Soil-Site Relationships for Young White Spruce Plantations In North Central Ontario

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ABSTRACT

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Keywords: Site-quality, site index, glaciofluvial, lacustrine, morainal, drainage, rooting depth.

Site index of white spruce (Picea glauca (Moench) Voss) in North Central Ontario was related to features of soil and topography using both multiple regression techniques and principal component analysis. Two different measures of site index, $TOTSI_{25}$ (site index is total height at total age of 25 years), and $BHSI_{15}$ (breast height site index is total height at 15 years breast-height age) were used as dependent variables; 81 soil and topographic values were independent variables considered for analysis. Preliminary regressions computed from 54 plots indicated poor relationships between $TOTSI_{25}$ and soil and topographic variables. Preliminary regressions also indicated that the correlations were much stronger using $BHSI_{15}$. Correlations also were much stronger when the plots were stratified into three landform types as opposed to unstratified regressions. Three final regression equations were based on the relationship between $BHSI_{15}$ and lacustrine, morainal, and glaciofluvial landform groups, and explained 77, 73, and 65 percent of the variation in $BHSI_{15}$, respectively. The final regression equation for the lacustrine landform included the type of clay deposit (CLAY), the depth to a root restricting layer (DRRL), and the hue of the C horizon (HUEC). The final regression equation for the morainal landform included the natural logarithm of the depth to a root restricting layer (LNDRRL), and the pH of the C horizon (PHC). The final regression equation for the glaciofluvial landform included the drainage class of the soil (DRAIN). The ability of the final regression equations to predict $BHSI_{15}$ was tested on 14 independent test plots; these tests showed close agreement between actual site index based on stem analysis and site index predicted from the regression equations.

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INTRODUCTION

Timber management in Canada was initially concerned with fire prevention and efficient harvesting of what seemed to be an inexhaustible virgin forest. Unfortunately, in Canada most of the original forests within an economical distance to the markets have been exhausted. Canadian foresters are now faced with the problem of supplying wood to existing wood dependent industries from land that is supporting second growth timber.

Canada is blessed with vast amount of forest land. Unfortunately, a large amount of this forest land is too far away from transportation routes and markets. Complicating this problem is the expansion of population and forest resource dependent industries. Corresponding to this increase in population, forest land has been developed into residential and urban areas and other land has been reserved for parks and wilderness areas. Despite these other competing uses Canada still has much forest land that is not economically suited for intensive management. Given financial limitations, foresters in Canada have attempted to concentrate intensive management practices only on the most productive lands close enough to markets to provide economic returns.

McLintock and Bickford (1957) stated that markets, labour supply, accessibility, and site quality are all factors which affect the intensity of management that can be profitably supported on a given site. Assuming markets, labour supply, and accessibility are constant for a geographic region, then site quality will dictate what intensity of management should be pursued on a particular area of land.

Foresters concentrate intensive management on productive sites for four reasons. First, the best sites produce a greater quantity of better quality products than do poorer sites. Second, good sites produce large trees in less time, thus rotation lengths are shorter and interest charges on investments are less. Third, higher valued tree species often require better site quality. Finally, good sites are more likely to respond to intensive management practices such as fertilization, thinning, weeding, or crop tree release (Carmean, 1975).

Ability to determine site quality for a number of alternative tree species will allow foresters to select those tree species best suited for each site. In Canada, with a large forest land base and limited finances, there is a need to identify the site quality of lands closer to the mills. There also is a need to identify the tree species which are best suited for each site. In addition, there is a need to determine what level of management intensity is economically feasible on these sites. By selecting proper tree species based on site suitability, foresters hope to produce more wood in shorter periods of time on those lands more readily accessible to markets.

White spruce was one of the major components of the original old growth forests. Therefore, it is not surprising that white spruce is one of the major commercial tree species in Ontario today. White spruce can yield high quality lumber, and the pulp from white spruce has long fibers which are essential to the production of high quality paper. In Ontario, the trend has been for increased planting after harvesting. But with this increased tree planting, foresters have encountered more variable site characteristics, thus there is a need to determine which among several alternative tree species are best suited for a particular site and are capable of producing the greatest quantities of commercially valuable forest products.

The objectives for this study were:

1. To determine the relationships of soil and topographic features to site index for young white spruce plantations in the North Central Region of Ontario.

2. To evaluate the variable selection methods used by Schmidt (1986).

3. To develop site index prediction tables which could be easily used by field personnel based on easily measurable soil features.

LITERATURE REVIEW

FOREST SITE QUALITY

Spurr and Barnes (1980) define site as "both the position in space and the associated environment." The Society of American Foresters (1983) defined site as "an area considered in terms of the environment particularly as this determines the type and quality of the vegetation the area can carry."

Forest site quality is a measure of the ability of forest land to grow trees (Carmean, 1975). The measure is the sum total of all the factors affecting the capacity of the site to grow trees (Spurr and Barnes, 1980). The factors that affect the ability of the site to grow trees can be broken down into four groups: genetic, climatic, biotic, and edaphic. These particular site factors and how they relate to white spruce growth will be discussed in greater detail later in this paper.

HISTORY OF FOREST SITE QUALITY EVALUATION

Site Quality Evaluation in Europe

Site quality evaluation is not a new concept. It can be traced back to the days of the Romans when Cato (234-139 B.C.) classified land based on its ability to grow grapes for wine (Tesch, 1981). Like many other fields, the field of forest site quality evaluation started in Europe, and was at first subjective. Observations indicated a wide range in the ability of the land to grow trees. A wide range of classification systems were recommended to explain variations in tree growth. Classification systems included a subjective ranking from 0 to 100 from the least to the most productive lands (Cotta, 1804). A subjective delineation of good, medium, and poor site classes based on soils was proposed by

Hartig (1795). Plant communities also were used to indicate different levels of forest productivity (Blomqvist, 1872).

Of all the systems proposed in Europe, volume became the most widely used. The strip method based on the yield of stands was made popular by Baur (1877) in Germany. The strip method consisted of measuring volume growth on a large number of even-aged, pure, uniform stands on a wide range of sites, and over a range of ages. Then the data were plotted and curves drawn free hand through the highest and the lowest volume measurements. The range of volume growth depicted by these curves was then divided into an arbitrarily chosen number of site classes.

Many felt that this method had the following problems:

1. the site classes were arbitrary and may not represent actual differences in site quality;
2. the curves were based solely on the highest and the lowest observed volume measurements;
3. and the curves were only applicable to normally stocked stands (Cajander, 1926).

Problems with the strip method led Baur (1877) to propose using the mean height of the stand as a measure of site quality, but he still analyzed the data using the same free hand method of developing the curves. Unfortunately, these curves were subject to the same problems as the volume curves. Also the mean height of the stand was dependent on the locality, stocking and thinning practices; and these curves were inadequate for uneven-aged stands.

Huber (1824) developed the index method which used the height of the dominant portion of the stand as a measure of site quality. Many believed that the dominant trees in the stand remained in the dominant crown position regardless of the thinning practice and locality. Dominant height of a stand was considered independent of the density of the stand. Also stand volume in pure, fully stocked even-aged stands was closely related to the height of the dominant trees because height is one of the major contributers to stand volume.

Site Quality Evaluation in North America

The history of forest site quality in North America has been discussed by many including Coile (1952), Mader (1963), McLintock and Bickford (1957), Jones (1969), Carmean (1975), Pritchett and Fisher (1987).

In North America the need for a standard method of measuring site quality led to the formation of a committee by the Society of American Foresters (SAF) in 1920. Three groups of researchers and foresters had divided opinion over which method provided the best means for classifying site quality of forests. The three schools of thought reflected the methods currently popular in Europe and consisted of (a) those who proposed height growth, (b) those who proposed volume, and (c) those who proposed "site types" based on plant communities as the ultimate measure of site quality (Mader, 1963).

Most agreed that volume was the ultimate measure of the productive capacity of the land, but the lack of available information and the difficulty of obtaining yield data for natural stands limited its application in North America. Many believed that volume was too dependent on insect and disease damage, and stand density for wide spread application (Watson, 1917). Advocates of height felt that it was simple to use, easy to understand, easy to obtain, flexible, and provided comparisons between species (Frothingham, 1918, 1921a, 1921b).

In 1923 the SAF committee concluded that volume was the most accurate measure of site quality, and recommended the construction of normal yield tables. However, the committee went on to state "that it did not recommend the adoption of any one method but was inclined to look with favor on the use of height-growth of dominant stands" (Sparhawk et al., 1923). The failure of the committee to recommend a standard site quality measure and the ease of use of site index based on height growth of the dominant trees in a stand has led to this measure being the most widely accepted and most commonly used measure of site quality in North America today.

DIRECT ESTIMATION OF SITE QUALITY

Site Index Curves

Site index based on height growth can be estimated either directly through the measurement of trees on the site, or indirectly through the relationship of site index to various site factors. Site index based on height growth has been defined by the SAF as "a particular measure of site class based on the height of the dominant trees in a stand at an arbitrarily chosen age" (S.A.F., 1983). The base age for most species in the United States (U.S.) and Canada has been 50 years, except in the southern U.S. where the base age for pine plantations is usually 25 years. On the west coast of the U.S. and Canada the base age is often 100 years for old growth conifer species (Carmean et al., 1989).

Site index can be used to estimate site quality if suitable site trees are present for estimating site index, and if accurate site index curves have been developed for the area and species in question (Lenthall, 1986). Early site index curves were based on total height and total age data from yield plots that were averaged to create a guiding curve. This curve was then used to create a set of curves for a range of site index levels. Graphical methods or least squares regression methods were used to construct a set of anamorphic curves that had the same shape regardless of site index level. These "harmonized" site index curves were often inaccurate because they were sometimes derived from data that did not adequately represent the height-growth patterns of the species on varying levels of site index. Also the harmonized curves were unable to show changes in height-growth patterns for different site index levels because the guiding curves were based on averaged data. In an effort to develop more accurate and useful curves, foresters have developed "polymorphic" site index curves. These newer curves are based on data from stem analysis, and individual curves are derived for each level of site index using nonlinear regression models (Carmean et al., 1989).

Care must be taken when selecting trees for estimating site index. Reliable estimates of site index can be obtained if the selected trees are free-growing, uninjured, dominants and codominants, such as occur in well stocked even-aged stands. Uninjured dominant and codominant trees should be used for the estimation of site index because trees of these crown classes and vitality are less subject to environmental factors such as suppression, wind and insect damage, and disease.

Thrower (1986) reviewed site index curves for white spruce plantations in Canada and the Lake States. Site index curves for white spruce plantations at the Petawawa Forest Experiment Station were developed by Stiell and Berry (1967) using older curve formulation techniques. These curves were later revised using more flexible polymorphic growth models by Stiell and Berry (1973), and metric equivalants were also developed (Berry, 1978). White spruce site index curves have been developed for southern Quebec (Bolghari, 1977; Bolghari and Bertrand 1984). The most recent site index curves for white spruce based on both total height-age and breast-height age were developed by Thrower (1986). Unfortunately no site index curves exist for white spruce plantations in the Lakes States (Nienstaedt, 1982).

Thrower (1986) developed site index curves based on both total age and on breast height age. He found that site index curves based on breast height were more precise in predicting site index for white spruce. Thrower showed that increased precision for breast-height age curves was due to the elimination of erratic juvenile height growth before trees reach breast height. This is supported by other researchers who have observed considerable variation in the amount of time it takes white spruce to reach breast height. Stiell and Berry (1973) reported that white spruce planted at Petawawa, Ontario, took between 6 and 12 years to reach breast height. Rudolf (1950) reported that many different species took between 5 and 15 years to reach breast height. Some researchers have suggested that the time needed to reach breast height for natural white spruce is related to the site index (Carmean and Hahn, 1981).

Growth Intercepts

Growth intercepts are another direct method of estimating site index that has most commonly been used with coniferous species that have easily recognized nodes marking annual height growth. The difference between the site index curve method and the growth intercept method of estimating site quality is the period of height growth used for estimating site quality. Site index curves use tree height growth to a specified base age (usually 50 years) for developing height-growth curves. In contrast, the growth intercept method only uses a selected period of early height growth rather than longterm height growth portrayed by site index curves (Carmean, 1975). The traditional period of height growth used with growth intercepts is the first five years of height growth after the tree reaches breast height (1.3 m); this period of height growth has been traditionally identified by measuring the total length of the first five internodes after trees reach breast height (Figure 1).

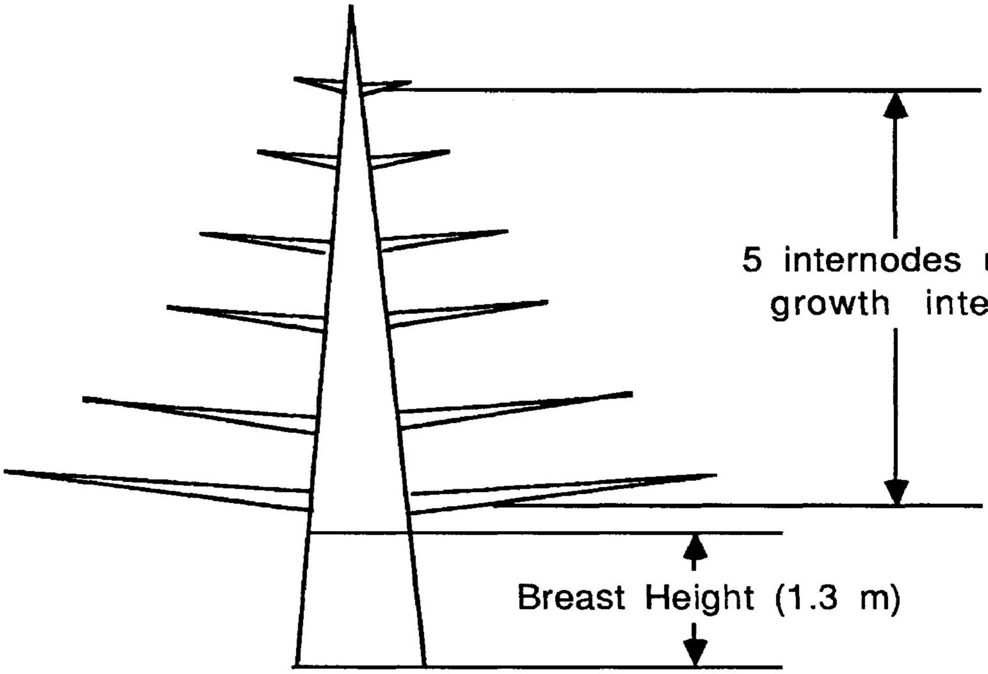

Figure 1. The growth intercept method of estimating site quality is commonly based on the total length of the first five internodes after dominant trees have reached breast height (1.3 m).

The growth intercept method has several advantages (Alban, 1972):

1. Total height is not measured, thus errors associated with measuring total height are avoided;

2. Measuring internodes above breast height eliminates the early slow and erratic juvenile height growth of many species;

3. Growth intercepts are useful in young stands that have not yet reached ages where conventional site index curves can be used;

4. Growth intercepts do not require the determination of age, thus eliminating errors associated with counting annual rings (Carmean, 1975; Wakeley and Marrero, 1958).

There also are disadvantages to using growth intercepts: (a) growth intercepts are only useful on species that exhibit a strong relationship between juvenile height growth and the height growth that occurs in later years; (b) the growth intercept method can only be used on species with easily recognizable nodes; and (c) the growth intercept method should only be used in young plantations where site index is estimated as dominant height at perhaps 15 or 25 years. Height growth observed from early internodes can be safely projected to 15 or 25 years (index age), but the projection to older ages involves estimation errors that may be associated with later polymorphic height-growth patterns.

Thrower (1986, 1987) developed growth intercepts for white spruce plantations in North Central Ontario based on detailed studies to determine the best starting height growth and the best number of internodes. He observed that precision for growth intercept measurements increased until a starting height of 2.0 m, thus indicating that for this region erratic early height growth continued to a height of 2.0 m rather than to the conventional breast height of 1.3 m. Thrower found little difference in precision of estimating $BHSI_{15}$ when using three, four, or five internodes after the 2.0 m starting point (Figure 2).

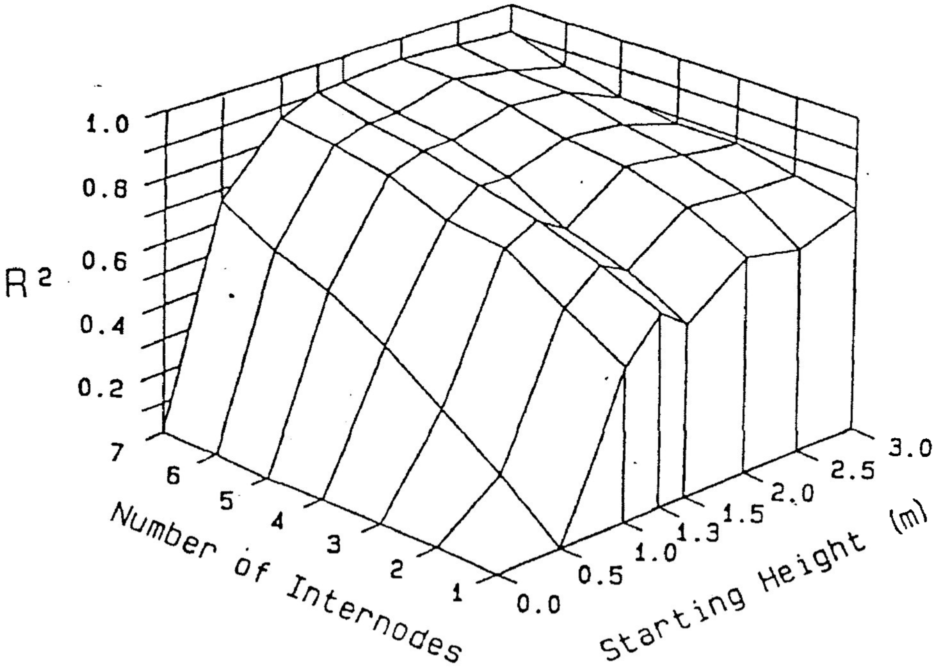

Figure 2. Three dimensional graph showing the precision for estimating site index ($BHSI_{15}$) of white spruce using different starting heights and different numbers of internodes (Thrower, 1987).

Species Comparisons

Many well-stocked and even-aged stands may have suitable trees for the measurement of site index, but these stands may not contain the tree species for which site index estimates are desired. For these stands, site index can be measured on the tree species that are present; then species comparison graphs or equations can be used to estimate site index for the desired tree species. Species comparisons are constructed by measuring site index on several tree species growing together on the same plot. This is done for a region across a wide range of site quality and soil conditions. These paired observations are then regressed against one another to develop regression equations that can be solved using both backward and forward procedures. These equations can be directly used for computing site index, or the equations can be used to construct a graph where relations are plotted for all species. A site index value measured for one tree species is located on the line for that species, then the corresponding site index estimate for the desired tree species can be determined based on its relationship to this species line.

Carmean (1975) pointed out the potential sources of inaccuracies using the species comparison technique. These may include use of inaccurate older harmonized site index curves, or the inappropriate use of regression techniques. Inaccuracies also may occur when short-lived species are compared to long lived species.

INDIRECT MEASURES OF SITE QUALITY

Many areas lack suitable trees for direct measurement of site index. Such areas include cutovers, burned areas, stands that have been repeatedly highgraded, very young stands, unevenaged stands and agricultural and other non-forested lands. For such areas indirect measures of site index are particularly useful. Indirect estimation of site index involves determining the relationships between site index and measurable soil, topographic, climatic, or vegetal characteristics of the site. When such consistent relationships have been identified, site index for various tree species can be estimated even when suitable site index trees are not available for measurement.

Plant Indicators

One characteristic that has been related to site index has been the presence, abundance, constancy of occurrence, and size of understory plants (Carmean, 1975). Most plant indicator studies first divide a region into areas of similar climate, topography, soils, and plant communities. These subdivisions are further divided into areas of similar site quality that can be recognized using certain plants termed plant indicators.

The classic use of plant communities to classify site quality based on productivity was done by Cajander (1926) in Finland. The system which Cajander developed divided the country into five vegetal classes based on plant communities. These vegetal classes were then divided into site types using species of understory plants (plant indicators) that consistently were found under a narrow range of site conditions. Finally these site types were classified based on their productivity.

Ecosystem Classification

Hills (1952, 1960) developed a system in which Ontario was classified based on a holistic approach. This system recognized site regions based on similarities in geology, plant communities, soil profiles, climate, moisture, animals, and the effects of man. These regions were identified as a basis for forest management, but site quality was not a recognized goal, therefore, Hill's regions only indirectly reflected site quality.

A Forest Ecological Classification (FEC) system was recently developed for the North Central and Northwestern Regions of Ontario (Sims et al., 1988, 1990). This system uses both soil characteristics and plant communities as a basis for developing a classification system to be used for forest management. Presently this system divides soils into a shallow to bedrock (less than 100 cm) group, and a deep to bedrock or boulder pavement (deeper than 100 cm) group. The deeper sites are then subdivided into 13 groups based on moisture, texture, depth of organic layers, presence of gleying, and mottles. The shallow sites are divided into nine soil groups based on texture and the thickness of the mineral or organic horizons. Vegetation is divided into 38 types based on the overstory species, i.e. 11 hardwood types, 9 mixedwood types, and 18 softwood types

(Sims et al., 1990). Efforts are now being made to relate these FEC soil types to site quality for various forest tree species.

Soil Surveys

Soil surveys have been made in the United States and Canada since the turn of the century. Traditional soil surveys involve digging soil pits and describing similar soil units termed pedons based on pedogenic history, soil texture, consistency, structure, pH, colour, and the presence and absence of soil boundaries. Soil pedons are further divided by topography, moisture regime, and stone content. These soil units are in theory homogeneous throughout and are termed polypedons. Each described and documented polypedon is given a name based on the location in which it was originally described, and is then classified using a soil taxonomic system. Soil surveys for a particular area, such as a county, will describe and map the soil series of the area and, furthermore, will provide information relating the characteristics of the soil series to various land uses such as agriculture, forestry, recreation, and engineering. For forestry uses, tables are usually included showing average site index for the various soil series or woodland suitability groups.

Soil surveys in the United States usually assign each soil series to a woodland suitability group designated by a 2 digit code. The first digit designates a site index class (usually low, medium, and high), the second digit is a letter designating the major limiting soil characteristics, i.e S indicates sandy soil, or a W indicates wetness. Each woodland suitability group has associated tables indicating relative severity for seedling mortality, operability, erosion hazard, and weed competition. More recently soil surveyors have included actual average site index for tree species most commonly found with the soil series.

Many studies show that soil series often have wide site index ranges, thus for many areas the range of site index is too wide for dependable forestry use. Reasons for such wide site index variation are that many soil series have a wide range of soil and topography features that are important for tree growth. As a result soil surveys based on such broad and variable soil series cannot accurately classify units of land of varying site quality (Carmean, 1961; Pawluk and Arneman, 1961; Farnsworth and Leaf, 1963; Shetron, 1969, 1972; Watt and Newhouse, 1973). There are several reasons for the inability of many soil surveys to classify site index based on soil series, and perhaps one of the most important is the lack of research information showing relations between site index and specific soil and topographic conditions.

Soil surveys have been conducted for many years on agricultural lands. Hilly and mountainous lands and poorer soils were often left for forest production because such lands were not suited for agriculture; thus agricultural soil surveyors only looked at forested land superficially or ignored these lands. As a result forest researchers have found that soil series defined for agricultural lands are often too broad and cover too large a range of soil and topographic conditions to represent forest productivity adequately. For example, Kittredge (1938) studied the relationship of site index of aspen (Populus tremuloides Michx.) to 22 soil profile groups in Minnesota and Wisconsin. A significant relationship was observed between the soil profile groups and site index ($R^2 = 0.795$), but the mean site indices of these soil profile groups were not significantly different from one another. Carmean (1975) cites other possible deficiencies such as biased sampling based on "model" soil profiles, and the lack of statistical analysis techniques to establish soil-site index relationships.

Soil-Site Studies

Soil-site studies relate the measurable features of soil, topography, and climate to the productivity of the site usually expressed as site index. This is commonly accomplished by establishing a large number of temporary site plots that represent the range of soils, topography, climate, and site quality of the study area. On each plot the soils and topography are described and an estimate of site index is obtained usually by stem analysis methods. Then statistical analyses (most commonly multiple regression) are used to define the relationships between site index and measured features of soil, topography, and climate (Carmean, 1975; Pritchett and Fisher, 1987).

Soil-site studies relate site index to specific soil and topographic features rather than to soil taxonomic units (i.e. soil series); thus research results define relationships often missed in soil surveys. The results of many soil-site studies can assist soil surveyors in refining or redefining soil taxonomic units that more accurately define site quality. For example, soil-site relationships for a given species and region can be used to subdivide soil series further into phases that more accurately define site quality.

History of Soil-Site Studies in North America

Soil-site studies were first made in Europe. In the United States these studies were first conducted by soil scientists, but foresters became interested in these relationships during the late 1920's. One of the first soil-site studies in North America was conducted by Haig (1929) who studied site quality on 95 plots established in 26 red pine (Pinus resinosa Ait.) plantations in Connecticut. He observed that site index was closely related to the silt plus clay content of the A horizon; the single most significant variable in his study was the total nitrogen content of the A horizon.

Another early soil-site study investigated soil characteristics and forest growth in northern Michigan and found that the rate of forest growth on a given soil type was related to the degree of stoniness of the soil (Westveld, 1933). This and other early soil-site studies concentrated on physical soil features. Eventually researchers began to explore the relationships between measures of site quality and chemical soil features as well as topography, and climatic features.

Soil chemical factors have received less attention in soil-site work because of difficulties in using chemical features in designing field methods of site classification. Also soil physical factors such as texture, stone content, and horizon depths are easily recognized in the field and are, therefore, more useful for practical field methods of site quality estimation. In many cases chemical factors are closely related to physical soil features. For example, Stoeckeler (1960) found that the content of calcium (Ca) and magnesium (Mg) was correlated with the silt plus clay content of the soil. Ralston (1964) stated that soil moisture variables in soil-site studies usually express the joint effects of soil moisture and soil nutrients. Ralston (1964) also cites a possible lack of sensitivity in chemical soil tests, thus these tests do not accurately indicate differences in nutrient uptake. Soil chemical variables often are expressed as total nitrogen, potassium, phosphorus, and cation exchange capacity. Thus total content of these variables alone may not accurately express available nutrient levels, or the level of available nutrients that may be limiting for tree growth.

Despite the neglect of soil chemical variables some researchers have found relationships between growth rates and nutrient levels in forest soils. As previously mentioned Haig (1929) found that the total nitrogen content of the A horizon was the variable most closely related to site index for red pine plantations in Connecticut. Voigt et al. (1957) also found a correlation between the productivity of trembling aspen in northern Minnesota and levels of calcium, potassium, and nitrogen.

Wilde et al. (1965) studied a number of commercial forest tree species in nurseries in Minnnesota and Wisconsin and presented minimum soil fertility standards for planting different commercial tree species.

However, this study was conducted on tree seedlings in the nursery and may not reflect nutrient needs of these species after planting and after they reach larger tree sizes.

Hills (1952) separated Ontario into site regions based partially on similar climate and geologic conditions. The trend in most soil-site studies has been to select study areas that are in a region of relatively similar climate thus eliminating the effects that large changes in climate might have on site quality. Despite the trend of selecting study areas of similar regional climate some studies have found that local changes in elevation, topography, wind patterns, cold air drainage, or transitional zones in climate are related to site quality. McClurkin (1953) found that the amount of rainfall from January to June was the most important variable affecting longleaf pine (Pinus palustris Mill.) growth rate in a region extending from Mississippi to Texas. Carmean (1954) found that site index of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) was related to annual precipitation and elevation.

The topography of a site can be related to the amount of soil moisture available for tree growth. The reason is that topography is related to local variations in microclimate, cold air drainage, and the amount of solar radiation and temperature. Topography also can be related to soil development. For example, shallow and stony soils usually are found on upper slopes or ridges while deeper, less stony soils frequently occur on lower slopes. Features of topography are often expressed as slope position, slope steepness, elevation, aspect or the direction in which the slope faces, and the shape of the slope. The best sites usually are found on north and east facing gentle slopes, and on lower slope positions (Graney, 1979). Relationships between site quality and topography differ depending upon area and location. Hills (1960) observed that warmer southern aspects favour growth in far northern latitudes, but the opposite is true in southern latitudes. In low lying areas where soil moisture is near the soil surface minor changes in elevation can have drastic effects on site quality (Ralston, 1964).

Soil-site studies have become quite diverse using soil profile features, physical and chemical variables, topography, climate, and plant indicator species. Reviews on soil-site studies have been made by Coile (1948, 1952), Doolittle (1963), Rennie (1963), Ralston (1964), Shrivastava and Ulrich (1977), Carmean (1975, 1982), and Hågglund (1981).

SITE FACTORS RELATED TO WHITE SPRUCE SITE QUALITY

Climate

White spruce has a very wide range covering a broad spectrum of climatic conditions (Fowells, 1965). Temperatures can vary from extremes of -70° C in Alaska and the Yukon to 44° C in the southern portion of Michigan, Minnesota, and Maine. Length of growing season can vary from a 160 day growing season in Maine to the northern portion of the white spruce range having only a 60-day growing season (Fowells, 1965). Climatic features such as frost and moisture have been found to be related to height growth and survival of white spruce. Leaf and Keller (1956) found that the amount of overhead shading is related to height growth. Figure 3 shows that height of 16-year old white spruce plantations in the Argonne Forest of Wisconsin is greatest when trembling aspen density is less than 30 percent. In addition to light, Figure 3 also may indicate indirect relationships between height growth and cooler soil temperatures, increased soil moisture, and possible protection from late spring frosts. However, this Wisconsin study had only 2 stands where aspen was absent; thus further study is needed before we can recommend using aspen as nurse stands for the management of white spruce.

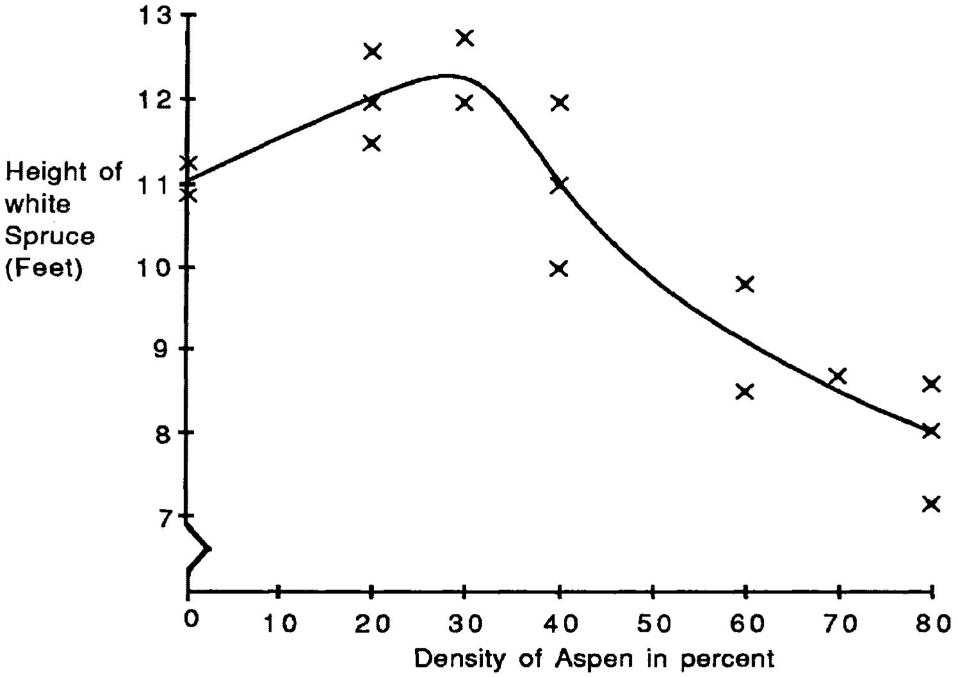

Figure 3.Total height of 16-year-old white spruce plantations in the Argonne Forest in relation to stand density of trembling aspen (Wilde et al., 1965).

Topography

Topography is significantly related to site index of white spruce in Michigan and Wisconsin (Russell, 1963). Russell classified land into three classes: (a) level land (0-2% slopes), (b) gently rolling (3-14% slopes), and (c) undulating (15% + slopes). Results showed that the last five years of height growth was best on gently rolling land (2.49 m), was intermediate on undulating land (2.18 m), but was poorest on flat land (1.93 m). The differences between gently rolling topography and undulating topography was significant at a 0.05 level and at a 0.01 level for flat and gently rolling land; there was no significant difference between flat and undulating topography. Russell (1963) attributed the slow white spruce growth on flat topography to frequent frost damage, and to higher water tables.

Olson and Perala (1981) observed that white spruce seedlings grown in depressions had reduced height growth; they attributed this poorer growth to excessive moisture conditions, or to cold air that tends to accumulate in depressions causing frost damage.

Physical Soil Factors

Soil Moisture

Soil moisture is often considered to be the single most important soil factor affecting growth of southern pines (Gaines, 1949). The more soil moisture available for tree growth the better the site quality up to a point where excessive soil moisture results in poor aeration. Soil moisture content is the result of many soil, climate, and vegetal characteristics including precipitation, relative humidity, the presence of vegetation affecting the amount of soil moisture, and the amount of evapotranspiration. Overland flow and seepage affects losses or gains of soil moisture. Topography, soil texture, soil structure, and organic matter content are related to the rate of water infiltration and the moisture holding capacity of water held in the soil.

The first soil-site study for white spruce in the United States was done by Kenety (1917) who observed that a water table near the surface of the soil was related to white spruce presence on sites that were sandier and coarser sites than normal. Kenety concluded that the available moisture in the soil was the most effective predictor of site productivity. Survival and growth of white spruce transplants in Connecticut were related to the effects of nitrogen, soil temperature, and soil moisture (Stephens, 1965); by the second growing season transplants on moist sites were significantly taller than those on dry sites. Pierpoint (1962) described the soil/ecological relationships of the Kirkwood Management Unit of Ontario and found that optimum sites for white spruce were those with fresh to moist moisture regimes. Pierpoint also stated that sites with moisture regimes of dry or wet showed decreased height growth of white spruce. Wilde et al. (1965) concluded that the lack of available moisture was the main cause for low site quality of white spruce in Wisconsin. In general, white spruce grows best on sites that are fresh to moist, but will occupy dry and wet sites if the soils are fertile. However most authors agree that very dry and very wet sites should be avoided when establishing white spruce plantations (Pierpoint, 1962; Nienstaedt, 1982; Stiell, 1976).

Some studies have observed relationships between soil moisture and bud morphogenesis. In late summer white spruce develops buds for the next years growth, termed bud morphogenesis. Then in the following year these buds open and shoot elongation continues until late July, (Owens et al., 1977). Some authors believe the environmental conditions at the time of bud morphogenesis predetermine shoot growth of the following year. For example, Clements (1970) and Pollard and Logan (1977) found that the availability of soil moisture at the time of bud morphogenesis was more closely related to height growth than soil moisture during the period of shoot elongation.

Soil Texture

Perhaps the single most commonly used variable in soil-site studies other than soil depth is soil texture. As previously stated soil texture is closely related to other soil characteristics such as soil moisture, nutrient relations, soil structure, and soil aeration. Many studies have reported relationships between white spruce growth and soil texture. For example, Russell (1963) reported that white spruce had optimum growth on soils with a silt plus clay content of between 20 and 60 percent, particularly soils having moisture-retaining bands of silt plus clay.

Wilde et al. (1965) found that poor site quality white spruce plantations in Wisconsin, were associated with soils that had a silt plus clay content of less than 15 percent and less than 3 percent organic matter. Conclusions were that this association between coarse soil texture and poor sites was caused by the lack of available soil moisture for coarse sandy soils. Olson and Perala (1981) compared 4-year-height growth of planted white spruce to soil texture in 12 plantations in Minnesota, and found that growth increased as silt plus clay increased. They also found that growth decreased with clay textured soils probably because of poorer aeration and soil drainage (Table 1). Early height growth of such young plantations have erratic growth patterns below breast height (Thrower, 1986), thus Olson and Perala's results may be questionable.

Table 1. Soil texture classes related to 4-year-old height growth in 12 white spruce plantations in Northern Minnesota (Olson and Perala, 1981).

Soil Texture Class	Total Height (cm)
Sands	42
Loamy Sands	43
Sandy Loams	46
Loams	50
Sandy Clay Loams	52
Clay Loams	71
Clay	35

Troung dinh Phu (1975) found that soil texture was related to early growth and survival even though the relations were quite variable. On medium to heavy textured soil of fluvial or till origin, white spruce growth was vigorous, and survival was better than on sandy soils of fluvial, moraine and outwash origin.

Chemical Soil Factors

Soil pH

Soil pH can have a significant effect on soil characteristics, soil organisms, and vegetation growing on and within the soil. Soil pH affects the availability of many soil nutrients, the ability of many plants to absorb nutrients, and the ability of soil microorgamisms to survive and reproduce. Soil pH can affect the ability of plants to absorb nutrients in two ways. First, at very low pH levels, there may be toxic quantities of aluminum and hydrogen ions. Secondly, soil pH affects plant nutrient absorbtion because of effects on the availability of soil nutrients (Brady, 1984). In soil-site studies soil pH relations can be expressed for each horizon or as an average overall soil pH, as reserve acidity (the buffering capacity of the soil), or as a depth measurement expressed as a depth to where soils exhibit a reaction to HCl, (e.g. depth to carbonates).

Stoeckeler (1938) contrasted two natural white spruce stands in Manitoba, one on a calcareous sand, and another on an acid moraine. Little can be drawn from this study except that white spruce can grow on soils with a wide range of soil pH. The study does show that growth on calcareous sites is slower than on more acid soils. This relationship of white spruce to soil pH was also observed in Wisconsin (Rawinski et al., 1980) where soil pH was observed to be negatively related to height growth of white spruce seedlings (Fig. 4). In this study seedlings had maximum height growth on soils having a range of pH between 5.1 to 5.5. Wilde (1966) recommended that the optimum range of soil pH for white spruce in Wisconsin is between 4.7 and 6.5. Harding et al. (1984) using discriminant analysis, found that the depth to carbonates was a useful indicator of white spruce growth in Minnesota.

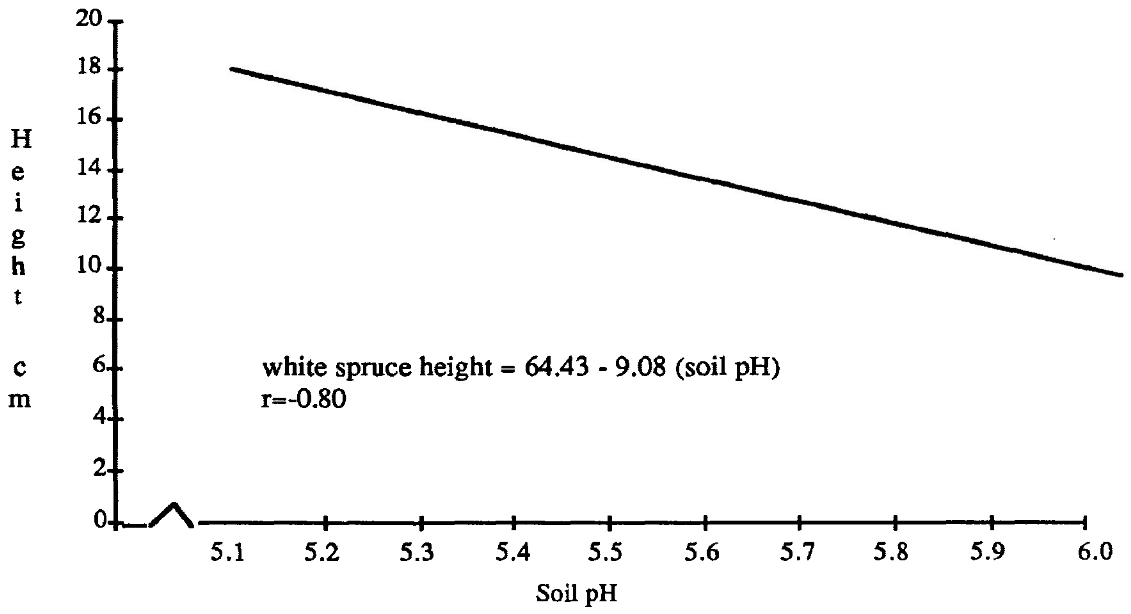

Figure 4. Relationship between height growth of white spruce seedlings and soil pH in northern Wisconsin (Rawinski _et al._, 1980).

A possible interaction exists between soil pH and the genetics of white spruce. White spruce limestone ecotypes have been observed in the laboratory (Farrar and Nicholoson, 1967). Also Teich and Holst (1974) observed that when limestone and non-limestone provenances were planted on calcareous soils the limestone provenances had 10% better height growth. However, when the two provenances where planted on soils derived from granite the "granite" provenances had 9% better height growth then did the limestone provenances.

Soil Nutrients

Wilde _et al._ (1965) found no significant relations between white spruce height growth and the amount of nutrients on medium to good sites. However, relationships were observed with the amount of mineral and organic colloids and with cation exchange capacity (CEC) of these soils. Wilde et al. (1965) summarized this relationship as follows:

$$H = 3.9 + 0.57\ (CEC)$$

$$r = 0.795$$

$$S.E = 2.15 \text{ inches.}$$

where H = height growth in inches

CEC = cation exchange capacity in meq/100 g of soil

Wilde et al. (1965) also observed that white spruce had rapid early height growth on soils having a high CEC and thus seedlings were able to overcome volunteer competition. In contrast, white spruce seedlings had slower early height growth on soils having moderate CEC levels, thus were not able to overcome the competition. Wilde (1966) used these observations as a basis for recommending minimum soil fertility levels for planting jack pine (Pinus banksiana Lamb.), red pine, white pine (Pinus strobus L.), and white spruce in Wisconsin and I have converted these minimum soil fertility standards to metric equivalents (Table 2).

Table 2. Minimum soil fertility standards for planting conifers in Wisconsin (all nutrients are given in elemental terms) (Wilde, 1966).

Tree species	Approx. Site index	Approx. optimum range of pH*	Silt and clay %	Organic matter %	Exch. capacity me/100g	Tot N %	Avail. P_2O_5	Avail. K_2O	Exch. Ca	Exch. Mg
							lbs/a		me/100g	
jack pine	53	4.7-6.2	7.0	1.0	2.5	0.040	30	60	0.50	0.15
red pine	57	4.8-6.2	9.0	1.3	3.5	0.050	60	80	0.80	0.20
white pine	60	4.7-6.5	15.0	2.5	5.7	0.100	70	110	1.50	0.50
white spruce	52	4.7-6.0	35.0	3.5	12.0	0.120	90	150	3.00	0.70

* Insufficient data above pH 6.5

Wilde (1970) reevaluated his earlier data and published a new site index prediction equation for white spruce plantations in Wisconsin. This equation relied more heavily on the concentration of available phosphorous and potassium in oxide form in the soil:

$$S = 1.8\ (8.1 + 0.2\ F + 2.3\ H + 0.03\ P_2O_5 + 0.01\ K_2O)$$

where:
S = site index (average height of stand at 50 years)
F = percent fine soil particles
H = percent organic matter
P_2O_5 = available phosphorous, (lbs/acre)
K_2O = available potassium, (lbs/acre)

Truong dinh Phu (1975) studied growth of white spruce plantations in Grand'Mere, Quebec, using basal area and total volume of white spruce before and after fertilization. Fertilizer treatments consisted of applications of magnesium (Mg) at two levels, potassium (K) at three levels, and nitrogen (N) at three levels of concentration. He observed that K resulted in highly significant (0.10 level) basal area increases of 11% compared to the unfertilized control; total volume increased 21.5% and 39.9% compared to the control for the two greater levels of K. Troung dinh Phu also found that the N and Mg appplications and all interactions failed to produce a significant growth response of white spruce after 5 and 10 years. He concluded that K_2SO_4 applications between 260 to 310 kg/ha produced the optimum growth response in white spruce on sandy soils of fluvial-moraine and outwash orgin.

Harding *et al*. (1984) used multivariate (discriminant) analysis to relate soil and topographic features to site quality in white spruce plantations in northern Minnesota. Harding used basal area (BA), site index, and mean annual increment (MAI) to classify 56 white spruce plots into three productivity groups: (a) Group 1 contained plots with both high potential productivity (SI) and high observed productivity (MAI and BA); (b) Group 2 contained those plots with high potential productivity, but only moderately observed productivity; and (c) Group 3 contained those plots which had both low potential productivity and low observed productivity. Two discriminant functions were developed from 50 of the plots with 6 plots held in reserve for independent testing. Seven soil and topographic variables were identified as useful discriminators of site quality and were selected for the final functions; these seven final discriminators and their canonical coefficients in both standardized and non-standardized form are listed in Table 3. These functions correctly classified 76% of the 50 plots; groups 1, 2,and 3 were correctly classified 69%, 80%, and 79%, respectively. Table 3 illustrates that in function 1 nutrient coordinates and the natural log of the amount of phosphorus were the best discriminators of white spruce site quality.

Table 3. Canonical coefficients of seven discriminators associated with three white spruce growth response groups in Northern Minnesota (Harding *et al.*, 1984).

	Function 1		Function 2	
Variable	Unstandardized	Standardized	Unstandardized	Standardized
Slope (%)	-0.14	-0.77	0.03	0.14
Nutrient coordinates	1.98	0.45	-1.33	-0.30
Depth to free carbonates	-0.32	-0.38	-0.41	-0.50
Depth to clay films	-0.11	-0.13	0.51	0.58
Natural logarithm % sand 100 cm	0.84	0.44	0.54	0.28
Natural logarithm (P) 100 cm	1.17	0.65	-0.16	-0.09
Depth to B horizon	0.01	0.21	0.05	0.88
(Constant)	-13.41		1.33	

NON-SITE FACTORS THAT AFFECT SITE INDEX OF WHITE SPRUCE

Site index is a measure of forest land productivity and integrates the combined effects of soil, topography, and climate. However, accuracy of site index estimates can be affected by several non-site factors that may affect tree height growth such as stand density, genetic variation, competing vegetation, disease, and insect damage (Carmean, 1975; Pritchett and Fisher, 1987).

Stand Density

Height growth for many species is considered to be independent of stand density except at the extremes of stocking (Jones, 1969; Oliver, 1967; Lloyd and Jones, 1983; Lanner, 1985). Height growth in very open stands may not be as great as in fully stocked stands. Conversely, trees in heavily over stocked stands may not express dominance; therefore, these stagnated trees may have slower height growth than trees in normally stocked stands. For example, overstocked stands of ponderosa pine (_Pinus ponderosa_ Laws) and lodgepole pine (_Pinus contorta_ Dougl.) have slower height growth, thus Lynch (1958) and Alexander _et al_. (1967) developed site index curves for different levels of stocking. There is little evidence to suggest white spruce growth is significantly affected by stand density because white spruce rarely occurs in dense, overstocked stands. Braathe (1952) reported that the mean height of Norway spruce (_Picea abies_ (L) Karst.) stands was not affected by different levels of stocking. Schaerer (1978) reported that in spacing trials in Thunder Bay, Ontario, white spruce height growth at 1.8 m x 1.8 m, 2.6 m x 2.6 m, 3.6 m x 3.6 m was not significantly related to stocking at a 90% level of confidence. These studies support the assumption that height growth of dominant trees in fully stocked white spruce plantations can be used to indicate site quality. For a more complete review of the affects of spacing on height refer to Evert (1971), and Lanner (1985).

Competition

The amount of competition may be one of the most important factors affecting the survival and early growth of white spruce. Competition can affect the growth of planted trees in two ways. Competing vegetation can limit tree growth by monopolizing available nutrients, light, moisture, and space; or competing vegetation can physically damage planted trees. Damage can occur through smothering by grasses and other herbaceous cover, or the upper stems can be damaged by whipping from codominant stems such as aspen (Stiell, 1976).

White spruce responds to release from competing vegetation. Dobbs (1976) and McMinn (1974) found that seedlings were taller, even though not statistically significant, on sites where competing vegetation was clipped. Three year results of an underplanting study in central Ontario indicated that site preparation was the key factor controlling the survival and height growth of planted white spruce (Wang and Horton, 1968).

Effect of competition on the early survival and growth of white spruce have been reported by Stiell (1976), Jarvis et al. (1966), Rowe (1962), and Rawinski et al. (1980). Light to moderate ground cover seem to benefit survival and early growth of white spruce. A light ground cover may provide protection from exposure, but heavy ground cover such as grasses may cause competition for available moisture (Stiell, 1976). Sutton (1975) found that the removal of competition from young white spruce transplants in southern Ontario resulted in highly significant increases in survival and height growth. The reason for increased height growth and survival was considered to be increased nutrient availability and not an increase in available moisture.

White spruce is considered a shade tolerant species that can survive 40 to 50 years of suppression and still respond to release (Fowells, 1965). Many have studied relations between light and height growth of white spruce. Logan (1969) grew white spruce seedlings under 13, 25, 45, and 100% full sunlight for nine years. He found that spruce seedlings were significantly smaller (30 and 31 cm, respectively) when grown under 13 and 25% full light, height growth was better (59 cm) under 45% light, and better still (63 cm) under full (100%) light. Logan concluded that white spruce achieved optimum height growth on sites having at least 45% full sunlight. Gustafson (1943) grew seedlings for 8 years under differing light conditions (25, 50, and 75% full light) and concluded that the spruce seedlings achieved their best height growth under 75% full sunlight. Results of both Logan (1969) and Gustafson (1943) are similar to those of Wilde et al. (1965) who found that 16-year-old white spruce had better height growth in areas having minimum density of trembling aspen (Figure 3).

Planting Stock and Planting Methods

The type and quality of planting stock, the time of planting, and the method of planting have all been studied in relation to the survival and early growth of white spruce seedlings. Differences in growth between container versus bare root, and transplants versus seedlings also have been well documented. Mullin (1968, 1970, 1973, 1980a, 1980b) observed that 2+2 white spruce transplants had better survival and height growth than did 2+0 white spruce seedlings. Wang and Horton (1968) compared the rate of height growth of 2+2, 3+0, and 2+0 white spruce transplants and seedlings. After 3 years the transplants had significantly better height growth than did the seedlings. Burdett et al. (1984) compared 2+2, 2+0, and 1+0 white spruce transplants, seedlings, and container stock, respectively. Two year results indicated that the 2+0 seedlings had the poorest height growth, and the 1+0 container stock had better height growth than all other stock types.

One possible reason for the superiority of transplants may be the size of the stock. Brace (1964) found that stock size was related to the rate of height growth after planting; stock that was less than 15 cm tall at the time of planting demonstrated poor growth even 9 years after planting. Dobbs (1976) sorted planting stock into small, medium, and large size classes to determine if stock size was related to stock performance. The third year results showed that the large size class of seedlings and transplants outperformed seedlings and transplants in the small size classes. Dobbs concluded that the variation in size within age classes was so great that age class alone was not adequate for determining stock quality, and recommended that stock be sorted into size classes before planting.

The type of container seems to have little effect on the rate of height growth. Alm (1983) grew seedlings (3+0) and transplants (2+2) from styroblock and paperpot containers, and tested for differences in growth 4 years after outplanting. The results showed that the 2+2 transplants outgrew the 3+0 seedlings, but there was no significant difference in height growth between the two container types. Waldron (1964) found little difference in height growth between 2+3 and 2+2 stock thus indicating that the number of years in a transplant bed has little affect on the height growth of outplanted white spruce. He noted slightly higher mortality for the 2+3 stock, but attributed this increased mortality to greater moisture stress due to increased evapotranspiration from the larger transplants.

The relationship between time of planting and height growth of young white spruce has been studied, but with conflicting results. Crossley (1956) planted 3+3 transplants once a week over the Ontario frost free season. Three years later, transplants from the June planting had the best rate of growth followed by those planted in July, but there were no significant growth differences between stock planted in any other month. However, Crossley concluded that planting during the period of active shoot elongation was detrimental to the growth and survival of planted white spruce. Mullin (1968) did not find any significant height growth differences between spring and fall planted 2+2 transplants.

The effects of planting method on white spruce growth are not clearly understood. Armit (1970) found no significant difference in height growth of stock planted using 5 different planting methods. Mullin (1966) studied height growth of white spruce seedlings and transplants planted using the wedge and "T" methods of planting; ten years after outplanting, white spruce planted using the wedge method had 10% better height growth, and 6% better survival than did spruce planted using the "T" method.

Genetics

Genetic mutation, selection,, migration, and isolation have resulted in genetically different populations of forest trees that grow differently and react differently to environmental conditions. These evolutionary processes have been very important in the survival and growth of commercial forest tree species. Yeatman (1976) stated "The proper genetic make-up of seed and plants used in reforestaton is a basic requirement to success in plantation management". In view of the role of genetics on plantation success, it becomes essential to know the origin of seedling stock. The first step toward the control of seed collection and genetic breeding stock is the delineation and use of seed zones.

Ontario Seed Zones

Originally, Ontario had natural forests made up of many wild genetic populations. Hills (1952) defined Site Regions of Ontario based on latitude, longitude, plant communities, plant succession, soil development, and climate. The Ontario Ministry of Natural Resources (OMNR) used these Site Regions as a basis for the delineation of seed zones (Skeates, 1979). The idea behind seed zones was to provide growing stock for the new forest from local native stock (Morgenstern, 1979). These seed zones were later modified to coincide with administrative districts of the OMNR.

The adequacy of these seed zones has not yet been determined, and provenance trials have not as yet been completed. However, early indications are that genetic variation exists within the seed zones, and this wide variation within seed zones may warrant further distinctions for larger stands (Morgenstern, 1979). The seed zones have been critized on the basis that they do not represent the biological realities of the region, and that the Ontario Site Regions have little to do with the genetic response of some species (Yeatman, 1976).

Genetics of White Spruce

White spruce height growth has been found to be related to the seed source of the planting stock. Limestone adapted ecotypes have been observed in the laboratory (Farrar and Nicholoson 1967) and in field trials (Teich and Holst, 1974). Provenance trials were reviewed in 1975 at the Petawawa Forest Experiment Station where 91 provenances were planted in 11 experimental plantations ranging in age from 13 to 20 years (Teich _et al_., 1975). The objective of their study was to determine broad patterns of variation and find the best provenances for further study. Results showed little variation in survival among provenances, but provenances had significant variation in height growth. Results indicated that local seed sources had average rates of height growth, but seed sources from southeastern Ontario were 21% taller. One experimental plantation was established in Thunder Bay, Ontario, with only one provenance from that region; results from this plantation indicated that the local seed sources obtained only 80 % of the plantation average height growth at 13 years (Teich _et al_., 1975).

Southeastern Ontario and western Quebec seed sources, particularly the provenances from the Beachburg-Cobourg corridor, have consistently achieved better height growth than other white spruce seed sources (Khalil, 1974; Nicholson, 1970; Radsliff _et al_., 1983; Stellrecht _et al_., 1974

Teich *et al.*, 1975; Wright *et al.*, 1977). Height growth of white spruce also seems to be related to the latitude where the seed was collected, with trees from seed collected further north growing slower than trees from seed collected further south (Wright, *et al.*, 1977).

White spruce is susceptible to late spring frosts that may occur soon after seedling bud break (Jarvis *et al.*, 1966). There is evidence indicating that the time of bud break is partly controlled by genetics (Nienstaedt, 1972; Nienstaedt and King, 1969; Wilkinson, 1977). Progeny tests have indicated that the time of bud break is a heritable trait, and genetic improvements to avoid frost injury are possible (Nienstaedt, 1972; Nienstaedt and King, 1969). Unfortunately some evidence also exists that the selection for late bud break and the selection for fast growth are almost mutually exclusive traits (Wilkinson, 1977).

METHODS

FIELD DATA COLLECTION

Plot Selection

Thrower (1986) studied site quality for white spruce in North Central Ontario using 46 temporary plots established in young white spruce plantations greater than 20 years of age. Plots established by Thrower were located in plantations identified using Ontario Ministry of Natural Resource's (OMNR) records. These records included plantation locations, planting date, and post planting treatments; records indicated that all plantings used 2+2 stock, spacing was approximately 1.8 m x 1.8 m, and seed sources were mostly Site Region 4W, but did include some stock from Site Region 3W (Hills, 1960). Thrower then visited all plantations to determine their suitability for plot locations except where poor road conditions prevented access. On each of these plots Thrower collected stem analysis data from three dominant trees; these data were used to construct height-growth curves, growth intercepts, and to determine site index (dominant tree height at 15 years breast-height age).

I revisited 44 of Thrower's temporary site plots in 1986 and made detailed soil decriptions, collected soil samples, and classified the plot into one of three major landform types (i.e. morainal, glaciofluvial, and lacustrine). Soil information, soil samples, and stem analysis information also were collected from an additional 29 plots using the same plot methods described by Thrower (1986). Figure 5 shows locations for the 44 Thrower plots and the 29 additional plots I established.

Stand Description

Height growth of three dominant trees on each plot was measured using stem analysis for the 44 plots established by Thrower in 1985, as well as for the additional 29 plots that I established. For all 73 plots a ten by ten metre plot was established and all trees within this area also were measured for their diameter at breast height (1.3 m). All trees in the plot were numbered and five trees were selected at random and their total height and "Kraft crown class" were recorded on a data collection form created by myself (Appendix I). Brief stand descriptions were recorded.

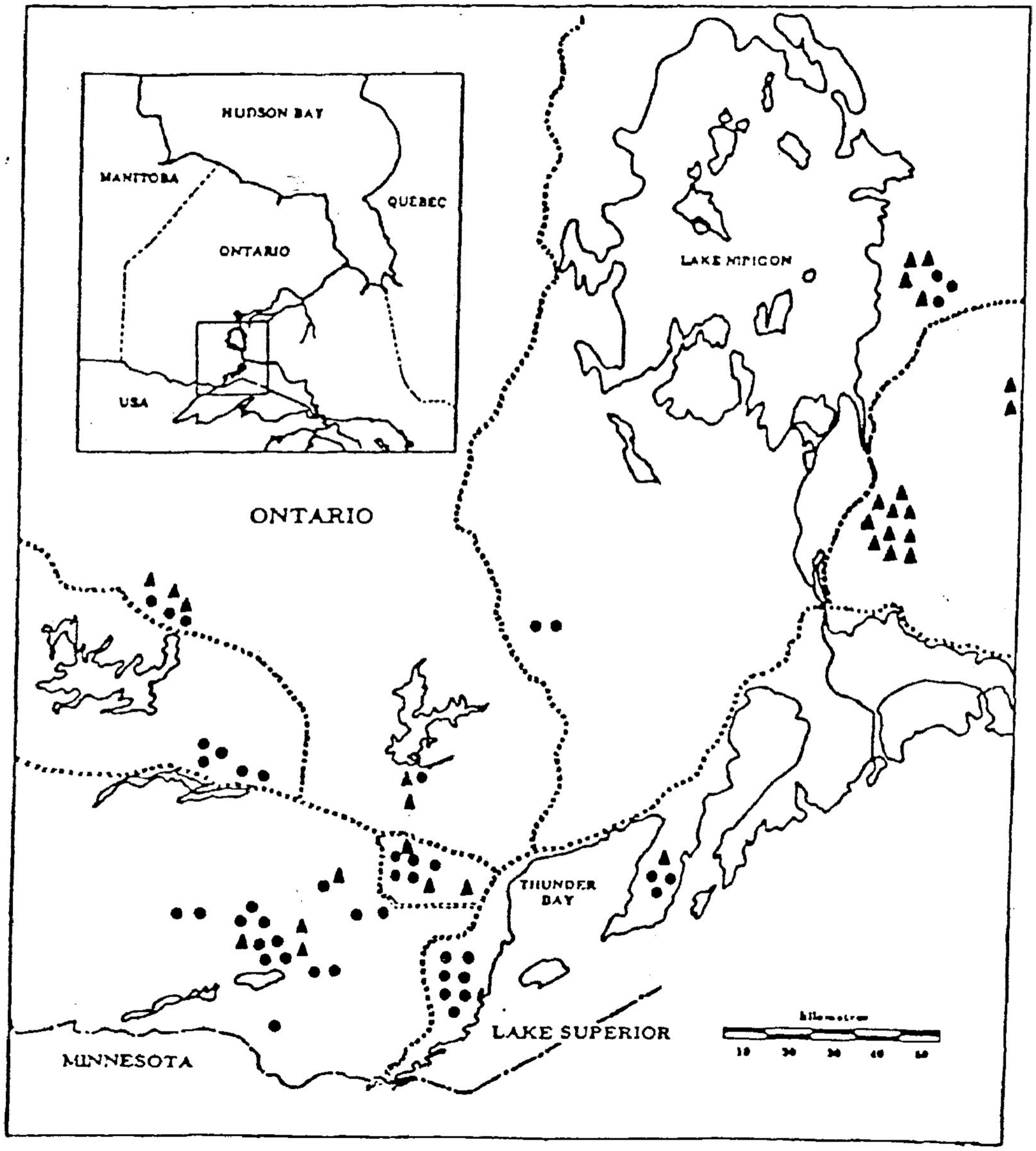

Figure 5. Map of North Central Ontario showing locations of 44 plots established by Thrower together with an additional 29 plots established for use in this study.

● Indicates Thrower's plots

▲ Indicates plots established for use in this study

Stem Analysis

Stem analyses were made on each plot using three selected dominant trees, that were well formed and showed no signs of suppression or injury. These site trees were then felled, limbed, total height and the height of each annual node were measured to the nearest 5 cm using a 30 m tape. Next the stump section was cut at ground level, and sections were cut at 25 cm intervals for the first 1.0 m above ground level, at breast height, and then at 0.50 m intervals to the top of the tree. Tree sections for Thrower's 44 plots had been transported to Lakehead University and stored at 2° C and subsequent ring counts were determined later in the year. For my additional 29 newly established plots, tree sections were transported to the Thunder Bay Forest Nursery and stored at 2° C for analysis using the computerized Tree Ring Increment Measure (TRIM) system provided by the OMNR (MacIver et al., 1985).

Soil and Topographic Descriptions and Measurements

Two one-metre-square soil pits were dug on each plot and a soil profile description was made for each pit using standard Canadian soil profile description methods (Bates et al., 1982; Canada Soil Survey Committee, 1978; Day, 1983). All observations were recorded on a tally sheet designed by Schmidt (1986) and modified by the author for this study (Appendix II).

Three mineral soil horizons (i.e. the A, B, and C) were identified from each soil pit indicating the zones of eluviation, illuviation, and weathered parent material. Depth measurements to the nearest 1 cm were recorded for the mineral horizons, and for the surface organic forest layers (i.e. the L, F, and H layers).

Additional descriptions recorded for each mineral horizon included texture class, soil colour, horizon boundary description, mottle description, structure, percent coarse fragment content by volume, and rooting abundance. All of the soil descriptions and measurements were made using techniques described in "The Field Manual for Describing Soils" (Bates et al., 1982). Soil texture was determined from its feel, moist cast, ability to ribbon, and the ability to reflect light called "shine". Soil colour was determined from moist soil samples using Munsell colour chips; mottles were described in terms of presence, size, abundance, and colour contrast to the soil matrix; soil structure was described in terms of grade, class, and kind; distinctness and form were used to describe the horizon boundaries. The percent coarse fragment content of each horizon was estimated by visually comparing area coverage charts to the pit face; percent coarse fragments were also divided into three fragment size classes, i.e. gravel (0.2 cm to 7.5 cm), cobbles (7.5 cm to 25 cm), and stones (greater than 25 cm).

Additional descriptions included depth and presence of bedrock, gleying, mottling, water table depth, seepage, and maximum rooting depth. The depth and presence of carbonates was determined through effervescense using 10% hydrochloric acid (HCL). Soil drainage class, pore pattern and moisture regime were determined using techniques in Bates et al. (1982). Topography of each plot was described in terms of total slope, upslope, aspect, and percent slope; site position was recorded as crest, upslope, midslope, lower slope, toe slope, or depression; slope shape was recorded as either convex, concave, or flat. Latitude and longitude of each plot was determined using topographic maps. A total of 46 soil and topographic variables were recorded or determined for each soil pit. Table 4 lists the values recorded in each soil pit by category code, and a brief description also is given for each value.

Soil samples of approximately one litre in volume were taken from the A, B, and C horizons in two soil pits on each plot. These samples were later combined to form a composite soil sample for each of the three horizons of each plot. Field samples included soil and gravel sized coarse fragments (0.2 cm to 7.5 cm) as well as the soil itself (<2.0 mm).

Table 4. Categories and descriptions for the observed soil, topographic, and climatic values.

Category	Code	Description
Climate	LONG	Longitude
	LAT	Latitude
Topography	SLLNGH	Slope length in metres
	UPSLLNGH	Upslope length in metres
	PRSLOP	Percent slope
	ASP	Aspect in degrees
	SURSHP	Surface shape (1= convex, 2= straight, 3= concave)
	STPOS	Site position (1= crest, 2= upper, 3= middle, 4= lower, 5= toe, 6= depression, 7= level)
Coarse Fragment Content	CFA	Percent coarse fragments in the A horizon
	CFB	Percent coarse fragments in the B horizon
	CFC	Percent coarse fragments in the C horizon
Soil Depth	THA	Thickness of the A horizon
	THB	Thickness of the B horizon
	THC	Thickness of the C horizon
	DPSEEP	Depth to seepage
	DBCARB	Depth to carbonates
	DPROCK	Depth to bedrock
	DWATER	Depth to water table
	DDM	Depth to distinct mottles
	DPM	Depth to prominent mottles
	DGLEY	Depth to gleying
	ROOT	Maximum rooting depth
Soil Moisture	MTA	Mottles in the A horizon (1= no mottles, 2= mottles present)
	MTB	Mottles in the B horizon
	MTC	Mottles in the C horizon
	PORE	Pore pattern (0=extremely open, 1=v. open, 2=open 3=mod. open, 4=mod. retentive, 5=retentive, 6=v. retentive, 7=mod. restrictive)
	MR	Moisture regime (0=dry, 1=mod. dry, 2=mod. fresh, 3=fresh, 4=v. fresh, 5=mod. moist, 6=moist, 7=v. moist)
	DRAIN	Drainage class (1=v. rapid, 2=rapid, 3=well, 4=mod. well, 5=imperfect, 6=poor, 7=v. poor)

Continued		
Category	**Code**	**Description**
Soil Colour	HUEA	Hue of the A horizon (0= 5YR, 1= 7.5YR, 2= 10YR, 3= 1.25Y 4= 2.5Y, 5= 5Y)
	VALA	Value of the A horizon
	CRMA	Croma of the A horizon
	HUEB	Hue of the B horizon
	VALB	Value of the B horizon
	CRMB	Croma of the B horizon
	HUEC	Hue of the C horizon
	VAIC	Value of the C horizon
	CRMC	Croma of the C horizon
Litter Layer	HUMUS	Humus form
	THL	Thickness of the L layer
	THF	Thickness of the F layer
	THH	Thickness of the H layer
Other	MODE	Mode of deposition (1= lacustrine, 2= morainal, 3= glaciofluvial)
	FEC	FEC soil groups
	RTA	Rooting abundance of the A horizon
	RTB	Rooting abundance of the B horizon
	RTC	Rooting abundance of the C horizon

LABORATORY ANALYSIS

Soil samples from the three horizons were air dried and sieved to remove coarse fragments larger than two millimetres; sticks, bark, roots, and other foreign material were also removed. The fine earth fraction (<2.0 mm) as well as the gravel was weighed, and percent gravel content (>2.0 mm) by weight was determined using the formula:

$$\text{percent gravel} = \frac{\text{weight of gravel (gm)}}{\text{weight of gravel plus fine earth (gm)}} \times 100$$

Particle size analysis to determine the relative percent of sand, silt, and clay in each soil sample (Bouyoucos, 1962) was done at the Great

Lakes Forestry Centre at Sault Ste. Marie, Ontario. Soil pH in water was determined for each horizon using a glass electrode; percent organic matter and the carbon/nitrogen ratio were determined for the A horizon of each plot using the modified Walkley-Black method (McKeague, 1978). Table 5 lists soil variables determined through laboratory tests, by category code and and also gives a brief description of each of the soil variables.

Table 5. Category and description for soil variables determined through laboratory analysis.

Category	Code	Description
Soil Texture	SA	Percent sand in the A horizon
	SIA	Percent silt in the A horizon
	CLA	Percent clay in the A horizon
	SB	Percent sand in the B horizon
	SIB	Percent silt in the B horizon
	CLB	Percent clay in the B horizon
	SC	Percent sand in the C horizon
	SIC	Percent silt in the C horizon
	CLC	Percent clay in the C horizon
Soil Reaction	PHA	pH of the A horizon
	PHB	pH of the B horizon
	PHC	pH of the C horizon
Organic Matter Content	CARB	Organic carbon expressed as a percent by weight through loss by ignition for the A horizon

Values used as independent variables are summarized by category in Table 6. This table also shows that the texture, coarse fragment, and depth values were used to calculate an additional 22 values involving various totals or averages. The additional 22 computed values are listed in Table 7 including their codes and methods, descriptions, and method of computation.

Table 6. Soil and topographic values and additional computed values.

Category	Measured Number of Values	Computed Additional Values	Total Numbe of Values
Climate	2	1	3
Topography	6	0	6
Soil Texture	9	17	26
Coarse Fragments	3	1	4
Soil Depth	11	3	14
Soil Moisture	6	0	6
Soil Reaction	3	0	3
Organic Matter	1	0	1
Soil Colour	9	0	9
Litter Layer	4	0	4
Other	5	0	5
Total	59	22	81

Averaging Plot Soil Data

Soil profile descriptions for the two soil pits on each plot were averaged to obtain an average plot soil profile description. These standard soil profile descriptions consisted of an A, B, and C horizon delineating the zone of eluviation, illuviation, and weathered parent material, respectively. Two plots were excluded from further study because they were outside the study area i.e. the North Central Region. One additional Thrower plot was eliminated due to excessive soil variation between the two soil pits, leaving 70 plots for further analysis.

Table 7. Additional values and descriptions about how values were computed. Also included are transformations that combined various values that expressed curvilinear relations.

Category	Code	Description
Topography	COSASP	Cosine of ASP (aspect) (Beers *et al.*, 1966)
Soil Texture	CLASSA	Texture class of the A horizon (plotted on texture triangle)
	CLASSB	Texture class of the B horizon (plotted on texture triangle)
	CLASSC	Texture class of the C horizon (plotted on texture triangle)
	CLASS	Average texture class of the soil profile
	TOTS	Average percent sand in the profile (SA+SB+SC/3)
	TOTSI	Average percent silt in the profile (SIA+SIB+SIC/3)
	TOTC	Average percent clay in the profile (CLA+CLB+CLC/3)
	FINEA	Silt plus clay content of the A horizon (SIA+CLA)
	FINEB	Silt plus clay content of the B horizon (SIB+CLB)
	FINEC	Silt plus clay content of the C horizon (SIC+CLC)
	TOTFIN	Average silt plus clay in the profile (FINEA+FINEB+FINEC/3)
	SBC	Average percent sand in the B and C horizons (SB+SC/2)
	SIBC	Average percent silt of the B and C horizons (SIB+SIC/2)
	CBC	Average percent clay of the B and C horizons (CLB+CLC/2)
	DIFSAB	Difference in percent sand between the A and B horizons (SA - SB)
	DIFSBC	Difference in percent sand between the B and C horizons (SB - SC)
	DIFSAC	Difference in percent sand between the a and C horizons (SA - SC)
Coarse Fragments	TOTCF	Average coarse fragment content in percent of the soil profile (CFA+CFB+CFC/3)
Soil Depth	THAB	Combined thickness of the A and B horizons (THA+THB)
	THBC	Combined thickness of the B and C horizons (THB+THC)
	DRRL	Depth to a root restricting layer (found by taking the value of the variable; DDM, DPM, DSEEP, DGLEY, DROCK, DWATER or a change of greater than 20% clay content between horizons)
Transformations	LN(x)	Natural logarithm of the variable
	Sq(x)	Square of the variable
	SQRT(x)	Square root of the variable
	IN(x)	Inverse of the variable

HEIGHT-AGE CURVES

Tree age for each section was determined by counting the number of annual growth rings to the end of the last growing season; these counts were confirmed by two independent counts of the growth rings. Age at each section height for each tree was determined by subtracting the number of rings from the total age of the tree. Total age from ring counts was confirmed through OMNR planting records for each plantation. The height-age values for each tree were then plotted to form a tree height-age curve. This preliminary curve has a slight positive bias due to section points not corresponding to tree height at the end of the growing season. The equation listed below was used to remove the bias by lowering the height where the tree section was taken by an amount equal to one half the estimated annual height increment (Carmean, 1972).

$$Ht_i = ht_i \quad (1/2) \quad - \quad \frac{ht_i - ht_i - 1}{age_i - 1 - age_i}$$

where Ht_i = adjusted height of tree section i
ht_i = height where tree section i was taken
age_i = age of section i

The resulting adjusted height-age curve for each tree was then compared to a curve based on annual node height measurements from each tree to confirm the accuracy of the height-age curve based on node measurements. This comparison aided in confirming node measurements and in recognizing nodes that might have been missed during field measurements; stem analysis was particularly useful below breast height where internodes were short and indistinct. The height of missing node measurements was estimated based on the adjusted height-age data from tree ring counts. The final tree height-age curve for each tree was based exclusively on the height of annual node measurements.

Height-age data were entered into the HTS program developed by Thrower (1986). This program recorded the tree height growth data for each of the trees measured on each plot. The program also recorded total height-age data for each tree, and generated paired breast height-age data for the tree. The program then generated graphs for each of the trees on each plot for both total age and breast-height age.

The final tree height-age curves were examined for abnormal height growth patterns. All data and field notes were re-examined for several trees having height-age curves indicating possible suppression. As a result, an additional two plots were eliminated from further analysis due to irregular height growth patterns, possibly caused by suppression. The remaining 68 plots all contained three dominant, undamaged sample trees suitable for use in estimating site index and for developing site index curves.

The adjusted height growth of the three dominant trees on each plot were averaged to obtain an average total age curve, and an average breast-height age curve. The average total age curve was based on years from seed, and the average breast-height age curve was based on age from the first year above breast height.

Estimating Site Index

Site index for each plot was defined as the average height of the three sample trees at 15 years from breast height ($BHSI_{15}$). A site index value also was obtained using the average height at a total age of 25 years ($TOTSI_{25}$). Unfortunately, one or more of the sample trees on 17 site plots were less than 15 years old after breast height. To avoid the loss of this valuable data, the height growth of the sample trees on these 17 plots were extrapolated an appropriate number of years in order to estimate $BHSI_{15}$ using a technique developed by Thrower (1986).

Thrower's extrapolations were accomplished using the expanded Chapman-Richards function presented by Ek (1971). Total height-total age data from the three trees on these 17 plots were fitted using this Ek model.

$$Ht = b_1 \ SI^{b_2} \ (1-e^{-b_3 \ Age})^{b_4 \ SI^{-b_5}}$$

where: Ht = predicted total height (m)

SI = site index (height at 25 years from seed)

Age = age from seed

b_i = model coefficents

e = base of the natural logarithms

The coefficients estimating the upper asymptotic height as a function of site index (b_1 and b_2) were reentered into the above model as constants thus deriving the following equation:

$$Ht = 13.1324 \ SI^{0.340352} \ (1-e^{-b_3 \ Age})^{b_4 \ SI^{-b_5}}$$

This equation was then used to extrapolate the total age curve for each of the sample trees on the 17 white spruce plots. Extrapolations were extended to a total age corresponding to a breast height age of 15 years; these extrapolations only required extending the curves an average of 2.6 years. Appendix III gives the actual number of years necessary to extrapolate the height-growth curve for each of the 17 plots and the standard error of the estimate for each individual extrapolation.

STATISTICAL ANALYSIS

All site index, soil, topographic, and climatic values (Tables 4,5, and 7) were entered on the Digital VAX 11/780 computer for analysis using the SPSSX statistics package (Nie, 1983). All data files were compared to original data sheets to verify that no entry errors occurred in the typing of these data sets. The statistics program S and SPSSX were used for the statistical analysis (Becker and Chambers, 1984; Nie, 1983). Graphics packages for the MacIntosh Computer were used in the presentation of results.

All 68 plots were analyzed in a single combined data set, as well as in three separate data sets stratified by surficial geology landform (Schmidt, 1986, Schmidt and Carmean, 1988). The three surficial geology landforms were lacustrine, morainal, and glaciofluvial. Definitions of each of these landforms were taken from Schmidt (1986) and are described as follows:

1. Lacustrine soils
    (a) the parent material was of glaciofluvial or glaciolacustrine origin; and
    (b) the fine earth fraction was less than 50% sand.

2. Morainal Soils
    (a) parent material was of glacial moraine origin; and
    (b) contained at least 10% coarse fragments.

3. Glaciofluvial soils
    (a) parent material was glaciofluvial or of fluvial origin; and
    (b) fine earth fraction contained more than 50% sand.

Schmidt (1986) used shallow to bedrock morainal soils as an additional landform. In this study only a small number of plots occurred on shallow to bedrock morainal soils, thus these plots were included with morainal soils. The total number of plots occurring on each of the three surficial geology landform types, and the range of $BHSI_{15}$, are listed in Table 8.

Table 8. Total number of plots by landform and range of site index ($BHSI_{15}$).

Landform	Number of Plots	Range of Site Index ($BHSI_{15}$)	Mean Site Index (m)	Standard Error of the Mean
Lacustrine	26	5.39 - 10.97	8.48	0.285
Morainal	22	5.28 - 9.62	7.42	0.264
Glaciofluvial	20	5.51 - 10.42	8.00	0.344

Ten percent of the plots from each of the three landforms were randomly selected for use as check plots; the remaining plots were used to compute multiple regressions expressing relationships between site index and the various soil and topographic features. The number of plots used for preliminary computations and the number of check plots is listed for the three landforms in Table 9.

Preliminary Screening and Computations

A large number of soil and topographic values were available for computation (Tables 4, 5 and 7). Thus a screening technique developed by Schmidt (1986) was used to eliminate soil variables that had little or no relationship to site index. An additional screening involved the use of Principal Component Analysis to derive component scores using each of the soil and topographic values. These scores provided a means for identifying significant variables and possible intercorrelations between independent variables. To eliminate intercorrelations in the independent variables, only the most significant variables within each principal component score were retained for further secondary analysis.

Table 9. Total number of plots by landform, the number of plots used for preliminary computations, and the number of check plots.

Landform	Total Plots	Computation Plots	Check Plots
Lacustrine	26	21	5
Morainal	22	17	5
Glaciofluvial	20	16	4
Total	68	54	14

The various soil and topographic features (Tables 4, 5 and 7) were screened using the backward elimination method in multiple regression to select a set of variables that were significantly correlated to $BHSI_{15}$ and $TOTSI_{25}$. Variables eliminated from further analysis were those with probability of F greater than 0.05. Variables selected using both principal component analysis and backward multiple regression were regressed against $BHSI_{15}$ and $TOTSI_{25}$ in subsets of one smaller than the sample size. The equations with the highest coefficient of determination (R^2) were considered to be the most precise.

The residuals for each equation were then examined to determine if the assumptions of regression had been violated. These assumptions were:

1. the errors belonged to the population, i.e. no values outside the population (Weisberg, 1980).
2. the error terms were random, i.e. exhibited no heteroscadisticity (Chatterjee and Price, 1977).

Assumption one was tested using Bonferoni's t-test, and assumption two was tested using scatterplots of the residuals vs. predicted values to determine if nonlinearity or heteroscadisticity existed.

Initial analysis indicated poor relationships when all 68 plots were combined into a single data set; relationships between soil-site variables and $TOTSI_{25}$ were much poorer than those for $BHSI_{15}$. Further analysis was then restricted to using data sets for each of the three glacial landforms, and regressing independent variables in each of those data sets to $BHSI_{15}$ alone. The regression equations developed from preliminary analyses were used to predict $BHSI_{15}$ on each of the 14 randomly selected check plots (Table 9). Site index ($BHSI_{15}$) computed using these preliminary equations was then compared to actual $BHSI_{15}$ based on stem analysis on the check plots as a means of evaluating the precision of the preliminary equations for predicting $BHSI_{15}$, and also to determine possible biases in these preliminary equations.

Secondary Analysis

The preliminary computations revealed that the three landforms usually had a large number of variables correlated with site index. Therefore, an effort was made to simplify the equations by eliminating variables that were interrelated based on criteria developed by Schmidt (1986). Schmidt's criteria were: (a) could the variable possibly reflect some biological relationship; and (b) could the variable be easily measured in the field or determined by simple laboratory analysis. All plot sheets were reviewed to determine if discrepancies existed between soil pits or to determine if the plot did not belong to the assigned landform. As a result of this final screening 6, 9, and 10 variables were eliminated from the lacustrine, morainal, and glaciofluvial landform, respectively (Table 10).

Final Computations

In the final analysis the S data analysis and graphics program was used; the "leaps and bounds" all subset regression technique was used for computing regression equations (Becker and Chambers, 1984). "Leaps and bounds" regression involves regressing site index against all possible combinations of the independent variables. Independent variables for these computations involved sets of independent variables identified from the regression screening, and also sets from the principal component analysis. The coefficient of determination (R^2) was used to evaluate the precision of each of the equations and aided in the determination of the "best equation" for each of the landforms. Both backwards regression and principal component analysis screening produces subsets of independent variables for later use in the final regression analysis. The regression screening has been traditionally critized for producing possible subsets of independent variables that may contain intercorrelation. Principal component analysis was used to eliminate this problem. However, the final regression equations selected from leaps and bounds regression using subsets from each of the preliminary variable screening were identical.

Table 10. The number of independent variables by variable class remaining after preliminary and secondary analysis.

Variable Class	Total Independent	Preliminary Analysis			Secondary Analysis		
		L	M	G	L	M	G
Climate	3	0	0	0	0	0	0
Topography	6	2	1	0	1	0	1
Soil Texture	26	5	13	11	5	1	6
Coarse Fragments	4	1	0	0	0	6	0
Soil Depth	14	6	4	3	4	1	0
Soil Moisture	6	0	3	4	0	4	0
Soil Reaction	3	0	2	3	0	2	4
Organic Matter	1	0	0	1	1	2	0
Soil Colour	9	2	2	2	0	0	2
Litter Layer	4	0	0	1	1	0	1
Other	5	2	0	1	0	0	2
Total	81	18	25	26	12	16	16

Variables were next entered into forward entry regression methods to insure that all the variables in the best leaps and bounds subsets contributed significantly to the final regression equations. The significance level of the correlation coefficient for each of the independent variables had to be less than 0.05.

To evaluate possible nonlinear relationships transformations of the independent variables in the final regression equations included logarithms, reciprocals, square roots, quadratics, and weighted regression. The interaction between each of the independent variables (their products) was explored to determine whether there existed a significant interaction. In addition, correlation between each of the independent variables was examined from a correlation matrix table. Since the glaciofluvial soil group contained the single variable drainage class which is qualitative, it was inappropriate to conduct transformations for this soil group.

Finally each of the final regression equations was used to determine how well they predicted site index ($BHSI_{15}$) on each of the 14 check plots held in reserve (Table 9). Site index on each check plot was estimated using the final regression equations for each of the landforms, respectively. Then estimated site index was compared to actual site index observed from stem analysis on each plot. The residual (observed site index vs. predicted site index) was examined to determine whether possible biases existed in each of the final regression equations. If site index prediction was acceptable and if residuals occurred in a random pattern, test plots were then added to the data sets and new regression equations computed. Schmidt (1986) felt that the inclusion of this additional data would further increase the accuracy of the final regression equations, particularly for those landforms having relatively few plots. The new and final regression equations were used to calculate trend graphs and site index prediction tables for each landform.

RESULTS

PRELIMINARY COMPUTATIONS

Exceptionally low nutrient values were obtained from the C, N, and H absorption analysis; therefore, these values were not used in preliminary screening. The rooting abundance of each of the horizons also was rejected from the preliminary screening because of the arbitrary nature of this variable. The remaining independent variables were screened using the backward elimination method in multiple regression. Then equations were computed using independent variables that showed relationships to breast height age site index ($BHSI_{15}$).

Equations also were computed using height at a total age of 25 years as site index ($TOTSI_{25}$), but these equations were consistently poorer then equations using breast height age site index ($BHSI_{15}$). Accordingly, $BHSI_{15}$ was used as the dependent variable for all subsequent analyses. Soil-site relationships were apparent in a regression using all 68 plots combined, and were particularly strong using subsets of independent variables, one smaller than the number of observations for each of the soil strata. In addition to an all plots combined equation, preliminary site index prediction equations also were computed for the lacustrine, morainal, and glaciofluvial soil group. These soil group equations predicted 0.93, 0.76, 0.63 (R^2) percent of the variation in site index, while, in contrast, the combined equation only predicted 0.25 percent (R^2) of the variation in site index (Table 11).

These preliminary landform equations (Table 11) were then used to predict site index on the 14 independent test plots (Table 12) to determine the precision of these equations, and also to determine if biases existed in the prediction of site index using these equations. Table 12 compares predicted and observed site indices for these independent test plots, and also lists the residuals of these predictions.

Table 11. Preliminary multiple regression equations for each soil group, the number of plots (N), multiple coefficients of determination (R^2) values, and their standard errors of the estimate (SEE).

Landform	Equation Number	Multiple Regression Equations	N	R^2	SEE (m)
Lacustrine Soils	L1	SI = 1215.718 + 51.799(CRMC) - 11.494 (TOTSI) + 3.052 (DRRL) - 35.227 (CRMA) - 0.393 (DPM)	21	0.93	0.476
Morainal Soils	M1	SI = 568.222 + 8.232 (THB) - 4.024 (SA) + 23.114 (CLASS)	17	0.76	0.673
Glaciofluvial Soils	G1	SI = 428.264 + 156.968 (DRAIN)	16	0.61	1.034
Combined Landforms Soils	U1	SI = 456.899 + 2.551 (SLLNGH) + 35.847 (PORE) + 2.116 (ROOT)	68	0.25	1.342

Table 12. Observed site index ($BHSI_{15}$) on the check plots, site index estimated using the preliminary regression equations, and residuals between predicted and observed site index.

Landform	Plot Number	Observed Site Index	Predicted Site Index	Residuals
Lacustrine Soils	18	6.82	7.24	-0.42
	45	9.45	7.00	2.45
(Equation L1)	46	10.42	9.60	0.82
	47	9.28	9.25	0.03
	56	7.60	6.60	1.00
Morainal Soils	7	9.41	6.47	2.94
	36	6.53	4.93	1.60
(Equation M1)	37	7.86	8.53	-0.67
	63	7.52	6.71	0.81
	67	9.62	5.94	3.68
Glaciofluvial Soils	11	9.17	8.96	0.21
	31	8.50	8.96	-0.46
(Equation G1)	49	6.38	5.84	0.54
	50	6.71	5.84	0.87

SECONDARY ANALYSIS

The backward elimination regression method described above showed 18, 25, and 26 independent variables that were related to $BHSI_{15}$ for lacustrine, morainal, and glaciofluvial soil groups, respectively. These independent variables were used in the secondary screening process described in the previous section. As a result of the secondary analysis 6, 9, and 14 variables were eliminated from the three respective landform groups. Table 13 lists independent variables selected during secondary screening and their correlation with $BHSI_{15}$.

Principal Component Analysis

Principal component analysis was used as a means for confirming and evaluating the screening technique used by Schmidt (1986, Schmidt and Carmean, 1988). In all cases a rather large number of principal components were derived for each of the three soil groups. The single most significant variable expressed in each component was selected for use in the final regression equation selection. This was done to eliminate any intercorrelation between independent variables, thus insuring one of the assumptions of multiple regression. Table 14 lists the variables selected and their correlation coefficients with $BHSI_{15}$.

Final Computations

Final regression equations were selected using "leaps and bounds" (Becker and Chambers, 1984) to identify groups of independent variables and their relationship to $BHSI_{15}$. The best equations based on R^2 were derived for each of the three soil groups. The three final equations were checked using SPSSX using the forward entry regression method to determine if each of the variables selected for each of the final regression equations contributed significantly to the precision of the equations.

Table 13. Independent variables in secondary screening found to be related to BHSI$_{15}$, and their correlation coefficients (r).

Independent Variable Category	Variable	Correlation Coefficients (r) with BHSI$_{15}$		
		Lacustrine	Morainal	Glaciofluvial
Topography	PRSLOP	---	0.3800	---
	SLNNGH	0.4348	---	---
Texture	SA	0.3287	-0.2185	-0.3747
	SB	---	0.3837	---
	SC	0.5832*	---	---
	SIA	-0.1739	---	---
	SIB	---	---	0.3357
	CLASSC	---	-0.2949	---
	CLA	---	---	-0.3119
	CLC	---	-0.3962	---
	TOTSI	-0.4966*	---	---
	TOTC	---	-0.2307	---
	FINEB	---	-0.2101	0.2496
	SIBC	-0.3160	---	---
Soil Depth	THA	---	-0.3205	---
	THB	0.2751	0.6158*	0.2156
	THAB	0.4193*	0.4517*	---
	DPCARB	-0.3287	---	---
	DRRL	0.5213*	0.7559*	0.5959*
Soil Colour	HUEC	-0.5782	---	-0.4191
Coarse Fragments	CFA	---	0.2921	---
Soil Reaction	PHA	---	-0.1575	-0.4464
	PHB	---	---	-0.3883
	PHC	0.4009*	-0.1710	---
Soil Moisture	MOTC	---	0.3150	---
	MR	---	0.1776	---
	DRAIN	---	---	0.7867*
Other	FEC	---	---	-0.2995
	CLAY	0.5848*	---	---
	CARB	0.3316	---	---

* Significant at an alpha level of 0.05

Again each regression equation was tested to determine if any of the assumptions of regression were violated as described in the previous chapters. Table 15 lists the final equations derived for each of the soil groups using this selection process, the number of observations, the multiple coefficient of determination (R^2), and the standard error of the estimate (m).

Table 14. Independent variables found to be related to $BHSI_{15}$ selected using Principal Component Analysis together with their correlation coefficients (r).

Independent Variable Category	Variable	Correlation Coefficients (r) with $BHSI_{15}$		
		Lacustrine	Morainal	Glaciofluvial
Topography	ASP	—	0.3062	—
	UPSLNNGH	0.2248	—	0.2246
	SURSHP	-0.2477	—	—
Texture	SIA	-0.1739	—	—
	TOTS	0.5199*	—	—
	SBC	—	0.2599	—
	FINEA	—	—	-0.1962
	SIBC	-0.3160	—	—
Soil Depth	THA	—	—	-0.1993
	THB	0.2751	—	—
	DROCK	0.3192	—	—
	DPCARB	—	—	-0.2536
	DRRL	0.5213*	0.7559*	—
Soil Colour	HUEB	0.1938	—	—
	HUEC	-0.5782*	—	—
Coarse Fragments	CFA	—	0.2921	—
	CFC	—	-0.3486	—
Soil Reaction	PHB	—	—	-0.3883
	PHC	0.4009*	-0.1710	—
Soil Moisture	MOTC	—	0.3150	—
	DRAIN	—	-0.4740*	0.7867*
Other	CLAY	0.5848*	—	—
	CARB	0.3316	—	—

* significant at an aplha level of 0.05

Table 15. Final regression equations for each soil group, the number of observations (N), the multiple coefficients of determination (R^2) values, and the standard errors of the estimate (SEE).

Landform	Regression Equation	N	R^2	SEE
Lacustrine Soils	$BHSI_{15} = 5.195 + 1.623\ (CLAY) + 0.028\ (DRRL) + - 0.502\ (HUEC)$	21	0.83	0.668
Morainal Soils	$BHSI_{15} = 5.868 + 0.034\ (DRRL) - 0.045\ (PHC)$	17	0.68	0.745
Glaciofluvial Soils	$BHSI_{15} = 4.283 + 1.560\ (DRAIN)$	16	0.62	1.031

EQUATION TESTING

All equations were tested to determine if they violated the assumptions of regression analysis mentioned on page 47; that is, to determine if errors belonged to the same population, and to determine if errors are random and not exhibiting heteroscedasticity. The degree of heteroscedasticity was determined using scatterplots showing the relationship between predicted site index and each of the independent variables. Examination of these scatterplots showed that none of the scatterplots exhibited heteroscedasticity. To examine if error terms belonged to the same sample population (i.e. no outlayers) the Bonferroni's "t" test was used. This procedure showed that none of the observations for each landform exhibited a Student deleted residual greater then the Bonferroni "t" value at an alpha level of 0.05.

Another test was made to determine if independent variables used in the final regression equations had significant interaction terms. A correlation matrix of the independent variables was obtained to observe the strength of the correlations between each of the independent variables. If the correlation coefficient between two independent variables was greater than 0.50 those two variables were considered too strongly intercorrelated to be used in the same equation. Table 16 for the lacustrine soil group, and Table 17 for the morainal soil group, show that the intercorrelations between each of the independent variables had very small interaction terms, thus these variables could be used in the same regression. No correlation matrix was developed for the glaciofluvial soil group because only one independent variable was used in the final regression equation.

In addition to checking the intercorrelation of each of the independent variables using a correlation matrix (Tables 16 and 17) the interaction of each of the independent variables listed in the regressions was also calculated (i.e. $x_1 * x_2$) and this transformation was used as a variable in the regression equation to see if the interaction terms explained a significant, additional amount of variation. In none of the equations did the interaction terms contribute significantly to the regression equations. To detect possible curvilinear relationships for the various independent variables, transformations were tested using natural logarithm (LN), inverse (IN), square (SQ), and square root (SQRT). Transformations were conducted on those variables which were suited for transformations i.e. quantitative variables.

Lacustrine Soils

Transformations of the independent variables CLAY and HUEC were considered to have little biological foundation. However DRRL could have a curvilinear relationship to site index, thus various transformations expressing curvilinearity were tested to determine if significant improvements in the precision of equations could be made. Table 18 lists the lacustrine equations including the various transformations of the variable DRRL, the adjusted R^2 and the standard errors of the estimate (m). Results show that these transformations of DRRL, did not improve the precision of the lacustrine equation, thus inferring that DRRL has a linear relationship to $BHSI_{15}$ for lacustrine soils. Transformations of DRRL did not improve the R^2 of the final regression equation, or lower the standard error of the estimate, thus equation L2 was adopted as the final regression equation for predicting $BHSI_{15}$ for the lacustrine soil group. The three significant independent variables (CLAY, DRRL, and HUEC) were plotted against $BHSI_{15}$ to examine their relationships visually. Figure 6, 7, and 8 show scatterplots of CLAY, DRRL, and HUEC in relation to $BHSI_{15}$ for the lacustrine soil group, respectively.

Table 16. Pearson correlation matrix for independent variables in the final regression equation for the lacustrine soil group.

Variable Code	$BHSI_{15}$	CLAY	DRRL
CLAY	0.5848 p=0.003		
DRRL	0.5213 p=0.008	-0.0949 p=0.341	
HUEC	- 0.5782 p=0.003	-0.1936 p=0.200	-0.0245 p=0.458

Table 17. Pearson correlation matrix for independent variables in the final regression equation for the morainal soil group.

Variable Code	$BHSI_{15}$	DRRL
DRRL	0.7559 p=0.000	
PHC	-0.1710 p=0.256	0.1227 p=0.3208

Table 18. Regression equations for the lacustrine soil group where transformations are used to express possible curvilinear relations for the various DRRL variables. Also listed for each equation are the multiple coefficients of determination (R^2), the adjusted R^2, and the standard errors of the estimate (SEE).

Equation Number	Regression Equation	R^2	Adj. R^2	SEE (m)
L2	$BHSI_{15}$ = 5.195 + 1.623 (CLAY) + 0.028 (DRRL) + - 0.502 (HUEC)	0.83	0.797	0.668
L3	$BHSI_{15}$ = 2.096 + 1.443 (CLAY) + 1.256 (LNDRRL) + - 0.457 (HUEC)	0.81	0.775	0.704
L4	$BHSI_{15}$ = 4.012 + 1.537 (CLAY) + 0.392 (SQRTDRRL) + - 0.475 (HUEC)	0.82	0.792	0.677
L5	$BHSI_{15}$ = 6.721 + 1.203 (CLAY) + 0.008 (SQDRRL) + - 0.410 (HUEC)	0.64	0.602	1.013
L6	$BHSI_{15}$ = 8.188 - 37.717 (INDRRL) + 1.280 (CLAY) + - 0.457 (HUEC)	0.75	0.707	0.803

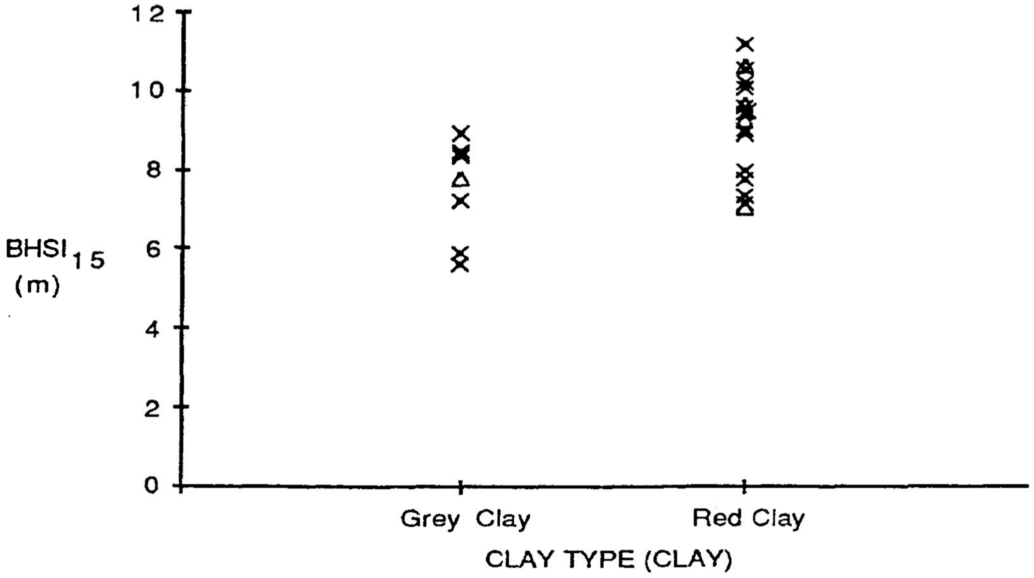

Figure 6. Relations between site index ($BHSI_{15}$) on lacustrine soils and the kind of lacustrine clay (independent variable CLAY).
× Indicates plots used in developing equation L2
Δ Indicates the five independent check plots.

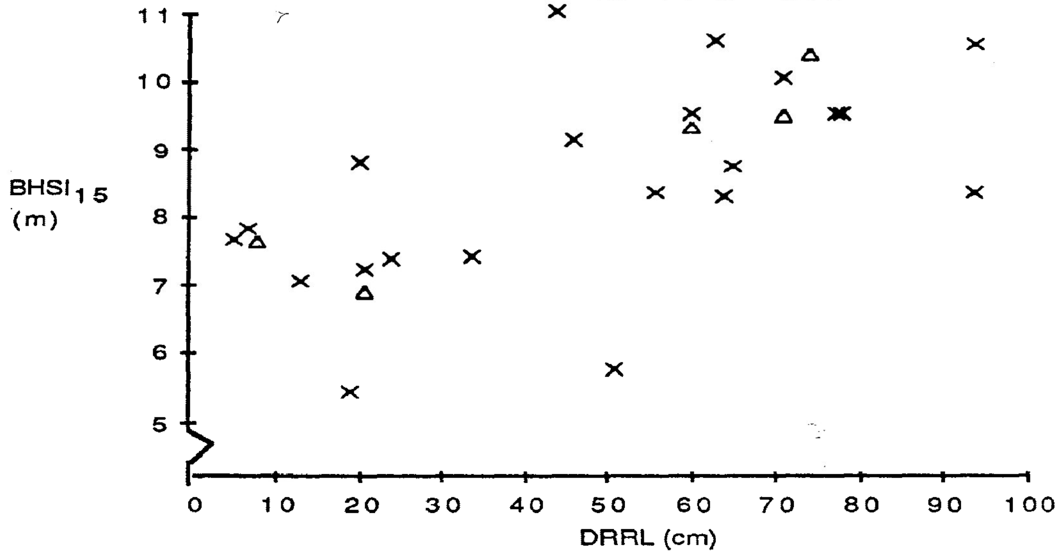

Figure 7. Relations between site index ($BHSI_{15}$) on lacustrine soils and the depth to a root restricting layer (DRRL).
× Indicates plots used in developing equation L2
△ Indicates the five independent check plots.

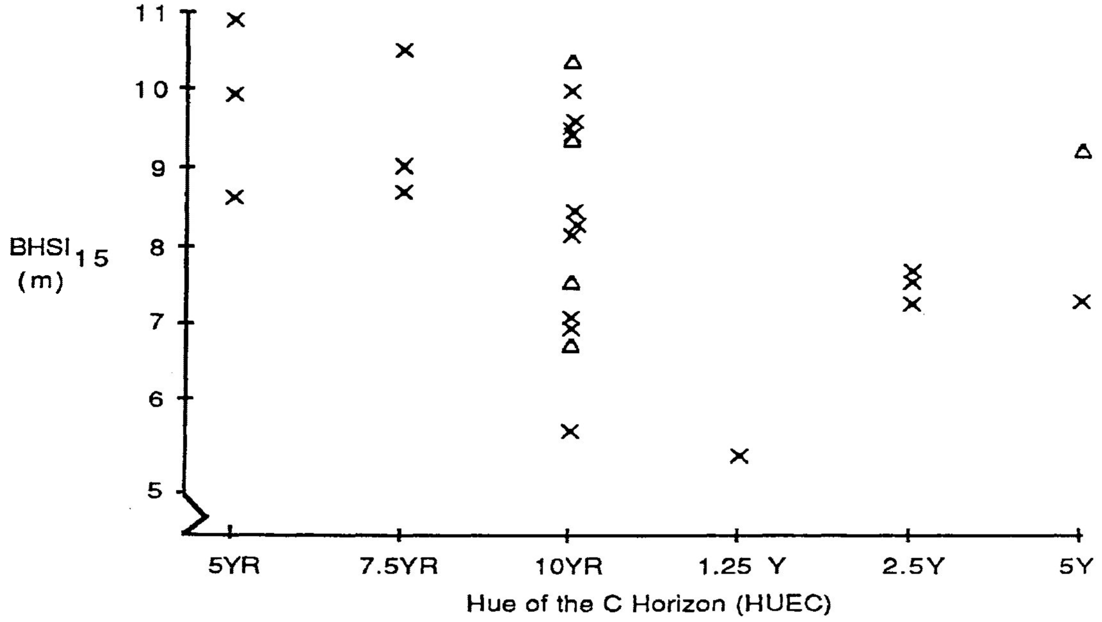

Figure 8. Relations between site index ($BHSI_{15}$) on lacustrine soils and the hue of the C horizon (independent variable HUEC).
× Indicates plots used in developing equation L2
△ Indicates the five independent check plots.

The final step was to determine the ability of equation L2 to predict site index on the five check plots. $BHSI_{15}$ was estimated on the five check plots using equation L2 and CLAY, DRRL, and HUEC values from each plot; estimated $BHSI_{15}$ was then compared to actual observed $BHSI_{15}$ determined by stem analysis. Table 19 lists observed $BHSI_{15}$, estimated $BHSI_{15}$ using equation L2, and the residuals between observed and estimated $BHSI_{15}$ for each of the five check plots. Table 19 also lists estimated $BHSI_{15}$ using equation L2, and the residuals between observed and estimated $BHSI_{15}$.

Table 19. Observed $BHSI_{15}$ for the five lacustrine check plots together with predicted $BHSI_{15}$ using the preliminary equation (eq. L1), and the final equation (eq. L2). Also listed are residuals between observed and predicted $BHSI_{15}$ for the two equations.

Plot Number	Observed Site Index	Predicted site index using preliminary eq. L1 (m)	Predicted site index using final eq. L2 (m)	Preliminary equation residuals (m)	Final equation residuals (m)
18	6.82	7.24	8.02	-0.42	-1.20
45	9.45	7.00	9.42	2.45	0.02
46	10.42	9.60	9.51	0.82	0.91
47	9.28	9.25	7.62	0.03	1.66
56	7.60	6.60	7.19	1.00	0.41

Schmidt (1986) attempted to increase the accuracy of the final regression equations by combining the check plots with the computations plots. This procedure also was followed and new equations based on all plots (21 computations and 5 checks plots) were computed. Table 20 lists equation L2 based on 21 computation plots and equation L7 based on all 26 lacustrine plots.

Table 20. Lacustrine regression equation L2 based on 21 computation plots, and equation L7 based on all lacustrine plot data. Also listed for each equation is the number of observations (N), the multiple coefficients of determination (R^2), and standard errors of the estimate (SEE).

Equation Number	Regression Equation	N	R^2	SEE (m)
L2	$BHSI_{15} = 5.195 + 1.623\ (CLAY) + 0.0281\ (DRRL) + - 0.502\ (HUEC)$	21	0.83	0.67
L7	$BHSI_{15} = 4.684 + 1.703\ (CLAY) + 0.0319\ (DRRL) + - 0.395\ (HUEC)$	26	0.77	0.74

Table 20 shows that the addition of the five check plots did not improve the precision of the regression equation for explaining $BHSI_{15}$. The R^2 decreased and the standard error of the estimate increased with the addition of the five check plots indicating that data from the five check plots might have been slightly different from the data of the 21 computation plots that were used to formulate the original regression equation (Eq. L2). Tests were made to determine if data from the five check plots contained outliers, exhibited heteroscedasticity, or showed nonlinear relationships. These tests indicated that none of these conditions existed, thus indicating that the equation based on 26 check plots was valid. A final comparison was made to determine if possible biases existed in equation L7. This comparison involved plotting $BHSI_{15}$ predicted by equation L7 against $BHSI_{15}$ observed on each plots (Figure 9).

Even though the R^2 value was somewhat lower, equation L7 was used to construct a site index prediction table (Table 21). Equation L7 was used because this equation was based on a larger number of plots and because this equation did not violate any of the assumptions of regression. This table used values describing CLAY, values for DRRL and values for HUEC to predict $BHSI_{15}$ for the range of site indices observed on the site plots.

Table 21 is designed for use in estimating $BHSI_{15}$ for planted white spruce on lacustrine soils in the North Central Region of Ontario. Note that dashed lines in Table 21 indicate where no data were available for making valid $BHSI_{15}$ estimates. Also note that C horizon hues of 2.5Y and 5Y for the red clays occurred with gleyed C horizons resulting in more yellow colours. Colour change caused by gleying of red clays apparently are associated with some reduction of $BHSI_{15}$, thus warranting separation of grey and red clays for 2.5Y and 5Y hues.

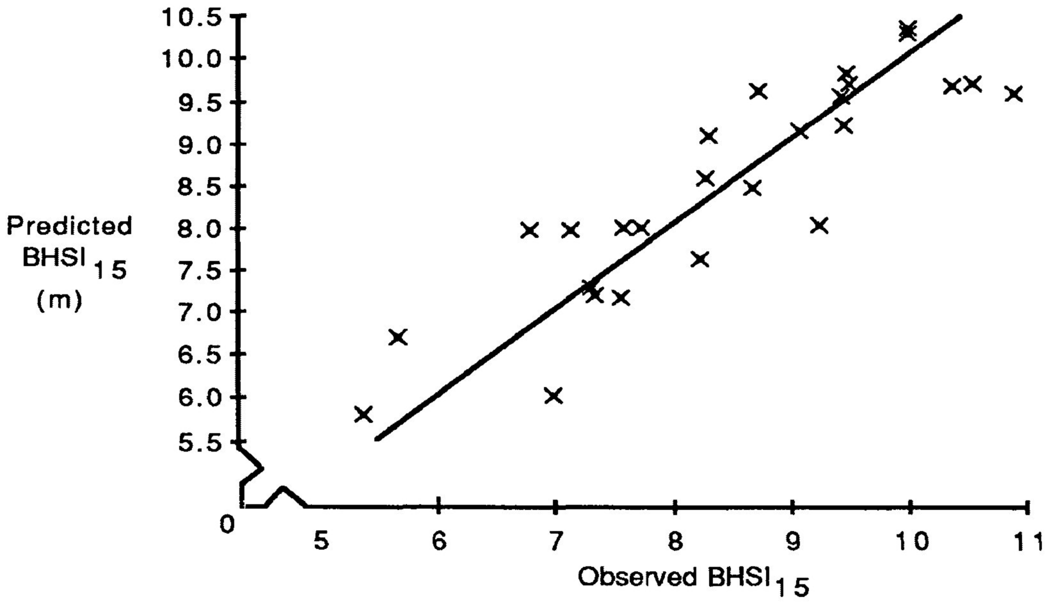

Figure 9. Relations between observed site index ($BHSI_{15}$) on lacustrine soils and predicted site index ($BHSI_{15}$) using equation L7.

Table 21. Site index ($BHSI_{15}$) prediction table for the lacustrine soil group.

Hue of C Horizon	Type of Clay	Depth to a Root Restricting Layer (cm)				
		10 - 30	30 - 50	50 - 70	70 - 90	100 <
5YR	Red	- - - to - - -	9.04 to 9.68	9.68 to 10.32	10.32 to 10.95	- - - -
7.5YR	Red	8.01 to 8.65	8.65 to 9.28	9.28 to 9.92	9.92 to 10.56	- - - -
10YR	Grey	5.91 to 6.55	6.55 to 7.19	7.19 to 7.82	7.82 to 8.46	8.78
	Red	7.61 to 8.25	8.25 to 8.89	8.89 to 9.53	9.53 to 10.16	10.48
1.25Y	Grey	5.52 to 6.15	6.15 to 6.80	- - - to - - -	- - - to - - -	- - - -
2.5Y	Grey	5.12 to 5.76	5.76 to 6.40	- - - to - - -	- - - to - - -	- - - -
	Red	6.83 to 7.46	7.46 to 8.10	- - - to - - -	- - - to - - -	- - - -
5Y	Grey	- - - to - - -	- - - to - - -	- - - to - - -	6.64 to 7.28	7.60
	Red	- - - to - - -	7.07 to 7.70	7.70 to 8.34	- - - to - - -	- - - -

Morainal Soils

The final variable screening for the morainal landform resulted in equation M2 for estimating site index ($BHSI_{15}$) (Table 22). The independent variables in equation M2 are the depth to a root restricting layer (DRRL), and pH of the C horizon (PHC) as measured with a glass electrode in distilled water. Several transformations of the DRRL variable were used to express possible curvilinear relations; resulting regression equations containing these transformations together with their R^2, adjusted R^2, and standard errors of estimates are given in Table 22.

The natural logarithm and square root transformations of the depth to a root restricting layer (DRRL) improved the precision of equation M1 (eqs. M3 and M5). This improved R^2 and lower a error term indicated that a nonlinear relationship exists between DRRL and $BHSI_{15}$. Scatterplots for equation M3 containing LNDRRL, DRRL, and PHC vs. $BHSI_{15}$ indicated that the data did not suffer from heteroscedasticity. The independent variables

DRRL and PHC were plotted against $BHSI_{15}$ to express visually their relationships with site index (Figure 10, 11, and 12).

Table 22. Regression equations for the morainal soil group listing the transformations of DRRL for morainal plots, their multiple coefficients of determination R^2, adjusted R^2, and standard errors of the estimate (SEE).

Equation Number	Regression Equations	R^2	Adj. R^2	SEE (m)
M2	$BHSI_{15}$ = 5.868 + 0.034 (DRRL) - 0.045 (PHC)	0.71	0.68	0.745
M3	$BHSI_{15}$ = 0.706 + 1.771 (LNDRRL) - 0.0053 (PHC)	0.74	0.71	0.718
M4	$BHSI_{15}$ = 6.806 + 0.0002 (SQDRRL) - 0.0570 (PHC)	0.64	0.61	0.831
M5	$BHSI_{15}$ = 4.011 + 0.511 (SQRTDRRL) - 0.028 (PHC)	0.74	0.71	0.719
M6	$BHSI_{15}$ = 8.897 - 67.265 (INDRRL) + 0.048 (PHC)	0.67	0.64	0.796

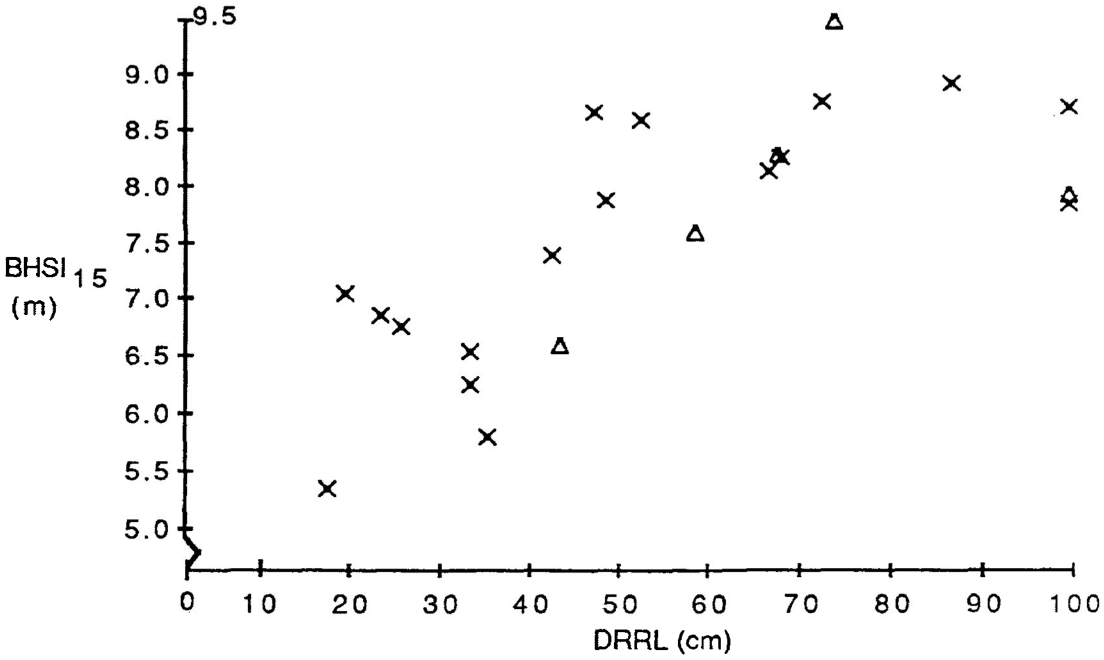

Figure 10. Relations between site index ($BHSI_{15}$) on morainal soils and the depth to a root restricting layer (DRRL).
× Indicates plots used in developing equation M2
△ Indicates the five independent check plots

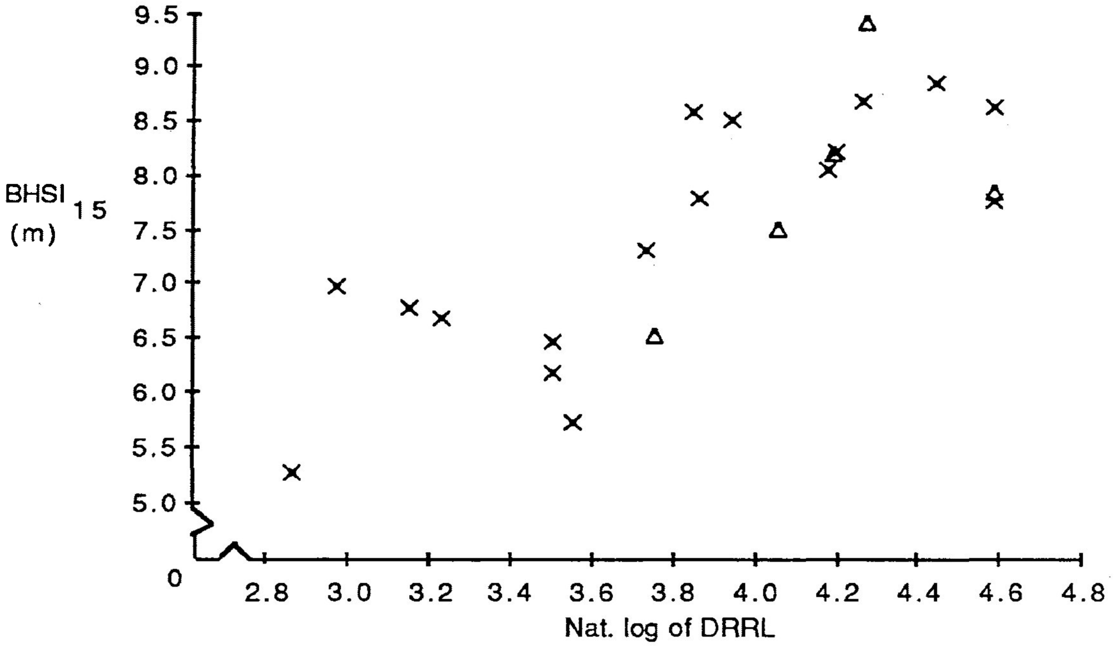

Figure 11. Relations between site index ($BHSI_{15}$) on morainal soils and the natural logarithm of the depth to a root restricting layer (LNDRRL).

X Indicates plots used in developing equation M3

Δ Indicates the five independent check plots

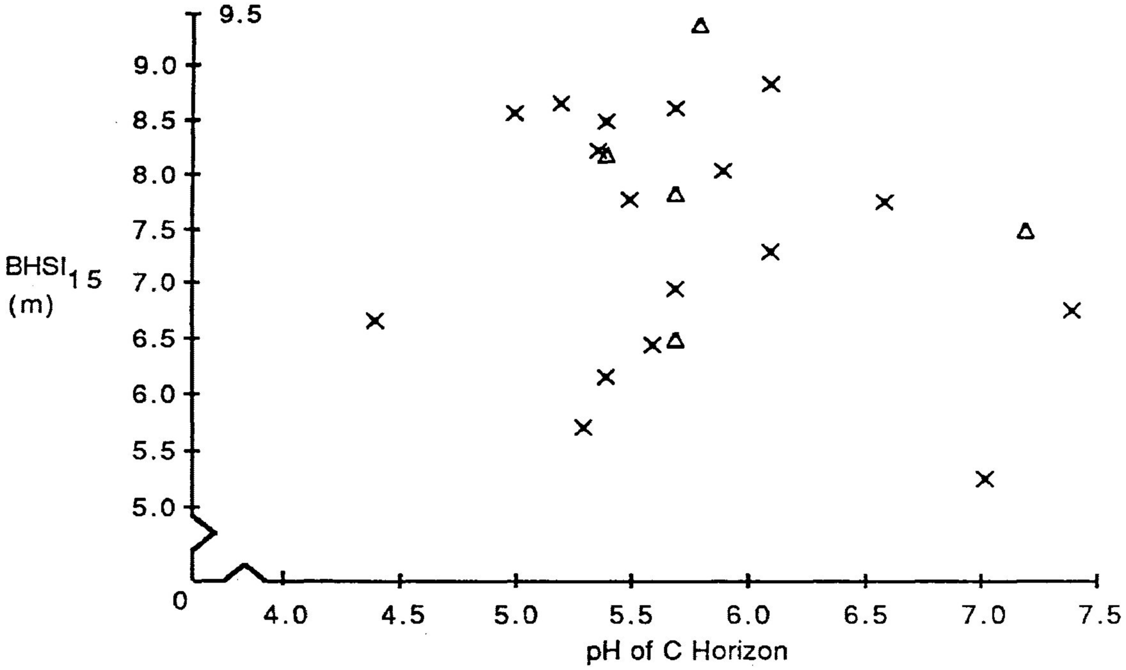

Figure 12. Relations between site index ($BHSI_{15}$) on morainal soils and the pH of the C horizon (PHC).
× Indicates plots used in developing equation M3
Δ Indicates the five independent check plots

The natural logarithmic transformation of DRRL for morainal soils (eq. M3) improved the precision of site index estimations; also equation M3 does not violate the assumptions of regression, thus is a valid equation. Accordingly, equation M3 was selected as the final regression equation for the morainal soils. Equation M3 was then used to predict $BHSI_{15}$ for the five independent check plots. Table 23 contains $BHSI_{15}$ predictions using the preliminary regression equation (eq. M1) as well as for the final regression equation (eq. M3); Table 23 also contains observed $BHSI_{15}$ measurements based on stem analysis for the five check plots and the residuals from the site index predictions using equations M1 and M3.

Table 23. Observed $BHSI_{15}$ for the five morainal check plots together with predicted $BHSI_{15}$ using the preliminary equation (eq. M1) and final equation (eq. M3). Also listed are residuals between observed and predicted $BHSI_{15}$ for the two equations.

Plot Number	Observed $BHSI_{15}$	Estimated $BHSI_{15}$ using eq. M1 (m)	Estimated $BHSI_{15}$ using eq. M3 (m)	Preliminary equation M1 residuals (m)	Final equation M3 residuals (m)
7	9.41	6.47	8.22	2.94	1.19
36	6.53	4.93	7.25	1.60	-0.72
37	7.86	8.43	8.87	-0.67	-1.01
63	7.52	6.71	7.72	0.81	-0.20
67	8.21	5.94	9.82	3.68	-1.61

Obviously equation M3 has improved the predictions of $BHSI_{15}$ on the five independent test plots. Accordingly, the five independent test plots appear to be from the same population as the 17 computation plots. Therefore, the 17 computation plots and the 5 check plots were combined and the regression was then recomputed (eq. M7). Table 24 lists the preliminary regression equation (eq. M3) that includes only the 17 computation plots; also included is the final equation (eq. M7) that includes all 22 morainal plots.

The curvilinear relationship between $BHSI_{15}$ and the depth to a root restricting layer expressed in equation M7 is shown in Figure 13.

Table 24. Final regression equations for the morainal soil group with and without the independent test plot data. Also listed are the number of observations (N), adjusted (R^2), and standard errors of the estimate (SEE) in metres.

Equation Number	Regression Equations	N	Adj. R^2	SEE (m)
M3	$BHSI_{15} = 0.706 + 1.771$ (LNDRRL) - 0.0053 (PHC)	17	0.71	0.72
M7	$BHSI_{15} = 0.987 + 1.751$ (LNDRRL) - 0.0489 (PHC)	22	0.66	0.73

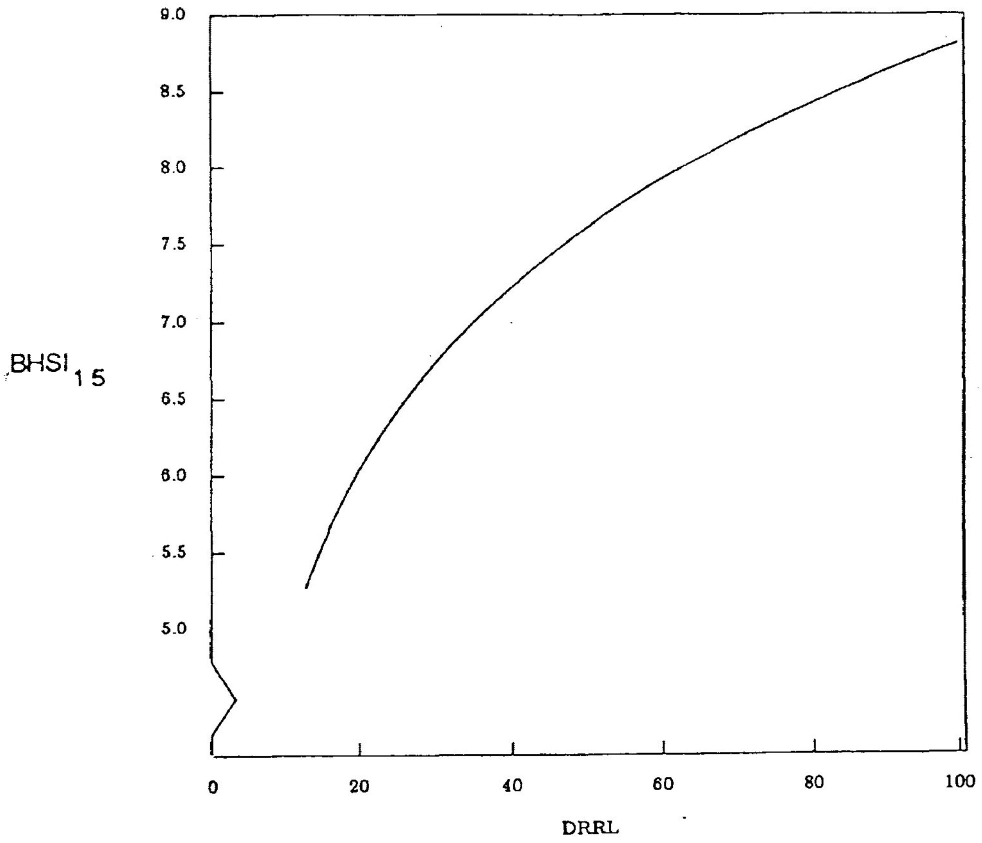

Figure 13. Curvilinear relations between site index ($BHSI_{15}$) on morainal soils and the depth to a root restricting layer (DRRL).

Observed site index ($BHSI_{15}$) was plotted against predicted site index ($BHSI_{15}$) using equation M7 (Figure 14). A random distribution of residuals on either side of and along the line indicates that the residuals or error terms are normally distributed and that the regression equation contains no biases when predicting $BHSI_{15}$ on morainal soils.

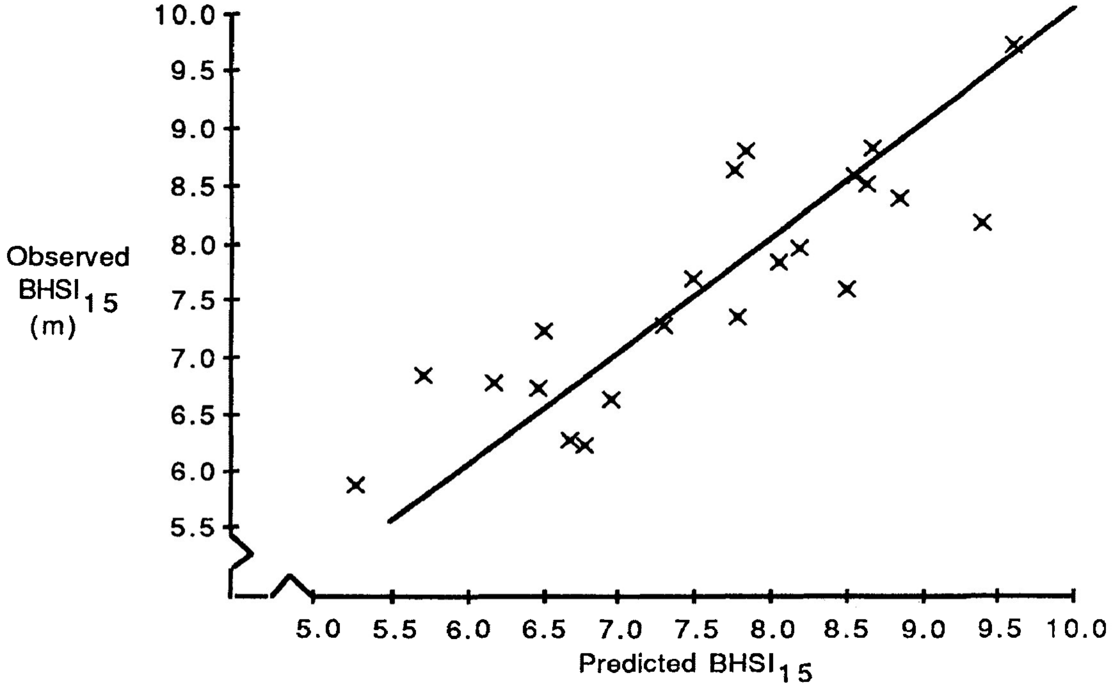

Figure 14. Relations between observed site index ($BHSI_{15}$) on morainal soils and predicted site index ($BHSI_{15}$) using equation M7.

The addition of the five check plots with equation M7 resulted in a lowering of R^2 and also slightly increased the standard error of the estimate. Equation M7 was examined to determine if any of the added check plots introduced outliers in the data set; scatterplots were also examined for heteroscedasticity. Both tests indicated that equation M7 was a valid regression equation, and did not violate any of the assumptions of regression.

In addition to lowering the adjusted R^2 value for the final regression equation, the addition of the 5 check plots also changed the coefficient b_2. This rather large change in the value of the coefficient may indicate that the pH of the C horizon may not be a good predictor variable or that the relationship between $BHSI_{15}$ and PHC may only be spurious.

Reexamination of the plot data indicates, however, that the relationship expressed by equation M7 may have biological meaning. The small number of plots on calcareous soils may have expressed a relationship that has not fully been explored.

Equation M7 was adopted for use even though the R^2 value was slightly lower, and also the large change in the coefficient b_2 from equation M2. Accordingly, equation M7 was solved for the range of data observed in the field, and a prediction table for $BHSI_{15}$ for morainal soils was developed (Table 25). Equation M7 also was used to construct a trend graph illustrating how $BHSI_{15}$ is related to depth to a root restricting layer (DRRL) and the pH of the C horizon (PHC) (Figure 15).

Table 25. Site index ($BHSI_{15}$) prediction table for morainal soil group.

pH of the C Horizon	Depth to a root restricting layer (cm)					
	<10	30	50	70	90	>100
4.0	4.82	6.75	7.64	8.23	8.67	8.86
5.0	4.78	6.70	7.59	8.18	8.62	8.81
6.0	4.73	6.65	7.55	8.13	8.57	8.76
7.0	4.68	6.60	7.50	8.09	8.53	8.71
8.0	4.63	6.45	7.45	8.04	8.48	8.66

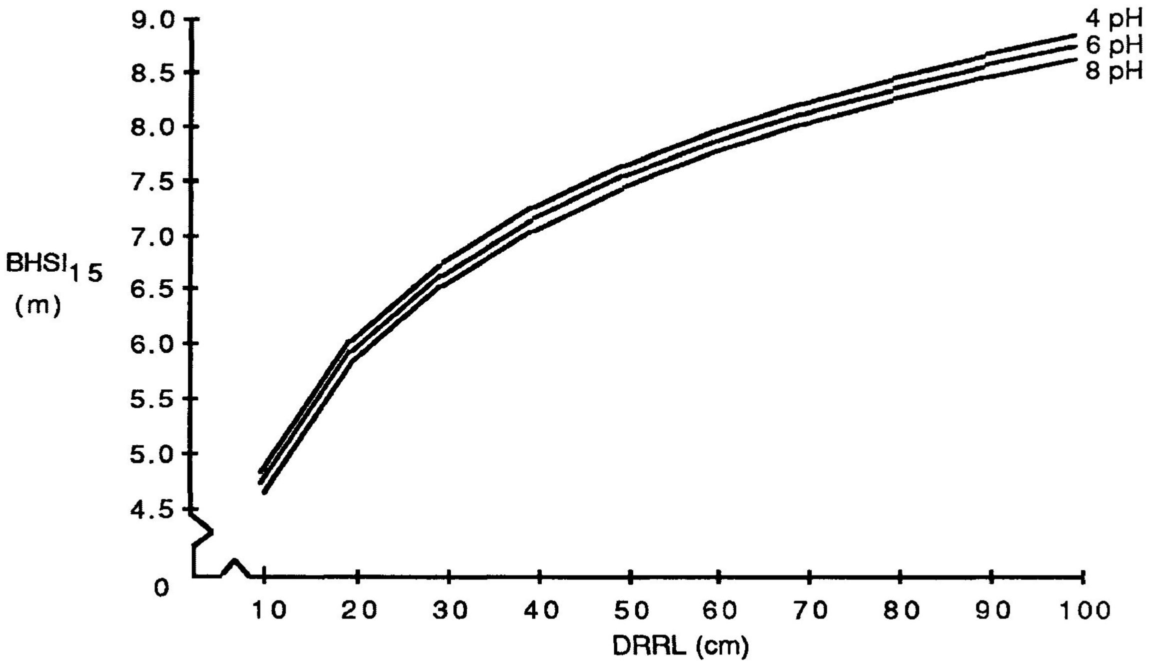

Figure 15. Relations between site index ($BHSI_{15}$) on morainal soils, the depth to a root restricting layer (DRRL), and the pH of the C horizon (PHC).

Glaciofluvial Soils

The preliminary equation (eq. G1, Table 11) for glaciofluvial soils was tested further and results showed that the preliminary equation was suitable as the final regression equation. Transformations were not tested on the variable drainage class since this variable is qualitative, and transformations of this type of variable would be inappropriate. Weighted regression was also tested with less well drained classes given less weight in an effort to produce a bell shaped relationship. However, few plots were available for moderately well drained soils, thus weighted regression did not improve the precision of the regression equations.

Drainage class for the glaciofluvial plots was plotted to inspect visually the relationship and see if the check plots were well distributed throughout the range of data (Figure 16). The data was well distributed across the range of data for the glaciofluvial soil group. Since the variable DRAIN was the simplest equation and most readily applioed in the field, Eq. G1 was selected as the final regression equation for the glaciofluvial soils.

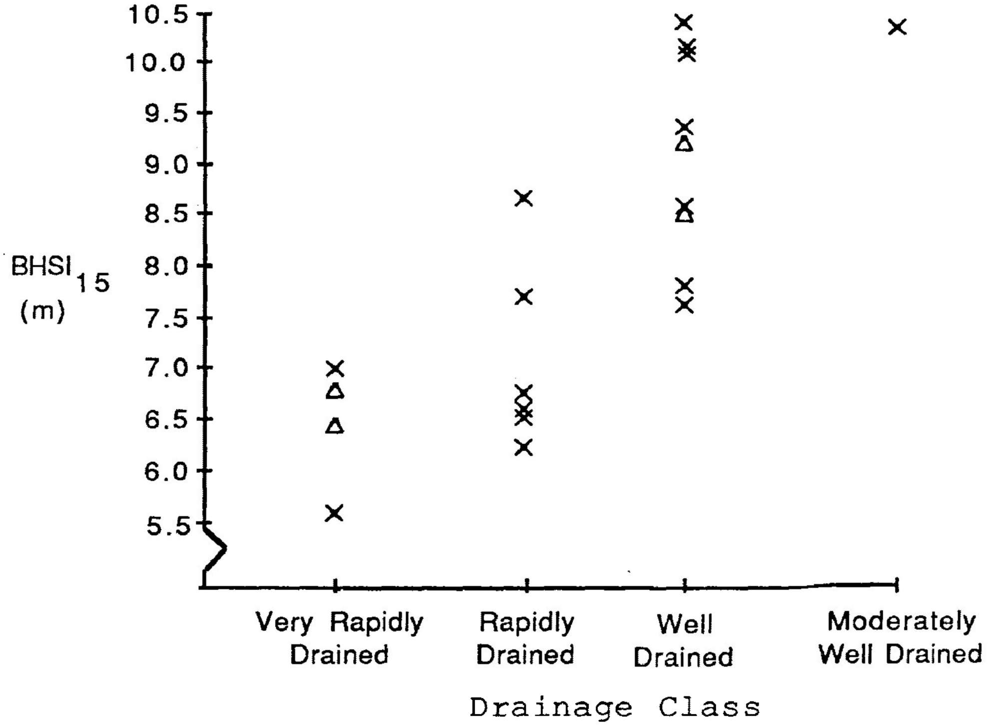

Figure 16. Relations between site index ($BHSI_{15}$) on glaciofluvial soils and drainage class (DRAIN)
x Indicates plots used in developing equation G1
Δ Indicates the four independent check plots

Since equation G1 was the same equation selected in the preliminary independent variable screening, the independent test plot site index ($BHSI_{15}$) predictions have not changed. For convenience Table 26 lists the site index predictions and the residuals for the four independent test plots on glaciofluvial soils. The predicted $BHSI_{15}$ for the four glaciofluvial test plots agreed closely with the observed $BHSI_{15}$. Accordingly, the four check plots were added to the 16 computation plots and the regression equation was recomputed (eq. G2). Comparisons between G1 and G2 show that precision was somewhat improved when all 20 plots were used (Table 27).

Table 26. Glaciofluvial test plots, their observed site index ($BHSI_{15}$), the predicted site index using equation G1, and the residuals from the predictions.

Plot Number	Observed site index	Predicted site index (Eq. G1)	Residuals (m)
11	9.17	8.96	0.21
31	8.50	8.96	-0.46
49	6.38	5.84	0.54
50	6.71	5.84	0.87

Observed $BHSI_{15}$ based on stem analysis was compared to predicted $BHSI_{15}$ using equation G2 (Figure 17). This comparison illustrates the close agreement between observed and predicted site index ($BHSI_{15}$), and also that residuals are minimized and evenly distributed.

Table 27. Final regression equations for the glaciofluvial soil group, with (Eq. G2) and without (Eq. G1) the independent check plots. Also listed are the number of observations (N), adjusted (R^2) and standard errors of the estimate (SEE).

Equation Number	Regression Equation	N	Adj. R^2	SEE (m)
G1	$BHSI_{15} = 4.283 + 1.560$ (DRAIN)	16	0.59	1.03
G2	$BHSI_{15} = 4.673 + 1.418$ (DRAIN)	20	0.62	0.94

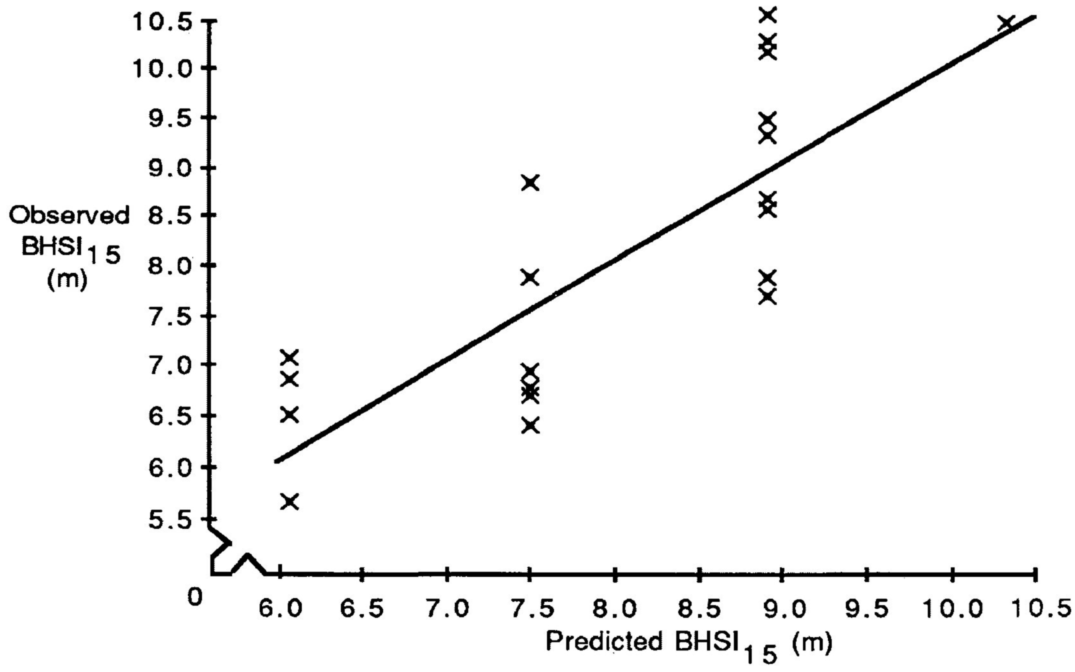

Figure 17. Relations between observed site index (BHSI$_{15}$) on glaciofluvial soils and predicted site index (BHSI$_{15}$) using equation G2.

The precision of equation G2 is further illustrated by Figure 18, where BHSI$_{15}$ is related to drainage class (DRAIN) and the lines for the 95% confidence interval are also included.

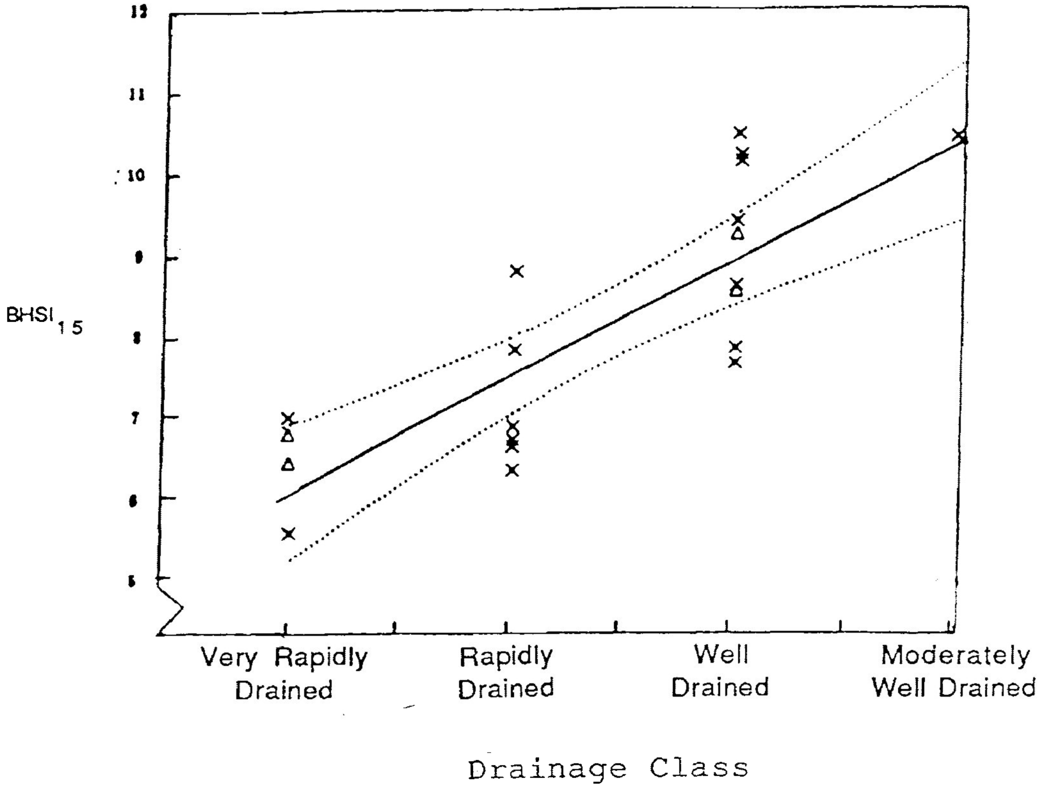

Figure 18. Relations between site index ($BHSI_{15}$) on glaciofluvial soils and drainage class (DRAIN). Also included are 95% confidence limits.
—— indicates the regression equation
······ indicates the 95% confidence limits.

Equation G2 using all plots was used to construct a site index prediction table (Table 28). This graph lists only drainage classes that were observed in this study i.e. very rapidly drained, rapidly drained, well drained, and moderately well drained. The simple G2 regression equation given in Table 27 also can be used for estimating site index ($BHSI_{15}$).

Table 28. Site index ($BHSI_{15}$) prediction table for the glaciofluvial soil group.

Drainage Class	Site Index ($BHSI_{15}$)
Very Rapidly Drained	6.09
Rapidly Drained	7.51
Well Drained	8.93
Mod. Well Drained	10.34

DISCUSSION

SCREENING OF INDEPENDENT VARIABLES

Many soil-site studies have large numbers of soil, topographic, and climatic measurements to be tested for relationships with site index. This problem can become so severe that the number of independent variables is often larger then the number of site plots, particularly if data are stratified into separate soil groups as in this study. Accordingly, many independent variables can have spurious correlations with site index, and many independent variables can be intercorrelated with each other (multicollinearity). The presence of multicollinearity in multiple regression models is a violation of the assumption of regression; therefore, if multicollinearity exists in a model, the relationships expressed by regression equations may not be real. Accordingly, independent variables must be screened to: (1) reduce the number of independent variables (dimension reduction); (2) select variables which have a higher probability of representing true biological relationships; and (3) select variables which minimize multicollinearity.

Screening procedures were used in this study to reduce the number of variables in the final regression equations, and also to select only those variables which represented (either directly or indirectly) real biological relationships. Also principal component analysis was used as a check on the variable screening procedures that were used by Schmidt (1986), Schmidt and Carmean (1988) and as an alternate means for selecting independent variables. In the preliminary screening the different methods of independent variable screening resulted in selecting slightly different independent variables, but the final multiple regression analysis resulted in identical multiple regression equations regardless of the methods used in the preliminary screening.

Efforts to reduce multicollinearity between independent variables involved closely observing regression equations for: (1) large changes in estimated regression coefficients when a variable is deleted or added; (2) large changes in coefficients when plots are added or deleted; and (3) the algebraic signs of coefficients do not conform to logical expectations (Chatterjee and Price, 1977). In addition, Pearson correlation matrices were derived for each set of independent variables. These matrices were then used to evaluate the magnitude of the interaction terms between each of the independent variables. The selected final regression equations were those that had limited signs of multicollinearity, and had nonsignificant interaction terms.

When collecting data from field plots it is possible to include plots having unusual or irregular soil conditions, or certain plots might belong to an entirely different soil group --- such unusual values are termed outliers by statisticians. An effort was made to eliminate such outliers using Bonferoni's "t" test to determine if residuals belonged to the population under study. Such outliers were not observed in this study.

Multiple linear regression is an analysis expressing linear relationships between X and Y. However, this procedure can produce poor results if certain independent variables (X) have curvilinear instead of linear relations to site index (Y). In an effort to detect nonlinear relationships between dependent and independent variables a number of different procedures were used. First, scatterplots of each independent variable in relation to site index were examined visually for nonlinear relationships. If such a relationship was detected a series of transformations expressing curvilinearity were made to determine if improvements could be made in the precision of the relationship (R^2) to site index. Scatterplots of the residuals also were examined to detect the presence of non-random clustering. These tests for curvilinearity resulted in a logarithmic transformations of the variable depth to a root restricting layer (DRRL) that produced a more precise equation for morainal soils (Table 22, eq. M3).

PRELIMINARY COMPUTATIONS

Prior to variable screening, preliminary regression equations were developed for each landform and for the entire data set. All regression equations for individual landforms were significant at the 0.05 level, with the lowest R^2 being 0.63. However, combining all data resulted in a non-significant equation having an R^2 of only 0.25 (Table 11). Further study of these preliminary equations indicated that some of the independent variables did not represent true biological relationships. For example, equation L1 given in Table 11 illustrates a relationship between $BHSI_{15}$ and chroma of the C horizon (CRMC), the average amount of silt in the total profile (TOTSI), depth to a root restricting layer (DRRL), chroma of the A horizon (CRMA), and the depth to prominant mottles (DPM). Further study showed a close interaction between DRRL and DPM indicating severe multicollinearity, and also indicating that mottles were related to root restrictions. In addition, the TOTSI and CRMA have little biological meaning indicating that their apparent relation to site index is spurious or an indirect relationship.

Equation L1 also lists the independent variable CRMC. Further study indicated that this variable may only signify a difference between the two common lacustrine deposits (red clays and grey silts) found in the North Central Region. However, this relationship was further complicated by gleying in the C horizon of some of the lacustrine plots. To eliminate this indirect relationship a dummy variable CLAY was added to the preliminary screening that indicated the two types of lacustrine deposits (red and gray).

Schmidt (1986; Schmidt and Carmean, 1988) reduced the number of the independent variables using the backward elimination method in multiple regression to select the 10 most significant independent variables that were related to site index ($BHSI_{15}$). The limit of 10 independent variables was an arbitrary decision that probably did not eliminate any variables having significant soil-site relationships. For this white spruce study a limit on the number of independent variables was held to one less than the number of observations, but this limit was never reached. The preliminary variable screening procedure resulted in the selection of 14, 16, and 11 promising independent variables for the lacustrine, morainal, and glaciofluvial landforms, respectively.

SECONDARY ANALYSIS

The first step in the secondary analysis process used by Schmidt (1986; Schmidt and Carmean, 1988) was to define more closely the glacial landforms. This procedure eliminated unexplainable variation introduced by certain plots having abnormal soils or plots that had an exceptional amount of internal soil variation within the boundaries of the plot. The glacial landforms used by Schmidt were;

1. Lacustrine Soils:
   (a) The parent material is lacustrine in origin;
   (b) the fine earth fraction contains less than 50% sand.

2. Morainal Soils:
   (a) The parent material is glacial till;
   (b) the profile contains more than 10% coarse fragments;
   (c) soil depth is greater than 100 cm; and
   (d) no exposed bedrock is visible on the plot.

3. Glaciofluvial Soils;
   (a) The parent material is glaciofluvial or fluvial in origin;
   (b) the profile contains less than 20% coarse fragments;

(c) the profile contains no cobbles or stones; and

(d) the fine earth fraction contains more than 50% sand.

Schmidt's stricter definitions of the glacial landforms may have resulted in more precise regression, however, this procedure also limits the inference space of the study. For example, Schmidt's procedure eliminated a few glaciofluvial soils that were shallow to bedrock, and also eliminated a few soils having mixed landform characteristics such as gravelly glaciofluvial soils. The research must balance the need for more precise regression equations with the applicability of the results, thus plots representing these soils should appear in the analysis if these unusual soils commonly occur.

In this white spruce study there were only a few shallow to bedrock plots. Schmidt separately anaysed these soils, but I added them to the other morainal soils. Thus this added data to the morainal landforms eliminated the one-metre limit for shallow to bedrock soils. The 20 percent gravel limit on glaciofluvial soils was eliminated because I felt it limited the inference space of the study. Other than these exceptions the definitions of the glacial landforms types were identical to those used by Schmidt (1986). These similarities help make my study comparable to Schmidt's study, and also improves the implementation of the results in the field.

The first step in secondary analysis was to study each of the independent variables and judge if these variables represented real biological relationships. This judgement was based on past relationships found in the soil-site literature, and also on observations and working hypotheses developed during the collection of field data. All the independent variables that lacked biological validity were removed from further analysis. The remaining variables were used in "leaps and bounds" all subset regression (Becker and Chambers, 1984) to select the final regression equations. This procedure was used with the three landforms, and with all possible subsets of independent variables within each landform. The final regression equations were selected based on the least number of independent variables having the highest R^2, and on the lowest standard errors of the estimate. These final regression equations were then checked using multiple forward regression to insure that the independent variables were all significant at an alpha level of 0.05.

LACUSTRINE SOILS

The secondary screening indicated that seven independent variables were significantly correlated with site index ($BHSI_{15}$) for lacustrine soils. Further analysis indicated that a negative relationship for chroma of the C horizon (CRMC) was an indirect relationship between $BHSI_{15}$ and lacustrine deposit types; that is, red clays (with lower silt content) tended to have higher site indices then the grey silty lacustrine soils. In addition, the independent variables CRMC (chroma of the C horizon) and SC (percent sand in the C horizon) indirectly indicated differences between the red clay and grey silts. Therefore, the dummy variable CLAY was introduced as a means for avoiding intercorrelations between these two independent variables. The exception was CRMC where this variable seemed to indicate plots having fluctuating water tables due to gleying in the C horizon. Hue of the C horizon (HUEC) also seemed related to this gleying effect; consequently, the use of HUEC in the final regression equation instead of CRMC helped eliminate intercorrelation.

Independent variables consistently and significantly related to site index ($BHSI_{15}$) on lacustrine sites were DRRL and THAB (the combined thickness of the A and B horizons). These variables apparently are good indicators of the amount of rooting space available to white spruce trees. The significance of these variables to site index ($BHSI_{15}$) indicates that white spruce at 15 years breast-height age have roots that have expanded to fill the available rooting space and that root competition for moisture and nutrients affects tree growth and consequently site index.

The final regression equations for lacustrine soils (L2 and L7) contained the independent variables CLAY, DRRL, and HUEC. Transformations of these independent variables indicated no non-linear relationships in the data set. The final regression equation (eq. L7) for these lacustrine soils indicates that the red clays support better growth than the grey silty lacustrine soils. Schmidt (1986; Schmidt and Carmean, 1988) also found that site quality for jack pine was better on red clays than on the grey silts. For these lacustrine soils the amount of available rooting space seems to be the most important soil feature associated with site index ($BHSI_{15}$), followed by evidence of gleying that indicates the presence of fluctuating water tables in the C horizon.

MORAINAL SOILS

The secondary screening indicated that three independent variables were significantly correlated to $BHSI_{15}$. These independent variables included DRRL, THAB, and PHC (pH of the C horizon in water). The variable DRRL was by far the most important of the independent variables for the morainal landform.

The final regression equation (eq. M2) included DRRL and PHC. Transformations of DRRL indicated that the relationship of this variable to $BHSI_{15}$ was curvilinear, and that an equation containing the natural logarithmic transformation of DRRL (eq. M3) was more precise than equation M1, and had lower standard errors of the estimate (Tables 22). Accordingly, equation M7 is the recommended regression equation for use in predicting $BHSI_{15}$ for white spruce on morainal soils.

The independent variable PHC by itself was not significantly correlated to $BHSI_{15}$ of morainal sites, but when used in conjunction with LNDRRL (natural log. of DRRL) this PHC variable contributed significantly to the equation. To explain this situation a closer look at the data was necessary. Some of the plots used in this data set were from the Limestone Lake and Tyrol Lake plantations near Lake Nipigon (Figure 5). Soils from these areas contained calcareous tills, often had larger amounts of silt plus clay, and higher pH values in the C horizon. The variable PHC indicated that the spruce growing on these more calcareous soils have somewhat poorer growth than spruce growing on more sandy, acidic tills.

There was a large change in the value of the coefficient b_2 from equation M3 to equation M7 due to the addition of the data from the 5 independent check plots. This large change in coefficient value indicates that the relationship of PHC to $BHSI_{15}$ should be examined in much more detail before the variable PHC can be recommended for use in predicting $BHSI_{15}$.

GLACIOFLUVIAL SOILS

The secondary variable screening (Table 13) indicated that three independent variables (DRRL, PHA, and DRAIN) were significantly correlated with site index ($BHSI_{15}$). However, drainage class (DRAIN) was the most significant of these three final variables, and the remaining two variables DRRL and PHA (pH of the A horizon) were less important. When DRAIN was used in a regression equation neither DRRL or PHA significantly contributed to the precision of the regression equation. This may be explained by looking at the possible relationships between DRAIN, DRRL and texture. Without DRAIN in the equation the moisture conditions of the site may be explained by the DRRL and the texture of the soil. For example, soils with a shallow DRRL or a coarse texture are poorer sites and would have very little available moisture. However, the corresponding very rapid drainage class combines the contributions of DRRL and texture to explain more adequately the variation. Consequently the final regression equation for glaciofluvial soils (eq. G1) was identical to the equation derived in the preliminary analysis.

Equation G2 indicates that the relationship between drainage class and site index ($BHSI_{15}$) was so strong that relatively little variation remained for correlation with other independent variables. The strong relationship for drainage is logical because glaciofluvial soils range from very dry coarse sands to moist, loamy, very fine sands. Thus drainage class apparently indicates the amount of available moisture.

Historically many soil-site studies have found that tree growth is related to the drainage condition of the soil. It has also been observed that the relationship between drainage class and site index is curvilinear. When soil drainage is slow soil aeration inhibits root development, thus site index is poorer. As drainage increases site index increases until an upper asympote is reached where moisture drains so quickly that available soil moisture is limiting thus site index is poorer. However, the range of observed drainage classes for this study was fairly narrow, only one moderately well drained plot was established (Fig. 16). A linear relationship of site index to drainage class may not continue if the range of drainage sampled was expanded and the variable used to express drainage class is of a quantitative nature.

The final regression equations for the three glacial soil groups contained at least one independent variable that could be termed a composite variable. A composite variable is a variable that is comprised of two or more primary variables, and thus expresses the multiple effects of the primary variables used in developing the composite variable. For example, DRRL is derived from several primary variables including depth to prominent or distinct mottles, depth to bedrock, depth to a water table, depth to gleying, depth to a hardpan, and depth to a basal till. Thus, the independent variable DRRL might express several primary variables that restrict rooting depth. Drainage class also can be considered as a composite variable that expresses effects of soil texture, and the presence and the depth to mottles, or gleying. An attempt was made to correlate other soil and topographic variables with drainage class. This was done in order to understand better the effects of drainage class, and also perhaps to develop means for predicting site index based on specific primary variables instead of the composite variable DRAIN. However, these attempts were inconclusive thus equation G6 (Table 28) using DRAIN alone seems to be the best method for estimating site index ($BHSI_{15}$) for planted white spruce in the North Central Region of Ontario.

AREA OF APPLICATION

The definition of the population of soils represented, and the sampling methods used in this study determine where and under what conditions results can be applied. The study area, glacial landforms, and plot selection methods used in this study are described in the methods section of this text. Briefly, a 100 percent survey was made of the white spruce plantations located in the North Central Region of Ontario that were at least 20 years of age. Those plantations that were fully stocked, and free of suppression were then selected for sampling. Plots were not randomly sampled but instead were located in areas of plantations having relatively homogeneous soil and topographic conditions. Plots were also located in areas judged to represent the full range of soil, topography, and site quality for white spruce plantations in North Central Ontario. This non-random plot selection procedure means that theoretically the results only apply to conditions found on the study plots. Thus, according to statistical theory the results cannot apply to plantations that were rejected due to poor stocking and suppression or even to areas where plantations have not been established. However, if one is willing to make a series of reasonable assumptions the results of this study can be applied to a much larger population.

The major assumption is that the height-growth curves (site index curves) and the soil-site equations developed in this study are similar to height-growth curves and soil-site conditions of plantations not sampled, or to areas where plantations were never established. Of course, the height-growth curves described in this study would not apply to suppressed trees or to trees in poorly stocked plantations, but we assumed that they would apply to other well stocked plantations having uninjured, unsuppressed, free-growing dominant trees. As for soil and topographic conditions, accepting the assumptions depends upon judgements regarding how well the study plots represent the range of soil and topographic conditions found with lacustrine, morainal, and glaciofluvial soils of North Central Ontario. It must be recognized that the small area of suitable, older white spruce plantations occurring in North Central Ontario may not be located on the full range of soil and topographic conditions of this region. For example, early planting practices may have avoided planting on poorly drained lacustrine soils, very stony or very shallow to bedrock morainal soils, or very shallow glaciofluvial soils on steeper slopes. Nevertheless, the wide range of soil and site quality conditions observed on these study plots probably mean that these plots do represent the more common soil and topographic conditions characterizing the lacustrine, morainal, and glaciofluvial soils of North Central Ontario. The results of this study cannot be applied to landform types and soil conditions not sampled in this study which include organic soils, alluvial soils, and tallus slopes; but such soils are traditionally not considered for the establishment of white spruce plantations.

An additional precaution taken to help support the assumption that the plots represent the range of soil conditions found on the three landforms in the North Central Region of Ontario is the random selection of check plots before variable screening began. Ten percent of the plots sampled in each of the landforms were selected at random and held in reserve to test the validity of the final regression equations. The final regression equations were successful in predicting site index ($BHSI_{15}$) on all check plots for all three landforms. The ability of the check plots to predict accurately the observed site index adds some validity to the assumption that these equations do represent relations between white spruce site index and soil characteristics of the three sampled landforms.

Additional insight on how well these soil, topographic, and height growth patterns apply to the overall population is given by Thrower (1986). Thrower commented that in the North Central Region early plantations usually were established on the best sites. More recently, plantation site selection has become less selective and white spruce has been established on a wider range of sites following logging.

Techniques in stock rearing, genetic selection, and planting may have an effect on soil-site relationships, and height-growth patterns. However, Thrower felt that these factors would only significantly affect early juvenile height growth below breast height and, as a result, $BHSI_{15}$ would not be seriously affected. It follows then that soil-site relationships based on $BHSI_{15}$ also would not be seriously affected.

Caution also should be observed in applying results of this study to areas outside the study area because the applicability of these results outside the study region is unknown. Accordingly, before these results are applied in other regions test plots should be located to determine how applicable these results are to these other regions.

COMPARISON TO OTHER STUDIES

Results of this study show that different soil-site relationships occur on the three different glacial landforms, but there are some underlying similarities. Both the lacustrine and morainal landform regressions had a variable representing depth to a root restricting layer (DRRL); this variable expresses rooting depth. Rooting depth is also expressed in the drainage class (DRAIN) variable for the glaciofluvial landform. The second underlying characteristic for each of the landforms is the influence of subsoil conditions. The lacustrine equation includes a variable for the type of lacustrine deposit (CLAY), and also a variable for colour of the C horizon (HUEC); for morainal soils the subsoil variable was the pH of the C horizon (PHC). Subsoil characteristics are also expressed in the variable DRAIN for the glaciofluvial landform.

The variables found to be correlated with site index ($BHSI_{15}$) in this study probably occur because soil depth and subsoil conditions are associated with moisture and nutrient conditions important to the growth of white spruce. Soil moisture has been found to be related to white spruce height growth (Kenety, 1917; Owens _et al._, 1977; Clements, 1970; Pollard and Logan, 1977; Wilde _et al._, 1965). This agrees closely with Wilde _et al._ (1965) who observed that white spruce achieves its best growth on fresh to moist sites, and poorer growth occurs on sandier sites. Soil having deep rooting depths usually have more available soil moisture, thus moisture is indirectly related to $BHSI_{15}$ for the lacustrine and morainal landforms where DRRL was significant, and the glaciofluvial landform where DRAIN was significant. Moisture may also be indirectly related to $BHSI_{15}$ for all equations where subsoil variables (CLAY, PHC and HUEC) were significant.

Soil pH has also been correlated to height growth of planted white spruce (Rawinski _et al._, 1980; Harding _et al._, 1984; Teich and Holst, 1974). Most agree that the optimum range of pH for white spruce is between 4.7 and 6.5. The majority of the soil samples taken in this study fell well within this range of pH, thus pH variables probably were not strong variables because neither very acid or very calcareous soils were represented. Morainal sites contained the only plots on calcareous soils, and the relations expressed by the M7 equation correspond well with those found in the literature.

The most common soil variable related to $BHSI_{15}$ in this study was the depth to a root restricting layer (DRRL). The most probable reason for this is that the variable represents the volume of the soil available for root development. Coile (1952) stated that site quality is a function of "... those properties which influence the quantity and quality of growing space for tree roots".

Note in Table 13 that course fragment content of the C Horizon (CFC) was related to $BHSI_{15}$ for morainal soils. This relationship, along with DRRL, corresponds well to the soil-site relationships Schmidt (1986) and Schmidt and Carmean (1988) observed for jack pine in the North Central Region of Ontario. However, in the final regression equation selection process the strength of the relationship of CFC to $BHSI_{15}$ was not significant enough to make the final regression equation.

RECOMMENDATIONS FOR FUTURE RESEARCH

This research helped me to understand better both the benefits and the limitations of soil-site and site quality research. As a result the following areas of research are suggested as possible means of improving the design and results of future soil-site research.

1. More white spruce site plots are needed representing a wider range of soil and topographic conditions. Also more check plots are needed to test the validity of these soil-site results, and more research is needed to develop better verification techniques for soil-site equations.

2. Future research is needed to develop improved sampling methods for locating soil-site plots within stands. Results of studies using improved plot selection techniques could be compared to present methodology to determine if present results are realistic.

3. Independent variable screening and selection methods could be improved using multivariate analysis techniques including cluster analysis.

4. Permanent sample plots should be established to provide information on the future height growth patterns and soil-site relationships of white spruce plantations as these plantations age and mature.

5. The Tree Ring Increment Measurement (TRIM) system could be used to gather yield data in addition to height-age data currently collected from the site trees. In addition to measuring the site index trees, yield studies would also require that all trees on the plot be inventoried. This tree inventory would include both height growth and tree ring width measurements along with measurements of stand density. Yield data from such expanded studies could be used to develop yield tables for all the commercial forest species in Ontario, both in plantations and in natural stands.

6. Soil-site work is needed for other species not yet studied in the North Central Region of Ontario including trembling aspen, black spruce, red pine, and white pine. Such soil-site information will provide species selection information useful in managing the commercial forests of the region.

7. Research also is needed on the economic feasibility of various levels of intensive management for different species based on yield and site index classes. This research will aid in concentrating intensive management on the most productive lands, and on the most

productive and valuable tree species. This will also provide a foundation for species selection based on the value of final products in respect to the cost of inputs needed to establish the species on the site.

8. Research is needed on the basic soil moisture and nutrient relations associated with statistical correlations obtained by soil-site research.

CONCLUSIONS

White spruce plantations greater than 20 years of age were identified using OMNR silvicultural records. All plantations were field surveyed and all fully stocked plantations that did not show signs of suppression were sampled. Height-age information from stem analysis, and soil and topographic characteristics were measured on a total of 73 plots. Two plots were eliminated because they were outside the study area, 1 plot was eliminated due to excessive soil variation on the plot, and 2 plots were eliminated because their height-age curves indicated suppression. Analyses of the 54 computation plots and the 14 independent test plots has led to the following conclusions:

1. Soil groups may have relatively few plots and numerous soil variables thus presenting difficulties in multiple regression analyses. This problem was avoided using screening methods that identified a small number of soil and topographic variables that were strongly correlated with site index.

2. Principal component analysis was used to validate the multiple regression analysis techniques. Principal component scores were derived for each of the landform types. The most significant variable expressed within each component score was selected and compared to the multiple regression equations. This comparison indicated that the significant soil and topographic variables selected in the multiple regression equations were identical to those selected in the principal component scores, which may add validity to the variable screening techniques used in this study and also used by Schmidt (1986) and Schmidt and Carmean (1988).

3. Preliminary regression equations combining all plots in an unstratified data base indicated that height growth was not strongly related to soil and topographic variables. The

regression equation explained only 25% of the total variation in the data set. However, once the plots were stratified into three broad landform types the relations between site index and soil variables became much more significant. The final regression equations for the lacustrine, morainal, and glaciofluvial landforms explained 77, 66, and 65 of the total variation of site index $BHSI_{15}$, respectively.

4. Preliminary analysis indicated that the relationship of soil and topographic variables to $TOTSI_{25}$ were much weaker than the relationships expressed using $BHSI_{15}$. This indicated that the slow and erratic height growth of white spuce before it reaches breast height is not necessarily a function of site quality. This slow and erratic early growth may be a function of handling at the time of planting, or competition in the early years after planting.

5. The final regression equations for lacustrine, morainal, and glaciofluvial sites predict $BHSI_{15}$ reasonably well for 14 independent check plots held in reserve. This may indicate that the final regression equations may be suited for field use in predicting site index for young white spruce plantations in the North Central Region which occur on lacustrine, morainal, and glaciofluvial soils.

6. This study along with studies by Thrower (1986, 1987), Lenthall (1986), and Carmean and Lenthall (1989) have a practical application for forest managers in the North Central Region of Ontario. Site index curves and growth intercepts provide forest managers with methods for directly evaluating site quality for both jack pine and white spruce when the species is present on the site. Soil-site studies for jack pine (Schmidt and Carmean, 1988)

and my soil-site study for planted white spruce can be used for indirectly estimating site index on lands that do not have the species, are uneven-aged, stands that have been partially cut, or in areas that have been clearcut. With this information foresters can make decisions regarding which species is most suitable for managing on different sites.

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APPENDIX I

Physical Properties

Plot # :	Longitude :	Latitude :	SI (bha) :
SI (tha) :	Depth L :	Depth F :	Depth H :
Depth A :	Depth B :	Depth C :	% Sand A :
% Silt A :	% Sand B :	% Silt B :	% Sand C :
% Silt C :	Hue A :	Value A :	Croma A :
Hue B :	Value B :	Croma B :	Hue C :
Value C :	Croma C :	Mottles A :	Mottles B :
Mottles C :	Grade A :	Class A :	Kind A :
Grade B :	Class B :	Kind B :	Grade C :
Class C :	Kind C :	% Co. Frag A :	% Co. Frag B :
% Co. Frag C :	Rt Ab A :	Rt Ab B :	Rt Ab C :
Slope Lth. :	Up slope :	Slope % :	Aspect :
Sur shp :	site pos. :	Seep. :	Carb. :
Dth bedrock :	Dth Water :	Dth Mottles :	Dth gley :
max rooting :	pore pattern :	Humus type :	Moist. Regime :
drainage :	FEC soil :	FEC Veg :	

Chemical Properties

N :	
K :	
P :	
Ca :	
Mg :	

Percent Organic Carbon :

Comments:

APPENDIX II

Plot:	STEM ANALYSIS	Date:
Township or basemap:	Avarage S.I.	Name:
Remarks:		Map #:

	Tree #: 1	Tree #: 2	Tree #: 3	Internode (m)	Tree #: 1	Tree #: 2	Tree #: 3
HT (m)	Code #:	Code #:	Code #:				
stump				1			
0.25				2			
0.50				3			
0.75				4			
1.0				5			
1.3				6			
1.5				7			
2.0				8			
2.5				9			
3.0				10			
3.5				11			
4.0				12			
4.5				13			
5.0				14			
5.5				15			
6.0				16			
6.5				17			
7.0				18			
7.5				19			
8.0				20			
8.5				21			
9.0				22			
9.5				23			
10.0				24			
10.5				25			
11.0				26			
11.5				27			
12.0				28			
12.5				29			
13.0				30			
13.5				31			
14.0				32			
14.5				33			

APPENDIX III

Plot	Standard Errors of the Estimate (m)			Years Extrapolated
	Tree 1	Tree 2	Tree 3	
7	0.155	0.176	0.142	1
18	0.184	0.254	0.374	1
19	0.110	0.102	0.049	3
20	0.141	0.102	0.123	5
24	0.176	0.107	0.192	3
32	0.149	0.088	0.148	4
33	0.065	0.110	0.074	4
35	0.266	0.104	0.185	1
36	0.081	0.169	0.170	2
37	0.176	0.201	0.146	2
38	0.149	0.192	0.123	1
48	0.110	0.109	0.137	3
49	0.071	0.085	0.071	4
53	0.264	0.297	0.341	1
57	0.103	0.199	0.151	3
60	0.222	0.225	0.208	3
69	0.169	0.169	0.168	2