 years it took for trees sampled from natural stands nearby black spruce plantations in this study. Vasiliauskas and Chen (2002) suggested the small seeds of black spruce and the further competition as the reason for the slow juvenile growth. In the 1960's and early 70's most commonly two- and three-year-old bare root stock black spruce seedlings were planted. However, today container seedlings (averaging 10 cm in height) and tall stock (averaging 30 cm in height) black spruce are often nutrient loaded, and some come from genetically improved seed. These trees may attain breast height faster than the 5.2 year average that was found in this study.

The variable GI models for black spruce plantations (Table 2.7) proved to be unbiased with the residuals being homoscedastic and normally distributed based on the RMSE. As expected the accuracy of GI models increased as BHA increased (Nigh *et al.* 1999, Guo and Wang 2006). GI models were developed for natural black spruce (Table 2.8) for both Carmean's data and the samples collected in natural stands from nearby plantations. The models were developed at index age 30 to allow for a direct comparison, however due to the low sample size the collected data from natural stands was omitted from the comparison to avoid bias (Huang *et al.* 2004b). Comparing natural and planted GI models (Figure 2.5) showed increased prediction potential of SI using the GI model derived for black spruce plantations in earlier breast height ages, up to BHA 20 before the models converge and estimate similar site indices. Schutz (1969) studied height and diameter growth of silver fir (*Abies alba* Mill.) and Norway spruce and found that suppression had only a temporary effect on height-growth in trees. Once released growth rates increased and were often higher than in unsuppressed trees. As black spruce trees get older, fast growing trees in young plantations begin to decrease in growth rate (height), while their natural counterparts increase in height growth rate due to inter- and intra-specific competition within the stand resulting in similar curves as BHA approaches index age. Maximum attainable heights are not significantly affected, but height growth rates are reduced by a decrease in site quality (Robichaud and Methven 1992). Silvicultural treatments in black spruce plantations is known to result in increased growth rates (Patterson 1992) in earlier years, however due to larger variation in early BHA of the GI models a bias as suggested by Feng *et al.* (2006) may exist in overestimating SI. This bias occurs as a result of dominance switching among juvenile trees before trees reach SI index age. The largest dbh tree at the time of sampling may not remain the largest trees as the stand develop, similarly dominance switching may occur after index age and could lead to underestimating SI (Feng *et al.* 2006). The variable GI model for black spruce plantations across northern Ontario in Table 2.7 is recommended for BHAs 1 – 30.

Based on the results of this study, height growth pattern of black spruce plantations were different from natural stands. Total height in natural stands is higher on richer sites than on poorer sites suggesting that trees growing on rich sites reach a maximum rate of height growth earlier than trees on poorer sites (Thrower 1987). Polymorphic height growth models for black spruce plantations and natural stands from Carmean's data have been developed at BHA 30. When comparing MSEs black spruce height growth models for plantations and for natural stands showed a significant difference (0.09 and 2.71 m respectively). The significant difference was also found in predicted heights using ANOVA and comparison of regression slopes from plots of predicted versus observed total heights. These differences are evident when graphically comparing the two sets of SI curves (Figure 2.14) at early BHA the difference between predicted heights for black spruce plantations and natural stands is the greatest with black spruce plantations predicted higher total tree heights. Based on previous studies (Farnden and Herring 2002; Huang *et al.* 2004b), and silviculture records attained for sample sites in Longlac on the Kenogami Forest, these differences are attributed to the silvicultural activities that occur in young plantations. Most of the sample sites in Longlac were treated with mechanical site preparation, herbicide (glysophate), rare mechanical brushing, and all sites were planted using black spruce bare root stock (Dorland 2007). Wood and von Althen (1994) found that chemical site preparation with no subsequent treatment improved survival, height growth, and ground-level diameter increment of black spruce compared to controls or single post-planting herbicide treatment. Silvicultural practices, especially herbicide applications, have become more common and the chemicals used have been improved since the mid to late 1960's and early 1970's. These improvements would suggest further increases in height growth of black spruce plantations being established in the 21st century can be expected. The SI curves (Figure 2.14) suggest that heights are relatively equal at BHA 50 between black spruce plantations and natural stands; however this may be difficult to accept with a MSE of 2.71 m for natural black spruce stands. A large MSE expands the confidence interval for the total height attained at BHA 50 for black spruce natural stands. Both models were validated for precision and accuracy and provided a satisfactory fit to the observed data (Figure 2.17). The acceptance of the black spruce height growth model for natural stands leads us to explain the high variation in total height due to the natural variability of ecological processes that occur in a natural stand without human influence. The SI curves for natural black spruce display the maximum site potential at BHA 50. However, the large variation causes a lack of accuracy less than desirable for a natural stand to reach maximum site productivity.

Due to the significant differences in observed SI between northeastern and northwestern Ontario (Table 2.3) and total predicted heights using SI_{30} model (Equation

10) developed for black spruce plantations in northern Ontario the dataset was divided into two regions, polymorphic height growth curves were developed and tested. Both models performed well, accounting for large degrees of variation, R^2 values of 0.97 and 0.98 for northwestern and northeastern black spruce plantations, respectively, and contained low MSEs of 0.09 and 0.06 m, respectively. The models showed a significant difference between predicted heights using ANOVA and when regression slopes were compared between height growth models for black spruce plantations in northeastern and northwestern Ontario using plots of predicted versus observed total heights. With such precision and accuracy the residuals for both models were minimal causing the slightest difference in slope of the regression lines (Figure 2.11) to test significant. For this reason the statistical test is rejected and a single polymorphic height growth model is suitable for black spruce plantations across northern Ontario. However, for use by practitioners in the field estimating SI in young juvenile plantations curves for northeastern and northwestern Ontario black spruce plantations were developed. Both models were validated for precision and accuracy, and adequately fit observed data (Figure 2.13). Some of the differences may be attributed to the differences between SI ranges for each region. Climatic factors and soil properties should be further explored in the differences between SI for black spruce plantations in northeastern and northwestern Ontario.

Black spruce has a shallow rooting nature making it unstable and susceptible to windthrow during stochastic events. Smith *et al.* (1987) studied the mechanical stability of black spruce in the clay belt region of northern Ontario. They found once black spruce stands reach a critical height of 20 to 21 m periodic storms create enough static force to cause serious windthrow. They suggest harvesting stands before reaching a dominant height of 20 to 21 m to avoid these excessive losses. This critical height may be increased in 100 % stocked stands to 22 m. Based on the polymorphic height growth models developed for black spruce plantations in northern Ontario critical heights of 20 and 21 m would be reached sooner than the 95 year rotation (Viereck and Johnston 1990) commonly used in high quality black spruce natural stands. Whitney (1962)

Figure 2.18. Windthrow damage, aided by tomentosus root rot, in a black spruce plantation on the Kenogami Forest outside of Longlac.

reported greater incidence of root and butt rot on good sites resulting in larger windfall losses on richer sites than on poorer sites due to the larger size of trees. In upland natural stands trees commonly develop butt rot at 70 to 90 years of age making them subject to windfall (Whitney 1962). Not only is the mechanical strength of the root weakened, resulting root mortality reduces and restricts the mass of soil held by the root (Whitney and Fleming 1995). Tomentosus root rot (*Inonotus tomentosus* [Fr.] Teng) is the most commonly found disease in wind fallen black spruce, and was found in a 51 year old plantation outside of Longlac on the Kenogami forest (Figure 2.18). This study supports Smith *et al.* (1987)'s recommendation of harvesting productive upland black spruce sites when they reach a critical height of 20 to 21 m in dominant tree height. More studies looking at the mechanical stability of black spruce outside the northeastern Ontario clay belt region should be conducted. Maximum attainable heights for black spruce could be derived and used in conjunction with height growth models to obtain rotation ages based on site quality.

CHAPTER 3. RELATIONSHIP BETWEEN SITE QUALITY AND SOIL CHARACTERISTICS IN THE C HORIZON

3.1. LITERATURE REVIEW

One of the major factors to consider when selecting sites for plantations is the soil characteristics and properties of the site (Wilde 1958). Soil is important to the growth of trees because the soil features determine the availability of water and nutrients on a particular site (Fujimori 2001). Soils are usually classified by their dominant texture. There are three general types of soil textures: sand, silt and clay. The difference between the textures is based on particle size, with sand (2.0 – 0.02 mm) having the largest particles, then silt (0.02 – 0.002 mm), and clay (less than 0.002 mm) having the finest (Barnes *et al.* 1998). Indirect estimations of site index exist from relating soil type, vegetation type, and site conditions found at the site in question (Carmean 1996a).

3.1.1. Black Spruce

The range of black spruce follows the boreal forest region, with the northern limit equalling the tree line and the southern limit surrounding the great lakes and prairie region (Figure 3.1). It is found on a wide variety of soil types including deep humus, clay, loams, sands, coarse till, boulder pavements and shallow soils over bedrock (Viereck and Johnston 1990). Pure stands are most often found on wet, poorly drained, organic soils sometimes associated with tamarack (*Larix laricina* (Du Roi) K. Koch) (Farrar 1995). Upland, well-drained, mineral sites produce the most productive black spruce stands, however these natural stands rarely occur in pure stands. Instead, mixedwood stands (in Ontario) containing white spruce, balsam fir, jack pine, white birch, and trembling aspen are formed (Viereck and Johnston 1990).

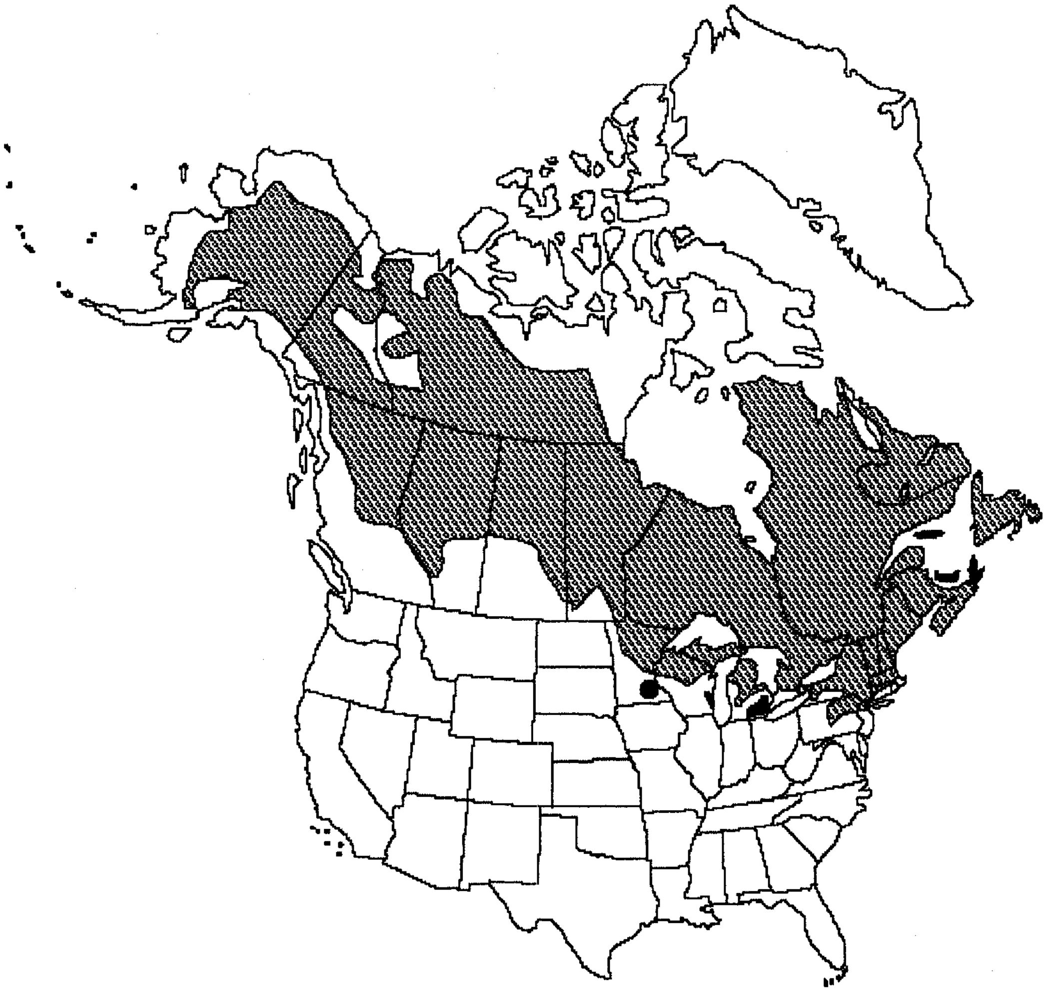


Figure 3.1. Native range of black spruce in North America (Viereck and Johnston 1990).

Regional factors, including soil moisture and nutrient availability, account for the variation within the average growth of black spruce (Jeglum 1974). Height growth in Ontario of natural black spruce varies between upland and lowland sites. Black spruce attains average heights from 12 to 20 m and a diameter at breast height (dbh) of 23 cm on productive sites, while poor sites exhibit heights of 8 to 12 m with 13 cm in dbh (Viereck and Johnston 1990). Vincent (1965) found black spruce trees that reached heights up to 27 m and a dbh of 46 cm in northeastern Ontario situated on the Ontario Clay Belt.

3.1.2. Research Findings

Productive black spruce stands and plantations have been found on sandy and silty soils. A study by Gordon and Simpson (1991) on two black spruce plantations in northern Ontario outside of Nipigon occurred on silty and sandy soils with moderate to imperfect drainage. These 30-year-old plantations met and exceeded the growth of natural stands of site class 1A, when Plonski's Yield Tables were used and recommended a thinning (the plantations contained 3239 and 4496 stem/ha) to encourage the exceptional growth.

A nutrient cycling study in upland black spruce on shallow soil (30 cm) by Foster *et al.* (1995) found nitrogen uptake to be limited by slow releases from humus layers. Satisfactory early growth may not be possible without N supplements if the release of nutrients from deep humus layers is not stimulated through harvesting or site preparation. This was further supported by Malik and Timmer (1998) that seedling growth after transplanting is highly dependent on internal nutrient reserves to help compensate for poor uptake from the soil. Carmean (1996b) suggested nutrient loading of seedlings to ensure satisfactory growth and establishment after transplanting.

Correlations between black spruce SI and the northwestern Ontario (NWO) forest ecosystem classification (FEC) soil types are researched attempting to link SI to the FEC guide. Carmean's (1996a) study and report (1996b) confirmed results from Fairbanks (1988) that correlations between black spruce site indices were not significantly different between NWO FEC soil types, due to extremely large standard deviations and standard errors. Since a wide range of site index occurs within each soil type, FEC soil types cannot be used for precise estimations of site index. Findings by Coile (1952) have been consistently confirmed that the soil properties most closely related to site quality are those which influence the quality and quantity of growing space for tree roots. Carmean (1996a) found depth to bedrock, a root restricting layer or to mottling, along with coarse fragment content and texture of surface soil horizons as the most significant soil features related to site index. NWO FEC soils classification is based on parent material (C horizon) and although parent material is important the classification also needs to recognize the importance of surface soil textures.

Specific soil and topographical features were observed in relation to SI. Carmean (1996b) reported on black spruce soil-site evaluation studies by Buse and Towill (1991) and Buse and Baker (1991). They found developed multiple regression equations were too imprecise for field use. However, the results showed definite relations between specific features of soil and topography and site index. Some effective measure of rooting depth (thickness of living moss, thickness of Oh horizon, depth of LFH layers, and depths to gley or bedrock) must be considered. For organic sites the decomposition of the upper organic layers and the surface texture underlying the organic soil must be considered. More work is required to achieve the goal of defining soil types and soil features (surface soil features within the effective rooting zone of forest trees) that are closely related to site index.

Principal component analysis (PCA) can be a useful tool in analyzing height growth. Sanchez-Rodriguez *et al.* (2002) used PCA to find key factors affecting stand growth in monterey pine (*Pinus radiata* D. Don) plantations. Site index was found to be positively correlated with foliar P concentrations, soil depth and pH, and negatively correlated with total soil N. Widespread deficiencies in P and Mg in these plantations were identified to cause low productivity and recommend fertilization as a routine practice.

A study by McKenney and Pedlar (2003) found that black spruce grew better on deep mineral soils, particularly in the southern part of Ontario where wetter, warmer conditions prevail. The precise variables were depth of organic soil layer, mean annual temperature, and annual precipitation. This coincides with Lowry's (1975) study that black spruce productivity was positively related to summer temperature for stands distributed across eastern Canada.

Parent materials have also been studied relating them to height growth in black spruce natural stands. Hamel *et al.* (2004) found that black spruce grew faster on glacial tills then it did on fluvioglacial or alluvial surface deposits, and suggesting that sandy loam sites or any fine textures soils produce faster growth rates. The positive relationship between forest floor depth and site index for black spruce reinforces findings by Strong and La Roi (1983) and Steele *et al.* (1997) that black spruce absorb more nutrients in the forest floor than in any other soil horizon since a large proportion of the total root biomass is located in the first 15 cm of soil.

Species composition of the understory vegetation was strongly related to concentrations of nutrients (N, P, K, Ca, and Mg) in the forest floor and mineral soil in managed stands of black spruce in northern Ontario (Hunt *et al.* 2005). This positive correlation could use the composition of understory vegetation to be indicative of productive managed black spruce stands. A study by Seynave *et al.* (2005) on Norway spruce (*Picea abies* (L.) Karst.) found that the main factors responsible for productivity are climate, soil moisture, and soil nutrients. Specifically, the joint effect of pH on C/N ratio is directly related to Norway spruce growth where lower productivity occurs on sites with high pH and high C/N ratios.

Climatic parameters have been used to predict lodgepole site index in Alberta (Monserud *et al.* 2006). The study concluded that climate is an important component of site productivity, accounting for almost 25 % of the variation in lodgepole pine site index across Alberta. The strongest predictors of site index were all measure of heat: growing degree days, mean temperature of the warmest month, and Julian date on which growing degree days reaches 100. The study also found that measures of precipitation and winter temperature were not correlated with site index. The objective of this part of the study is to observe which independent variables (elevation, slope, soil pH in water, soil pH in calcium chloride, sand content, silt content, clay content, calcium, potassium, magnesium, sodium, carbon, sulphur, and nitrogen) will have a significant relationship with SI.

3.2. METHODS

3.2.1. Soil Sampling

A small soil pit was dug at each site and soil horizons and textures were identified and depths were measured and recorded. A soil core sample was taken from the C layer to be further analyzed in the Soils lab at Lakehead University. The samples were air dried for 24 hours in the field (in Motel/Camp) after they had been collected. In addition drainage class, moisture regime, soil type, and vegetation type were determined in the field using the "Field Guide to the Forest Ecosystem Classification for Northwestern Ontario" (Sims *et. al* 1997) in the northwest and " A Field Guide to Forest Ecosystems of Northeastern Ontario" (Taylor *et. al* 2000) in the northeast.

3.2.2. Soil Sample Preparation

The soil samples were air dried for another 24-48 hours once they were returned to the Soils Lab at Lakehead University. The next step in preparation required each sample to be ground using a mortar and pestle and any particles larger than 2 mm were separated from the sample (coarse fragments). The coarse fragments and fine particle soil samples were weighed to determine coarse fragment percentage as well as to ensure that sample size requirements were met to conduct tests on texture, carbon-nitrogen-sulphur content (CNS), cation exchange capacity (CEC), and pH in both water (H_2O) and calcium chloride ($CaCl_2$).

3.2.3. Soil Tests

3.2.3.1. Texture Analysis

Soil texture was analyzed using a conventional hydrometer method (Appendix I). Here are the equations used to determine the percentage of sand, silt, and clay of each texture sample:

Eq.15 $$Sand\% = \frac{(OvenDrySoilMass) - (R_{sand} - R_{C1})}{OvenDrySoilMass} X100$$

Eq.16 $$Clay\% = \frac{(R_{clay} - R_{C2})}{OvenDrySoilMass} X100$$

Eq.17 $$Silt\% = 100 - (Sand\% + Clay\%)$$

Results are reported to the nearest 0.01% content.

3.2.3.2. CNS Analysis

Carbon-Nitrogen-Sulfur (CNS) analysis was carried out using conventional methods (Appendix II). The samples were than taken to the Lakehead University Instrumentation Lab where the analysis was conducted by trained professionals using the CNS machine.

3.2.3.3. CEC Analysis

Cation exchange capacity (CEC) was carried out using conventional testing methods (Appendix III). These samples were then analyzed using ICP analysis by lab professionals at the Lakehead University Instrumentation Lab.

3.2.3.4. Soil pH in Water

Standard pH analysis procedures were used in testing all soil samples for pH in water (Appendix IV).

3.2.3.5. pH in Calcium Chloride

Repeat the procedure above replacing $CaCl_2$ solution for H_2O solution throughout the procedure.

3.2.4. Soil Data Analysis

3.2.4.1. Multiple Regression - Partial Regression Plots

Partial regression plots for a particular predictor variable are constructed by computing the regression of site index on all the predictor variables except the predictor variable in question and saving the residuals. Then the regression of the predictor variable in question against the other predictor variables is computed and the residuals are saved, and then these residuals are plotted against each other. For example, to construct a partial regression plot for soil pH in $CaCl_2$ predictor variable: first a regression would be computed of site index against elevation, sand %, and silt % and those residuals would be saved (y-residuals), next pH in $CaCl_2$ would be regressed against elevation, sand %, and silt % and those residuals would be saved (x-residuals), finally the y-residuals would be plotted against the x-residuals.

3.3. RESULTS

3.3.1. Lab Testing Results

On average the soils sampled in northwestern Ontario black spruce plantations were more acidic than those sampled in northeastern Ontario. When tested in water and calcium chloride, pH was 5.57 to 6.53 and 4.72 to 5.82 respectively.

Table 3.1. Summary of soil pH in water and calcium chloride of all sampled black spruce plantations.

Site	pH in		Site	pH in		Site	pH in		Site	pH in	
	H2O	CaCl		H2O	CaCl		H2O	CaCl		H2O	CaCl
A2	7.77	7.26	D8	7.12	6.69	G1	5.35	5.38	K2	5.21	4.41
A3	8.22	7.39	D9	6.96	6.43	G2	5.76	5.16	K3	5.47	4.87
A4	n/a	n/a	D10	n/a	n/a	G3	5.36	4.74	L1	5.90	4.89
A5	8.28	7.56	E1	4.88	4.24	G4	7.66	6.43	L2	5.90	4.89
B2	7.01	6.65	E2	6.74	6.00	G5	5.03	4.60	L3	4.64	3.72
B3	8.05	7.49	E3	5.91	5.50	G6	5.75	4.79	L4	5.59	4.79
B4	7.70	7.09	E4	7.94	6.91	G7	5.72	4.63	L5	5.71	4.86
C2	5.52	4.77	F1	5.14	4.52	G8	5.20	4.21	L6	5.96	5.40
D1	7.29	6.43	F2	4.97	4.28	I1	5.27	4.16	L7	5.39	4.19
D2	6.75	5.75	F3	5.26	4.68	I2	5.38	4.82	L8	5.54	4.71
D3	7.74	7.15	F4	5.08	4.23	I3	5.16	4.01	M1	5.73	4.82
D4	6.98	6.41	F5	5.16	4.11	J1	6.39	5.33	M2	5.49	4.49
D5	7.61	6.79	H1	5.51	4.46	J2	5.21	4.70	M3	4.38	3.60
D6	4.86	3.93	H2	6.30	5.28	J3	5.61	4.77	M4	5.49	4.22
D7	7.50	6.98	H3	5.33	4.63	K1	5.55	4.90	M5	5.94	4.84
			H4	5.82	5.20				M6	5.94	4.84
Northeast Average				**6.53**	**5.82**	**Northwest Average**				**5.57**	**4.72**

* A = Smooth Rock Falls; B = Cochrane; C = Timmins; D = Kapuskasing; E = Hearst; F = Chapleau; G = Longlac; H = Kirkland Lake; I = Dryden; J = Kenora; K = Kirkland Lake; L = Nipigon; M = Thunder Bay

The most acidic site was found on the Dog River – Matawin Forest with pH values of 4.38 in water and 3.60 in calcium chloride. While the most basic site was found on the Smooth Rock Falls Forest with pH values of 8.28 in water and 7.56 in calcium chloride. Two sites in northeastern Ontario were not tested for soil pH, those being the only two organic sites that were sampled. Only 2 sites had pH values greater than 6.00 in water in northwestern Ontario, compared to 17 out of the 29 sites tested in northeastern Ontario (Table 3.1).

On average the soil in black spruce plantations sampled from northwestern Ontario contained higher amounts of sand and silt, but less clay than the soil in northeastern Ontario. The two organic sites were not tested for soil texture. The site containing the highest sand in the soil was found in the Romeo-Malette Forest with a sand content of 91.25 %. The site with the most silt was found on the Kenogami Forest just east of Longlac where the soil was composed of 79.15 % silt. The second highest amount of 71.61 % was found on a site north of Kenora on the Kenora Forest that yielded the highest site index of all sampled black spruce plantations, which were sampled at 14.40 m in height at breast height age 30. The site containing the most clay was found in Kapuskasing on the Gordon Cosens Forest, the heart of the northeastern Ontario clay belt, consisting of 78.89 % clay (Table 3.2).

Black spruce plantations in northeastern Ontario had higher concentrations (mg/kg) of available Ca (calcium), K (potassium), Mg (magnesium), and Na (sodium) in comparison to plantations in northwestern Ontario, especially for Ca and Mg. An organic site in Kapuskasing had the highest Ca concentration at 17,204.43 mg/kg. The highest concentration of available Ca on a mineral site was 6,377.53 mg/kg in the Cochrane Moose River Forest. The lowest concentration of available Ca was on the Superior Forest with only 3.76 mg/kg. The site with the highest concentration of K was found on the Kenora Forest with 244.28 mg/kg. The lowest available K concentration was a site found on the Kenogami Forest at 2.53 mg/kg (Table 3.3).

Table 3.2. Summary of texture analysis (percentage of sand, silt and clay) of black spruce plantations sampled in northern Ontario.

Site	Sand %	Silt %	Clay %	Site	Sand %	Silt %	Clay %
A2	0.95	41.91	57.14	G1	88.74	7.51	3.75
A3	10.60	56.66	32.74	G2	78.13	16.87	5.00
A4	n/a	n/a	n/a	G3	78.12	16.88	5.00
A5	6.92	65.41	27.67	G4	85.59	9.40	5.01
B2	0.86	35.59	63.55	G5	9.54	79.15	11.31
B3	1.55	32.82	65.63	G6	78.07	19.42	2.51
B4	2.05	42.89	55.06	G7	73.10	24.40	2.50
C2	91.25	5.00	3.75	G8	28.82	64.88	6.30
D1	0.76	20.36	78.89	I1	24.83	56.38	18.79
D2	10.48	41.27	48.25	I2	24.83	56.38	18.79
D3	0.70	26.73	72.56	I3	10.06	61.01	28.93
D4	0.01	29.48	70.50	J1	25.70	19.36	54.95
D5	0.72	40.73	58.55	J2	7.04	71.61	21.36
D6	29.13	37.97	32.91	J3	41.21	55.04	3.75
D7	2.59	36.29	61.12	K1	71.79	25.70	2.51
D8	7.48	36.37	56.15	K2	71.79	25.70	2.51
D9	0.66	47.12	52.22	K3	71.79	25.70	2.51
D10	n/a	n/a	n/a	L1	40.15	49.66	10.19
E1	8.79	40.54	50.67	L2	40.15	49.66	10.19
E2	8.79	40.54	50.67	L3	0.91	53.36	45.74
E3	8.79	40.54	50.67	L4	0.91	53.36	45.74
E4	10.31	61.90	27.79	L5	49.76	28.89	21.35
F1	35.83	55.36	8.81	L6	3.37	66.11	30.51
F2	79.16	12.00	8.84	L7	3.37	66.11	30.51
F3	75.43	19.53	5.04	L8	3.37	66.11	30.51
F4	79.16	12.00	8.84	M1	45.25	43.42	11.33
F5	60.39	28.29	11.32	M2	52.86	34.57	12.57
H1	70.50	24.48	5.02	M3	59.01	30.90	10.09
H2	90.00	3.75	6.25	M4	27.67	64.78	7.55
H3	89.35	6.89	3.76	M5	40.59	45.50	13.90
H4	84.96	10.03	5.01	M6	40.59	45.50	13.90
NE avg.	**29.94**	**32.84**	**37.22**	**NW avg.**	**41.20**	**43.01**	**15.79**

* Refer to Table 3.1 for site annotation

The organic site that was found in Kapuskasing also had the highest available Mg at 2,029.65, followed very closely behind by the same mineral site that was previously mentioned on the Kenora Forest with 1,916.43 mg/kg of available Mg. The site with the lowest concentration of available Mg is the same as the site with the lowest K concentration located on the Kenogami Forest at 1.62 mg/kg of Mg. The site with the highest concentration of Na is the same site on the Kenora Forest with high levels of available K and Mg, with 74.32 mg/kg of Na available in the soil. The lowest site was found on the Timiskaming Forest at only 1.71 mg/kg of available Na (Table 3.3).

Table 3.3. Concentrations (mg/kg) of Ca, K, Mg, and Na cation exchange capacities (CEC) in black spruce plantations sampled in northern Ontario.

Site	**Available Cations (mg/kg)**				**Site**	**Available Cations (mg/kg)**			
	Ca	**K**	**Mg**	**Na**		**Ca**	**K**	**Mg**	**Na**
A2	4661.73	121.88	506.34	14.86	G1	3.81	2.53	1.62	2.02
A3	4061.13	56.85	193.85	14.36	G2	45.05	7.85	4.34	3.24
A4	8709.52	74.42	887.05	42.87	G3	213.70	113.27	31.91	13.69
A5	3867.99	39.78	160.23	13.40	G4	1021.78	10.92	49.08	11.71
B2	1953.75	115.26	617.01	29.54	G5	13.20	16.09	3.97	7.69
B3	4632.46	106.98	352.50	23.31	G6	22.12	5.90	6.11	3.66
B4	6377.53	121.26	597.45	17.56	G7	38.18	9.07	11.84	5.49
C2	26.17	6.08	3.68	4.46	G8	51.44	13.97	12.58	4.17
D1	3562.70	158.10	698.85	41.01	I1	147.14	34.06	53.78	10.13
D2	2998.47	117.65	456.93	27.06	I2	35.61	33.74	11.55	14.05
D3	5731.45	130.41	541.10	31.92	I3	456.04	96.59	121.61	10.46
D4	4335.48	162.28	568.46	29.01	J1	3775.22	244.28	1916.43	74.32
D5	5596.76	115.56	389.27	18.03	J2	422.47	102.38	148.22	14.76
D6	879.39	76.08	157.08	12.11	J3	47.06	12.13	15.56	5.16
D7	3779.64	148.02	538.29	17.97	K1	47.90	15.42	6.87	4.38
D8	3681.02	130.17	503.39	15.46	K2	24.89	10.55	5.20	6.72
D9	4199.90	103.77	399.86	10.40	K3	140.51	42.78	21.38	8.69
D10	17024.43	85.41	2029.65	35.30	L1	259.40	37.71	61.79	9.12
E1	306.24	83.55	69.85	7.73	L2	752.31	92.91	248.17	7.57
E2	1792.57	81.77	362.90	12.44	L3	182.04	43.95	129.04	8.43
E3	601.30	61.02	103.95	6.73	L4	954.10	100.55	168.92	11.28
E4	1547.36	66.01	528.10	17.02	L5	426.08	96.27	87.99	4.18
F1	33.29	9.30	8.40	4.37	L6	896.24	160.68	225.79	8.11
F2	3.76	7.68	1.83	2.31	L7	410.50	78.93	44.24	17.31
F3	28.81	14.37	3.90	3.43	L8	727.42	71.74	192.16	14.48
F4	28.17	17.01	4.80	3.49	M1	166.26	28.82	30.72	6.16
F5	491.27	27.51	61.41	5.61	M2	175.78	42.62	42.89	7.62
H1	51.02	18.13	5.93	3.05	M3	55.74	36.54	19.27	12.40
H2	37.48	5.82	7.66	1.71	M4	167.11	23.69	33.89	9.14
H3	16.29	4.08	2.52	3.23	M5	897.66	60.95	188.36	10.19
H4	30.27	6.72	4.03	1.92	M6	1145.17	62.86	331.44	23.95
NE Avg.	**2937.01**	**73.32**	**347.30**	**15.22**	**NW Avg.**	**442.64**	**55.15**	**136.35**	**11.30**

* Refer to Table 3.1 for site annotation

Sites on the Smooth Rock Falls, and the Cochrane Moose River Forests contained high levels of available Ca, K, Mg, and Na in the soil (Table 3.3) as most of these sites appeared to be afforested agricultural lands or in close vicinity to existing agricultural lands where overspray of adjacent crops with fertilizer may have occurred. The site on the Kenora Forest (J1) that contained the highest concentrations of Ca, K, Mg, and Na in black spruce plantations sampled in northwestern Ontario (Table 3.3) and in some cases all of northern Ontario is located just south of Sioux Narrows. The site is on rich soil across the Trans Canada Highway from a large and productive 50-year-old red pine (*Pinus resinosa* Ait.) plantation. The high Na levels could be directly related to the Ministry of Transportation applying salt to the highway during slippery winter conditions, which subsequently gets plowed and runs off into the nearby stand in the spring.

On average the soil in black spruce plantations sampled in northeastern Ontario had higher concentrations of C (carbon), S (sulfur), and N (nitrogen) in comparison to northwestern Ontario. However, the northeast averages are skewed due to the two organic sites. When these are removed, soils sampled in northeastern Ontario are similar to those sampled in northwestern Ontario. Black spruce plantations sampled in northeastern Ontario on mineral soil contain 1.54 %, 0.00 %, and 0.06 % of C, S, and N nutrients respectively. All the values for mineral soils are very small since the c-layer of the soil was sampled and analyzed. The organic site (A4) on the Smooth Rock Falls Forest contained a higher C concentration at 48.08 % to 45.42 % than the organic site found in the Gordon Cosens Forest (D10), however site D10 contained higher concentrations of S (0.44 % to 0.34 %) and N (1.93 % to 1.75 %). For mineral soil sites, the Cochrane Moose River Forest contained the site with the highest C concentration at 4.59 %, while a site on the Kenora Forest contained the lowest C concentration at 0.11 %. Most mineral sites did not contain any traces of S in the C-layer with a few sites with concentrations of 0.01 % or 0.02 %. Low concentrations of N were also exhibited across all the sampled mineral soil sites with a site on the Lake Nipigon Forest containing 0.19 % nitrogen while some sites had only traces (less than 0.01 %) of nitrogen in the C-layer (Table 3.4).

Table 3.4. Total nutrient (C, S, N) concentrations, as a percentage, in the soil of black spruce plantations sampled in northern Ontario.

Site	**Total Nutrients**			**Site**	**Total Nutrients**		
	C %	**S %**	**N %**		**C %**	**S %**	**N %**
A2	1.92	0.00	0.04	G1	0.17	0.01	0.02
A3	3.84	0.00	0.03	G2	0.23	0.00	0.01
A4	48.08	0.34	1.75	G3	1.29	0.01	0.07
A5	4.49	0.00	0.03	G4	0.98	0.00	0.02
B2	0.90	0.00	0.06	G5	0.65	0.00	0.02
B3	2.23	0.00	0.03	G6	0.26	0.00	0.00
B4	4.59	0.01	0.14	G7	0.32	0.00	0.00
C2	0.30	0.00	0.01	G8	1.54	0.00	0.06
D1	0.51	0.00	0.05	I1	0.64	0.00	0.04
D2	0.41	0.00	0.03	I2	0.76	0.00	0.03
D3	1.64	0.00	0.05	I3	1.81	0.01	0.10
D4	1.53	0.00	0.11	J1	0.62	0.00	0.05
D5	1.80	0.00	0.08	J2	0.75	0.00	0.05
D6	3.17	0.02	0.14	J3	0.11	0.00	0.01
D7	1.38	0.00	0.12	K1	0.45	0.00	0.02
D8	2.69	0.02	0.18	K2	0.84	0.00	0.03
D9	2.37	0.00	0.11	K3	1.20	0.00	0.07
D10	45.42	0.44	1.93	L1	2.18	0.01	0.13
E1	1.36	0.00	0.06	L2	1.50	0.00	0.09
E2	1.19	0.02	0.07	L3	0.71	0.00	0.05
E3	0.66	0.00	0.03	L4	0.62	0.00	0.05
E4	1.03	0.00	0.02	L5	1.75	0.00	0.10
F1	1.14	0.01	0.04	L6	1.52	0.01	0.10
F2	0.76	0.00	0.02	L7	2.57	0.02	0.19
F3	1.11	0.00	0.06	L8	1.28	0.00	0.07
F4	1.15	0.00	0.05	M1	1.12	0.00	0.06
F5	1.46	0.00	0.06	M2	0.71	0.00	0.04
H1	0.60	0.00	0.03	M3	2.33	0.00	0.10
H2	0.15	0.00	0.01	M4	0.65	0.00	0.03
H3	0.18	0.00	0.01	M5	1.77	0.00	0.10
H4	0.14	0.00	0.01	M6	0.36	0.00	0.02
NE avg.	**4.46**	**0.03**	**0.17**	**NW avg.**	**1.02**	**0.00**	**0.06**

* Refer to Table 3.1 for site annotation

3.3.2. Soil-Site Index Relations in Black Spruce Plantations

3.3.2.1. Simple Regression Analysis

A simple linear regression was conducted for each independent variable to determine the strength of the relationships with site index for black spruce plantations at breast height age 30. Seven independent variables are significant at $\alpha = 0.10$ level, with only Na, and C not being significant at $\alpha = 0.05$ level (Table 3.5). All the independent variables contain a negative relationship with black spruce plantation site index at breast height age 30 (Figure 3.2 & 3.3). The independent variable accounting for the most variation in the data was pH in $CaCl_2$ at 22.8 %. Total C in the soil accounted for the least variation at only 5.3 %. An outlier in the Mg and Na scatterplots was removed as it proved to have a large amount of leverage on the rest of the data. The site that was found on the Kenora Forest (J1) with extremely high nutrient levels was removed from the dataset allowing for a better linear fit for the data.

Table 3.5. Regression coefficient, R^2, and the *p*-value of simple linear regression analysis between SI_{30} and independent variables of black spruce plantations.

Variable	**Coefficient**	**R^2**	***p*-value**
Soil pH in H_20	-0.543919	0.169	0.0012
Soil pH in $CaCl_2$	-0.595933	0.228	0.0001
Clay %	-0.022826	0.147	0.0027
Ca (mg/kg)	-0.000341	0.203	0.0003
Mg (mg/kg)	-0.002633	0.159	0.0018

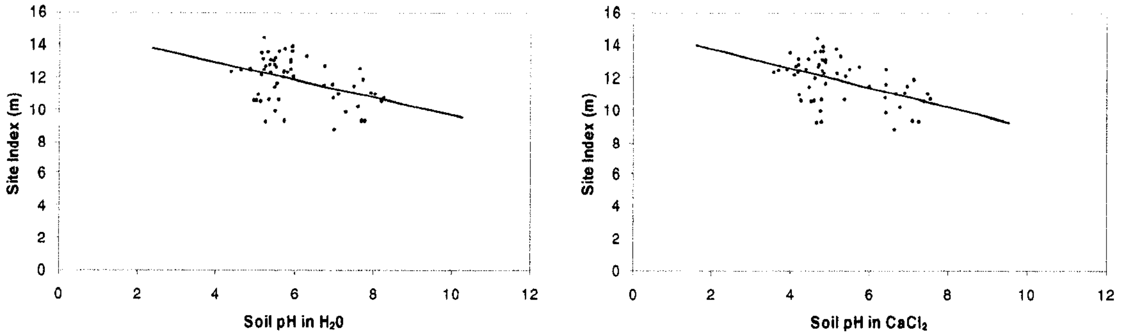


Figure 3.2. Scatterplots of soil pH in H_2O and $CaCl_2$ in relation to SI_{30} of black spruce plantations.

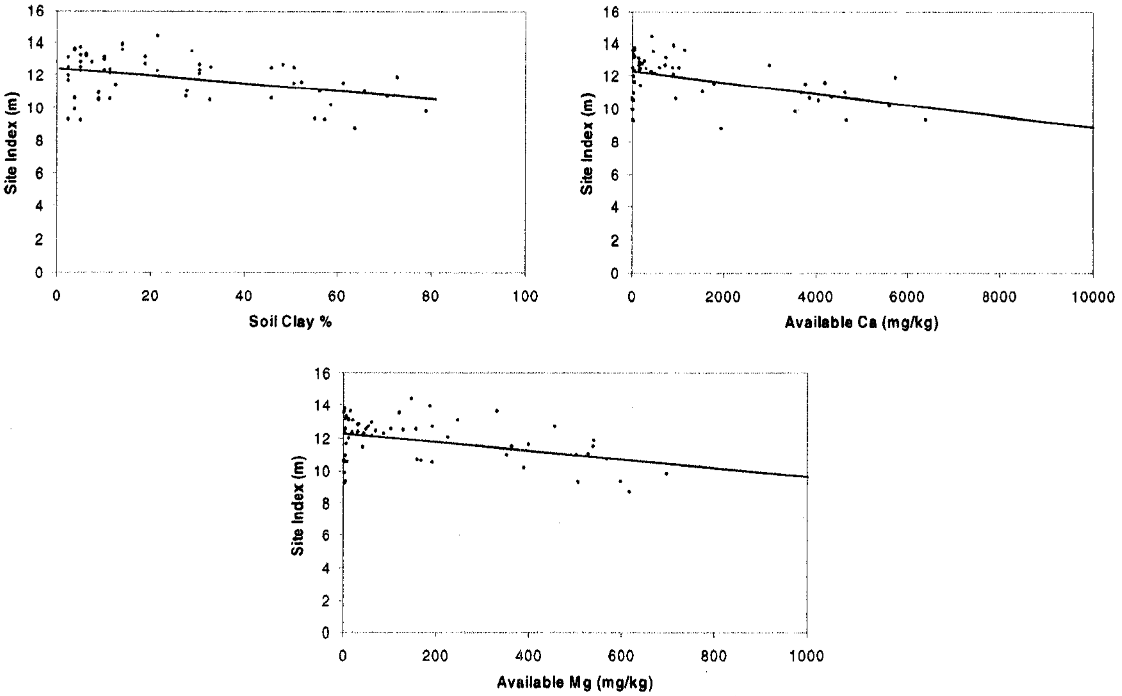


Figure 3.3. Scatterplots of clay %, available Ca, and Mg (mg/kg) concentration in relation to SI_{30} in black spruce plantations.

3.3.2.2. Multiple Regression Analysis

Multiple regression analysis was conducted using the independent variables that had significant linear relationships with site index at breast height age 30 for black spruce plantations (Table 3.5). The best fit model using these independent variables was determined using backwards elimination method and is comprised of soil pH in H_2O and soil pH in $CaCl_2$. These were the two main factors in explaining the variation in site index in black spruce plantations at breast height age 30 (Table 3.6).

Table 3.6. Best fit multiple regression equation using independent variables that have a significant simple linear relationship with SI_{30} for black spruce plantations.

Regression Equation	N	R^2	R^2_{adj}	SEE	*p*-value
SI = 13.3829 + 1.302 (H_2O) - 1.79044 ($CaCl_2$)	59	0.28	0.254	1.175	<0.0001

Where,
SI = site index (m) at BHA 30
H_2O = soil pH in water
$CaCl_2$ = soil pH in calcium chloride

The regression equation is significant at $\alpha = 0.05$ level, however accounts for 28.0 % of the total variation in the dataset. Due to the low R^2 value and few predictor variables a best fit model using backwards elimination was performed using all the independent variables. The best fit model was composed of soil pH in $CaCl_2$, elevation (m), percentage of sand, and silt (Table 3.7).

Table 3.7. Best fit multiple regression equation using all independent variables in relation to SI_{30} for black spruce plantations.

Regression Equation	N	R^2	R^2_{adj}	SEE	*p*-value
SI = 15.3027 - 0.61053 ($CaCl_2$) - 0.00764 (Elev) + 0.023988 (Sand) + 0.03723 (Silt)	59	0.372	0.326	1.117	<0.0001

Where,
SI = site index (m) at BHA 30
$CaCl_2$ = soil pH in calcium chloride
Elev = site elevation (m)
Sand = percentage of soil texture that is comprised of sand
Silt = percentage of soil texture that is comprised of silt

The new regression equation, with four predictor variables opposed to two, is significant (p = <0.0001) and accounts for more variation in the dataset (37.2 %) in comparison to the regression equation in Table 3.6. Three of the predictor variables in the regression equation (Table 3.7) did not have a significant simple linear relationship with site index at breast height age 30 for black spruce plantations. The combination of sand and silt % is collinear with clay %, thus if all three variables are present they become not significant in the regression. Substituting clay %, since it was a significant variable in the simple linear regression, for sand and silt % yielded a regression model with a lower R^2 value than the best fit model (Table 3.7). In a multiple regression each coefficient is estimated once the relationship between site index at breast height age 30 for black spruce plantations and any of the predictor variables in question have been adjusted for all the effects of all other variables in the multiple regression model. Thus looking at the partial regression plots of these variables may unveil a significant linear trend once the variable in question has been adjusted for by all other variables in the

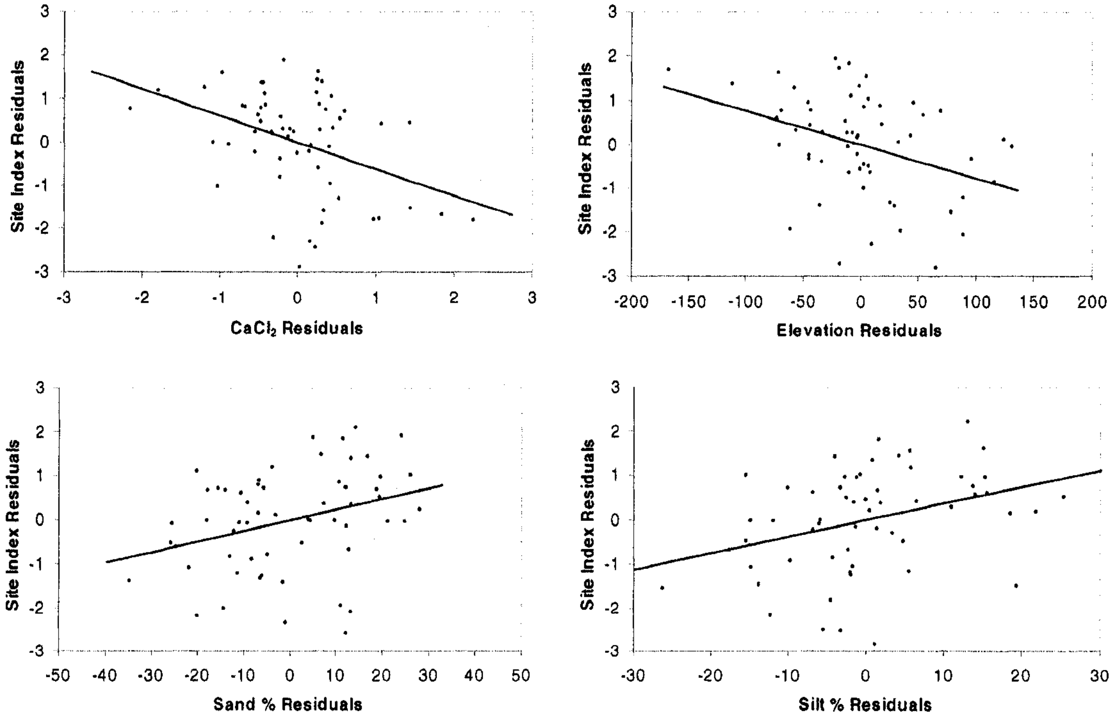


Figure 3.4. Partial regression plots for four predictor variables (pH in $CaCl_2$, elevation (m), sand %, and silt %) of the best fit regression equation (Table 3.7) describing SI_{30} in black spruce plantations.

regression equation (Figure 3.4).

Using the site index regression equation that was derived from the multiple regression analysis the regression assumptions must be satisfied in order to accept the proposed equation. The regression assumptions are verified using the internally studentized (IStud) residuals derived from site index. The IStud residuals are obtained by dividing the computed residuals by the residual standard deviation. First, the IStud residuals from site index are tested for a normal distribution (Figure 3.5). Despite a couple of points that are off the diagonal line Figure 3.5 shows that the site index residuals follow a normal distribution.

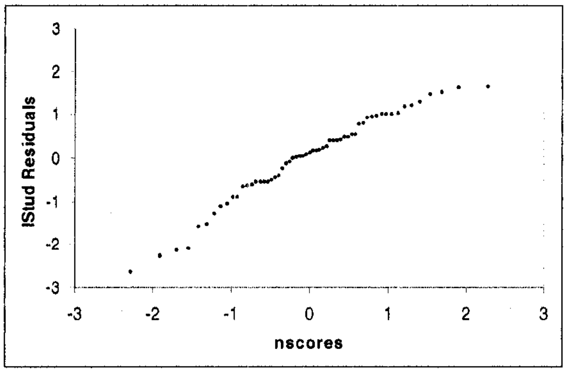


Figure 3.5. A normal probability plot of the IStud residuals for SI_{30} for black spruce plantations derived from the multiple regression analysis.

Next the IStud residuals are plotted against the predictor variables to ensure they are not correlated with the response variable site index (Figure 3.6). All four predictor variables ($CaCl_2$, elevation, sand, and silt) are not correlated with the response variable, site index, as the data is randomly spread across the scatterplot for each predictor variable.

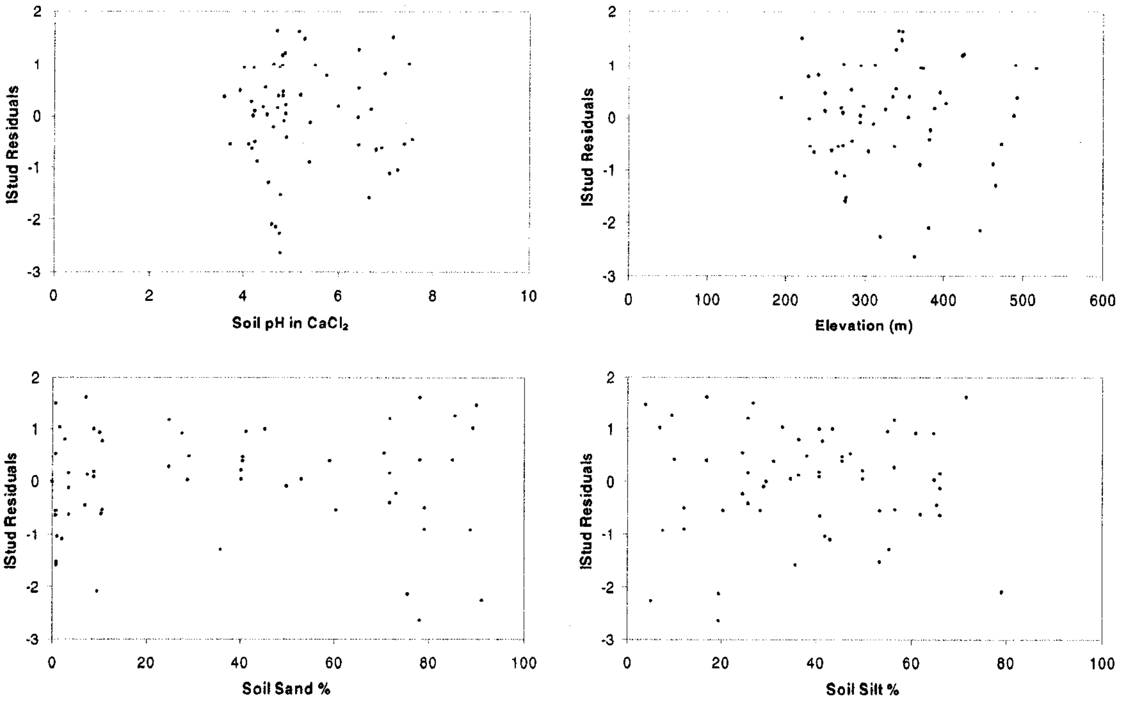


Figure 3.6. Scatterplots checking for correlation of the IStud residuals for SI_{30} for black spruce plantations against the predictor variables.

The next assumption to be met is that the IStud residuals have a constant variance across the predicted values (Figure 3.7).

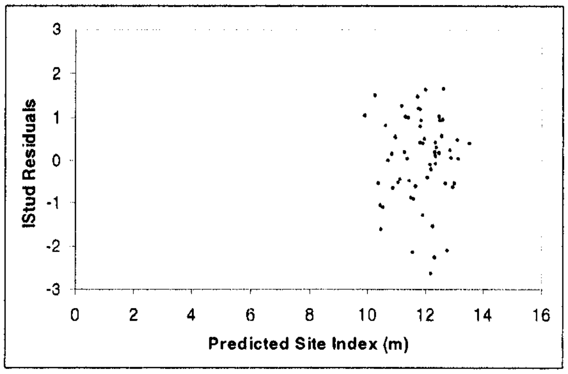


Figure 3.7. Scatterplot checking for a constant variance of IStud residuals for SI_{30} for black spruce plantations derived from the regression equation against the predicted site index values (m).

The data are distributed randomly with no obvious trends (flair or fan shaped) that occurs in the IStud residuals as the predicted values increase. Thus, the assumption that the residuals have a constant variance is not violated for this analysis. The final assumption is that the IStud residuals are uncorrelated and that the observations are independent from one another (Figure 3.8).

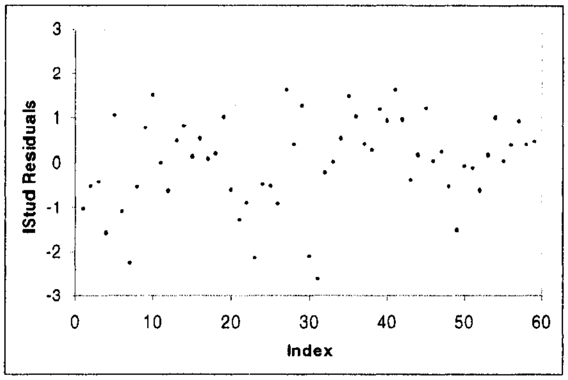


Figure 3.8. Scatterplot checking for independent observations of the IStud residuals for SI_{30} for black spruce plantations derived from the regression equation against the order (Index) in which the observations were entered.

The IStud residuals are randomly scattered among the observations verifying that the IStud residuals are not correlated and observations are independent of one another. Thus, the final multiple regression assumption has been met and the multiple regression equation from Table 3.7 describes the independent variables that account for the variance in site index for black spruce plantations.

3.3.3. Factor Analysis

Factor analysis (FA) is a mathematical procedure that transforms a number of (possibly) correlated values into a smaller number of uncorrelated variables which are called factors or principal components. The first component accounts for as much of the variability in the data as possible with each succeeding component accounting for as much of the remaining variability as possible. Environmental variables make it difficult to simultaneously envision all these variables. The objective of this analysis is to discover or reduce the dimensionality of the data set by taking the cloud of data points and rotating it such that the maximum variability is visible in displaying the most important factors or components. First, Eigen values are calculated to determine the number of principal components. There is one component for each variable and the sum of the Eigen values equals the number of independent variables. There are two approaches to determining the number of components, first to accept all components with Eigen values greater than one (Table 3.8), or to plot the Eigen values in a "scree plot" and accept components until the values tend to level off and approach zero (Figure 3.9). Two factors or components have Eigen values greater than one; from the scree plot one could argue that four factors could be used since values level off after the fourth factor.

Table 3.8. Calculated Eigen values for factor analysis of variables relating to SI_{30} of black spruce plantations.

Component #	Eigen values	Component #	Eigen values
1	6.134737	6	0.252818
2	1.539585	7	0.109217
3	0.958827	8	0.075111
4	0.484606	9	0.022202
5	0.422898	10	0.000000

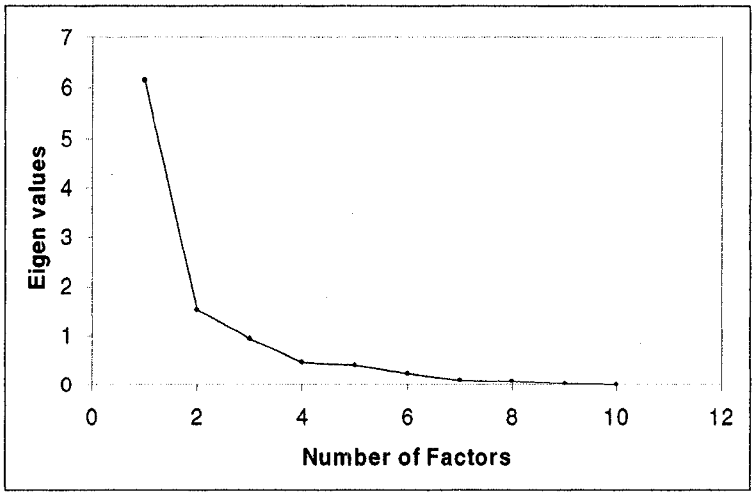


Figure 3.9. Scree plot of the Eigen values calculated for the factor analysis of variables relating to SI_{30} of black spruce plantations.

The method that accepts components with Eigen values greater than 1 was used as this method is more commonly used and because, unlike four factors or components, two factors and their corresponding component loadings can be visually represented. The first factor explains 61.3 % of the total variance from the dataset and positively related to the presence of soil pH in H_20 and $CaCl_2$, % clay, Ca, Mg, and Na, while being negatively related to the presence of elevation and % sand. The second factor explains 15.4 % of the total variance of the dataset and has a strong negative correlation with % silt (Table 3.9). The two factors or components explain over 76% of the total variance within the dataset.

Table 3.9. Component loadings and the total variance explained by each component.

Component Loadings		
Factor	**Component**	
	1	**2**
Soil pH in H_20	0.848385	0.332466
Soil pH in $CaCl_2$	0.848980	0.355200
Clay %	0.893488	-0.073343
Ca (mg/kg)	0.929847	0.151381
Mg (mg/kg)	0.922120	0.093290
Na (mg/kg)	0.810600	-0.004048
C %	0.527468	-0.279623
Elev (m)	-0.752487	-0.136579
Sand %	-0.781483	0.587169
Silt %	0.262156	-0.907888
% of Total Variance Explained		
	Component	
	1	**2**
	61.347371	15.395851

The component loadings of the two components are graphically displayed in Figure 9 to show which variables are correlated with the two factors as well as the groupings of variables that account for similar variances in the dataset. There are three groupings fairly close together, soil pH in H_20 and $CaCl_2$, Ca and Mg, and % Clay with Na. These six variables are clustered together and making similar contributions to both factors. Total C does not have a strong correlation with the other variables in terms of the first factor and also has a weak negative correlation with the second factor. Elevation, % silt, and % sand are fairly dispersed among the two factors with only elevation having a negative correlation with both factors. Percentage sand has a strong negative correlation with the first factor and an average positive correlation with the second factor, while % silt has a slight positive correlation with the first factor and a very strong negative correlation with the second factor (Figure 3.10).

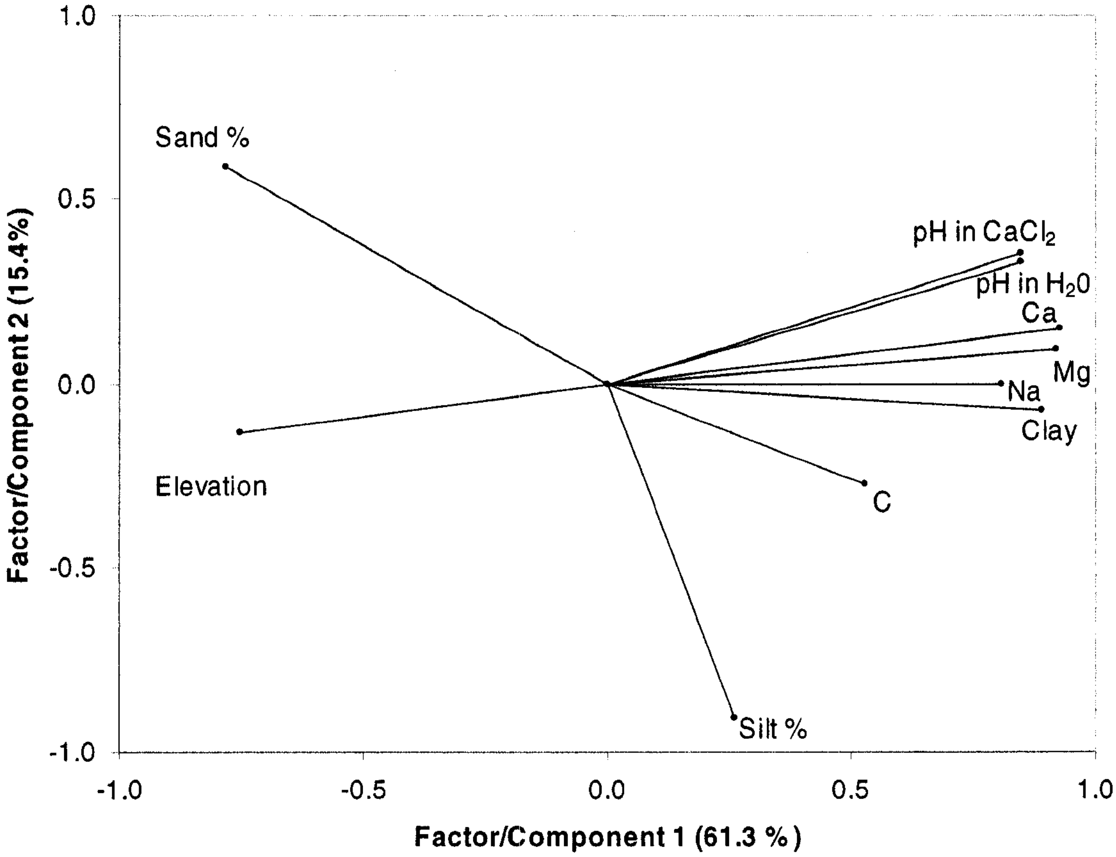


Figure 3.10. Two-axis plot displaying the two factors and the respective loadings accounting for over 76% of the variance within the dataset.

3.4. DISCUSSION

The soil section of this project was minor, attempting to link soil and site properties with site index. Due to the preliminary nature of this section the project decided to focus on relating FEC to site index, specifically what factors in the C horizon attribute to site quality in black spruce plantations since the C horizon is used to classify sites according to the FEC guide (Sims *et al.* 1997; Taylor *et. al.* 2000).

When independent variables were simply regressed on SI, soil pH in H_20, soil pH in $CaCl_2$, clay %, Ca, and Mg all proved to have significant negative relationships with SI. Coniferous stands thrive in more acidic soils as their needle litter decreases soil pH. SI increased as the percentage of clay in the soil decreased, which coincides with Gordon and Simpson (1991) that exceptional black spruce plantations in northern Ontario occurred on silt and sandy soils with moderate to imperfect drainage (Gordon and Simpson 1991). Calcium has a negative effect on SI in black spruce (Hunt *et al.* 2005), which was also found in this study. Magnesium has been found to have a positive correlation with increasing site quality (Foster *et al.* 1995), however in our study the relationship between SI and available Mg concentrations was negative. Since the C horizon was tested in this study perhaps the negative correlation deals with rapid leaching of Mg through the surface horizons and not having sufficient time to be absorbed by roots of black spruce.

The multiple regression using independent variables that had a significant relationship with SI proved to be unsuitable ($R^2 = 0.25$). An equation using all the variables produced an equation with an adjusted R^2 value of 0.33. Generally, an equation accounting for 33 % of the variation is considered low, however, in contradiction since ecological data is extremely variable it is sometimes difficult to account for the variation with the data collected for the independent variables. A negative correlation with soil pH in $CaCl_2$ remains consistent with simple linear regression findings in this study. Site elevation is now a significant factor with a negative correlation to site index. However, it is a secondary indicator when considering different climatic factors and site position (Barnes *et al.* 1998). Elevations ranged between 195 and 517 m in this study, which is well within the most common range of 150 and 760 m identified for black spruce (Viereck and Johnston 1990). This could explain why when regressed separately it did not show a significant relationship with SI. Although the percentage of clay was not found significant in the multiple regression it was replaced with positively correlated values for both sand and silt content (%). This further supports studies (Gordon and Simpson 1991; Hamel *et al.* 2004) linking sites on silt and sandy soils of glacial tills to higher quality sites. Insignificant variables in simple regression can be found to be significant in multiple regression since each coefficient is estimated once the relationship between SI and any of the other predictor variables, included in the analysis, have been adjusted for all other variables in the multiple regression model. Partial regression plots help identify trends of predictor variables once adjusted by all other variables included in the regression equation (Figure 3.4). The multiple regression equation developed to relate SI with properties of the C soil horizon has been tested and met all regression assumptions. The large variances between soil types were consistent with findings by Carmean (1996a and 1996b) that FEC groups cannot be used to estimated site index in black spruce. The large standard deviations and large standard errors of the mean indicating that site index varied greatly and no significant relationship was found with the FEC guide (O'Neill 2007).

The PCA provided 2 principal components that accounted for 76% of the variance. The first component was divided with strong positive loadings in soil pH in H_20 and $CaCl_2$, clay %, Ca, Mg, and Na, while negatively loaded by elevation and sand %. The second component was negatively loaded with silt %, while sand % had a weaker positive correlation. Plotting the component loadings show that Clay %, Na, Mg, Ca, soil pH in H_20 and $CaCl_2$ are all clumped together accounting for similar variance in SI, which would explain why only one of the variables (soil pH in $CaCl_2$) appears in our multiple regression model for estimating SI. Soil pH in $CaCl_2$ accounted for the most variation, and since other variables such as Clay %, Na, Mg, Ca, soil pH in H_20, and C accounted for less variation they were deemed insignificant in the equation. The clumping of soil nutrients is probably a result of the lack of nutrients available in the C horizon at the sampled sites. The two soil pH measures are also clumped together as expected since they provided parallel results with the calcareous test providing slightly higher acidic soils. Total C is also near the large grouping, however close enough to account for similar variation as the other models in relationship to SI. The other variables significant in the multiple regression, sand %, silt %, and elevation are all spread out among the two components accounting for different variances in relation to SI. These three individual groupings in the PCA, all proved to be significant factors in the multiple regression and display in the component loadings plot (Figure 3.10) how their loadings account for different variations in site quality.

A multiple regression equation has been developed relating soil, in the C horizon, and site factors. Due to the limited scope of this study (C horizon was the only one sampled) relating soil and site properties to SI in black spruce plantations, it is recommended that further soil studies in plantations focus on upper soil horizons. A large proportion of the total root biomass for black spruce is located in the first 15 cm of soil (Strong and La Roi 1983; Steele *et al.* 1997). By sampling from the C horizon this large proportion of total root biomass is neglected and so are the nutrient stores found within the surface horizons that black spruce are dependent on. As well, many important nutrients vital to black spruce height growth are found in humus layers of black spruce sites (Foster *et al.* 1995). The range of site quality sampled mostly occurred on mineral soils, with only two organic sites being sampled. This is directly due to low planting densities on lowland sites with plenty of natural ingress occurring making it difficult to segregate planted trees from naturally regenerated trees. Finally, a larger sample size with multiple samples per plot should be collected from each sample site to sufficiently analyze soil and site factors in their influence on SI.

CHAPTER 4. MANAGEMENT IMPLICATIONS AND CONCLUSION

4.1. MANAGEMENT IMPLICATIONS

GI models for black spruce plantations have been developed for use in young plantations. These GIs have been linked to SI to provide accurate and precise polymorphic height growth models for black spruce plantations in northern Ontario, as well as separate models for northwest and northeast regions of Ontario. Site indices for black spruce plantations have been derived from SI curves based on height and BHA in northern Ontario for use in the field to get a relatively quick estimate of site index in young plantations (Table 4.1). The SI values refer to SI at BHA 30. SI values presented do not exceed 17 m since the highest observed SI value at BHA 30 has been 14.98 m on a site in the Kenora Forest north of Kenora, ON.

Table 4.1. SI_{30} values based on tree total height (m) and BHA (yrs) for young black spruce plantations across northern Ontario.

BHA	**Total Height (m)**								
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	12.65	15.89							
2	10.83	13.84	16.02						
3	9.68	12.53	14.62	16.36					
4	8.77	11.55	13.56	15.27	16.79				
5	8.03	10.75	12.71	14.37	15.86				
6	7.32	10.04	11.98	13.60	15.07	16.42			
7	6.68	9.40	11.32	12.92	14.36	15.70	16.97		
8	6.10	8.84	10.72	12.31	13.74	15.06	16.30		
9	< 6.00	8.29	10.18	11.75	13.16	14.46	15.71	16.89	
10	< 6.00	7.80	9.67	11.23	12.62	13.92	15.15	16.33	
11	< 6.00	7.30	9.19	10.74	12.13	13.41	14.63	15.80	16.93
12	< 6.00	6.83	8.72	10.27	11.65	12.93	14.14	15.31	16.43
13	< 6.00	6.34	8.30	9.84	11.21	12.48	13.68	14.83	15.96
14	< 6.00	< 6.00	7.88	9.41	10.79	12.05	13.24	14.38	15.49
15	< 6.00	< 6.00	7.46	9.01	10.37	11.63	12.81	13.97	15.07

Quick reference tables were also developed by region and the shapes of the curves for northwestern (Table 4.2) and northeastern (Table 4.3) Ontario black spruce plantations are represented in the tables. Since SI curves for northeastern Ontario black spruce plantations resulted in higher predicted total heights the tables show higher total heights are required in the northeast region to attain similar SI to the northwest region.

Table 4.2. SI_{30} values based on tree total height (m) and BHA (yrs) for young black spruce plantations across northwestern Ontario.

BHA	**Total Height (m)**								
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	19.83								
2	12.55								
3	9.33	16.67							
4	7.40	13.44	18.70						
5	6.17	11.32	15.83						
6	< 6.00	9.75	13.69	17.39					
7	< 6.00	8.56	12.10	15.42					
8	< 6.00	7.63	10.81	13.82	16.71				
9	< 6.00	6.91	9.80	12.54	15.21				
10	< 6.00	6.30	8.95	11.50	13.95	16.35			
11	< 6.00	< 6.00	8.26	10.60	12.91	15.13			
12	< 6.00	< 6.00	7.67	9.87	12.00	14.09	16.14		
13	< 6.00	< 6.00	7.17	9.22	11.22	13.20	15.14		
14	< 6.00	< 6.00	6.76	8.67	10.56	12.42	14.26	16.06	
15	< 6.00	< 6.00	6.37	8.20	9.98	11.74	13.43	15.19	16.90

Table 4.3. SI_{30} values based on tree total height (m) and BHA (yrs) for young black spruce plantations across northeastern Ontario.

BHA	**Total Height (m)**								
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	11.09	14.78							
2	9.32	12.56	15.02						
3	8.29	11.25	13.52	15.51					
4	7.52	10.30	12.44	14.32	16.07				
5	6.97	9.56	11.60	13.40	15.06	16.63			
6	6.45	8.96	10.91	12.54	14.23	15.75			
7	6.05	8.42	10.29	11.97	13.52	14.99	16.40		
8	< 6.00	7.94	9.78	11.38	12.90	14.32	15.70		
9	< 6.00	7.55	9.31	10.88	12.33	13.72	15.08	16.39	
10	< 6.00	7.18	8.89	10.41	11.83	13.20	14.51	15.80	
11	< 6.00	6.83	8.58	9.98	11.37	12.71	14.00	15.26	16.50
12	< 6.00	6.52	8.13	9.58	10.95	12.26	13.53	14.77	15.98
13	< 6.00	6.23	7.80	9.22	10.55	11.84	13.09	14.30	15.49
14	< 6.00	< 6.00	7.49	8.88	10.18	11.44	12.66	13.87	15.05
15	< 6.00	< 6.00	7.19	8.55	9.84	11.07	12.27	13.45	14.62

For example looking at a tree at 3 m tall and with BHA of 4 would result in a SI of 10.30 m using the northeast table in comparison to 13.44 m in the northwest region.

Using the northern Ontario table (Table 4.1) a SI value of 11.55 m would be given to the site, however as the BHA increases the difference between SI estimation decreases just as in the curves between northwest and northeast regions of Ontario. For example at BHA 15 with a tree height of 7 m SI values are 11.74 and 11.07 m for northwest and northeast regions respectively.

Smith *et al.* (1987) found black spruce trees susceptible to windthrow causing sufficient stand damage at critical heights of 20 to 21 m, thus recommending using those top heights as an indicator for stand harvest. Using the polymorphic height growth curves developed for young black spruce plantations I would recommend shorter rotation ages (Table 4.4) on productive sites than traditional rotation ages reported by Viereck and Johnston (1990) on good sites.

Table 4.4. Rotation ages of intensively managed black spruce stands based on site quality (SI_{30}) and critical top height of dominant and co-dominant trees.

Site Index	**Rotation Age (Total Years) @ Critical Height 20 m**	**Rotation Age (Total Years) @ Critical Height 21 m**
15	54	58
14	58	62
13	62	67
12	67	72
11	73	79
10	82	89
9	101	112

On high quality sites a rotation age of 60 years is attainable through intensive forest management that would yield on average 292 m^3/ha of merchantable volume. Current average merchantable volumes of all sampled sites is 140 m^3/ha, with an average of 160 m^3/ha on sites with a site index of 12 m or greater. A 53-year-old stand in the Stanley Spacing Trial just outside of Thunder Bay currently holds 306 m^3/ha, while a 48-

yeard-old sample site east of Kapuskasing on the Gordon Cosens Forest near the Groundhog River has a merchantable volume of 305 m^3/ha.

A comparison among three scenerios concerning black spruce over a 300 year time period: harvesting intensively managed stands using a proposed 60 year rotation age; harvesting good natural stands using a rotation age of 92 as stated by Viereck and Johnston (1990); and harvesting natural stands once the trees have reached maturity, where a mature tree is defined as 80 years old (Table 4.5).

Table 4.5. Results of a harvesting scenario over a 300 year time period in black spruce natural and planted stands.

Stand Management	Rotation Age (yrs)	# of Rotations	Merchantable Volume (m3/ha)	Years until next Harvest
Planted Stand	60	5	1460	60
Natural Stand	80	3	654	20
Natural Stand	92	3	654	68

The planted stand has completed five full rotations yielding more than twice as much merchantable volume than the two natural stands. Also, the planted stand will be harvested a sixth time before the natural stand with a 92 year rotation is harvested for a fourth time.

Another scenario compares the amount of volume loss if these managed stands that are ready to be harvested at 60 years old are not harvested until 80, or 92 years of age. Whitney and Fleming (1995) studied affects of disease on windfall in upland black spruce strip cuts. They sampled the amount of windfall in uncut strips, with plots over 20 m away from the stand edge and found 1.8 % of volume losses in black spruce stands due to windfall. Using this factor on a yearly basis if high quality black spruce plantations were harvested at 92 year rotations the stand would incur a volume loss of 128 m^3/ha leaving only 164 m^3/ha of merchantable volume on site. Comparing to when a tree reaches maturity, harvesting at 80 years, these stands would still lose 89 m^3/ha of merchantable volume. However, this scenario looked at volume loss in a linear fashion whereas Smith *et al.* (1987) stated that as the stand begins to open up and stocking decreases the wind velocity required for trees in a stand to reach their critical turning moment decreases. Thus, as the stand begins to deteriorate losses due to windthrow should theoretically increase in a curvilinear trend causing an increase in merchantable volume losses. Due to black spruce's susceptibility to root rotting fungi harvesting at 60 years of age avoids the onset of butt rot usually found in upland spruce at 70 to 90 years of age. Not only would this increase volume losses due to butt rot but also makes black spruce more susceptible to windthrow since the mechanical strength decreases as does the of soil that is held by the rooting system (Whitney and Fleming 1985).

This study recommends harvesting upland black spruce intensively managed stands on high quality sites at 60 years of age. Due to black spruce's shallow rooting nature and susceptibility to root rotting fungi, such as tomentosus root rot, that could result in excessive losses due to wind throw. By decreasing rotation age these losses can be avoided and annual allowable cuts can be increased due to more productive upland black spruce sites.

4.2. CONCLUSION

With the increasing concern in the forestry sector in terms of future wood supply and the closure of mills in northern Ontario it is essential for forest companies to ensure adequate return on their investments. Accurate growth and yield models are crucial in estimating future forest conditions that have a direct effect on timber supply models and future forecasts. As the forest industry continues harvesting the last of our virgin forests the focus has been diverted towards intensive forest management. This has included the planting of more trees, which results in the increasing number of plantations that are being established, as the reality of relying on our second growth forests is rapidly approaching.

Currently site index models that are being used in order to estimate future stand volumes have been generated from naturally established trees. The trees sampled in these models have not been exposed to silvicultural activities, such as scarification, planting, and stand tending (chemical spray and thinning). These activities are applied to a site to accelerate growth and improve growing conditions (Farnden and Herring 2002; Huang *et al.* 2004b). The goal is for plantations to become more productive in a shorter period of time, which would change the rotation age and site quality (increased site index), and thus have a direct effect on timber supply models and annual allowable cut (AAC) calculations. Therefore, the importance of developing site index curves for plantations in northern Ontario has been addressed in this study, and comparisons with site index curves for natural stands displays the underestimation of future yields of established plantations.

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APPENDICES

APPENDIX I: TEXTURE ANALYSIS

- Weigh out 40.0 g (+/- 0.05 g) of air-dried soil and pour into 200 mL Erlenmeyer flask.

- Add 100 mL of sodium hexametaphosphate (HMP) solution, cover the flasks using Parafilm and place on a reciprocating horizontal shaker for sixteen hours.

- Transfer the suspended solution into a sedimentation cylinder using deionized water to make sure all the particles are removed from the Erlenmeyer flask and bring the cylinder to 1.0 L final volume. When bringing the cylinder to 1.0 L final volume ensure that the hydrometer is suspended in the solution, so once removed the total volume will be slightly below 1.0 L.

- Allow the suspension to equilibrate to room temperature for two hours.

- Stopper the cylinder and use end over end shaking method for one minute, shaking vigorously to ensure that all the sediment is dislodged from the bottom of the cylinder.

- Add 2 mL of amyl alcohol to the surface of the suspension to dissipate the foam that has formed at the top of the cylinder.

- Lower the hydrometer into the suspension carefully and take a reading after thirty and forty seconds since shaking recording to the nearest +/- 0.5 g/L (R_{sand}).

- Remove the hydrometer, rinse and wipe dry. Repeat these steps and record the hydrometer reading on a blank solution (deionized water and 100 mL HMP) to the nearest +/- 0.5 g/L (R_{C1}).

- After six hours record the room temperature using a thermometer to the nearest +/- 1^0C and refer to the table below (Table A1) to determine the settling time for 2.0 μm size fraction.

- Based on time after initiating the settling of the suspension, reinsert the hydrometer and take a reading to the nearest +/- 0.5 g/L (R_{clay}). Repeat the process again for the blank solution recording to the nearest +/- 0.5 g/L (R_{C2}).

Table A1. The influence of suspension temperature on the hydrometer method of determining soil clay (2.0 μm) based on a particle density of 2.65 g/cm^3 and a solution density of 0.5 g/L.

Temperature ^{0}C	Settling Time for Clay (Hours and Minutes)
18	8:09
19	7:57
20	7:45
21	7:35
22	7:24
23	7:13
24	7:03
25	6:53
23	6:44
27	6:35
28	6:27

Gee and Bauder (1986)

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APPENDIX II: CNS ANALYSIS

- Weigh out 0.30 g of each soil sample and place it in a small plastic capped test tube.

- Label each sample numerically corresponding to the specific sample in the field.

- Take the samples to the Lakehead University Instrumentation Lab where the analysis is conducted by trained professionals using the CNS machine.

APPENDIX III: CEC ANALYSIS

- Weigh out 2.5 g of soil from each sample and place into a 50 mL Erlenmeyer flask.

- Record weight on the tally sheet and label the Erlenmeyer flask with the appropriate sample ID.

- Weigh 2.5 g of a quality control sample (QCS 109) and place into a 50 mL Erlenmeyer flask recording its weight on the tally sheet and labelling it accordingly.

- A quality control sample is run at the start than after every ten soil samples.

- Using the bottle top dispenser, adjust to 25 mL and add 25 mL of 1 *M* Neutral Ammonium Acetate and cover flask with Parafilm.

- In an empty 50 mL Erlenmeyer flask, add 25 mL of the 1 *M* Neutral Ammonium Acetate solution. This is the blank sample which is run at the start, in the middle, and at the end of all the trials.

- Place and secure all the samples including the quality control and blanks on the reciprocating shaker set at 70 for 15 minutes.

- Set up the filtration apparatus and wear new, clean gloves while handling the funnels, extraction jars, and filter paper.

- The filter paper is folded and placed in the funnels. The funnel spouts will be in the extraction jars.

- Remove the samples from the reciprocating shaker and filter the samples (including the quality and blank) through the folded filter paper and into the extraction jars.

- Any filtrates that are cloudy need to be re filtered until they are transparent. Place the corresponding lids on the extraction jars and mark the jar number on the tally sheet next to the appropriate sample.

- These samples are then sent to the Lakehead University Instrumentation Lab where trained professionals handle the ICP analysis.

APPENDIX IV: pH ANALYSIS

- Weigh 10 g (+/- 0.02 g) of each soil sample and place into an extraction jar.
- Record the weight and jar number on the tally sheet.
- Add 20 mL of desired solution (H_2O or $CaCl_2$) and allow the soil to absorb the desired solution without stirring.
- Once absorbed stir for 10 seconds using a glass rod and continue stirring the suspension four to five times in the next thirty minutes.
- Allow the suspension to settle for 30 minutes before measuring the pH by immersing the combination electrode in the suspension.
- Finally, record the pH value once the read has stabilized (usually 1 minute).