SOIL - SITE RELATIONS
FOR JACK PINE
(*Pinus banksiana* Lamb.)
IN NORTHEASTERN ONTARIO

Paul A. LeBlanc ©

A thesis submitted in partial
fulfillment of the requirement for the Degree
of Master of Science in Forestry

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ABSTRACT

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Keywords: jack pine (*Pinus banksiana* Lamb), site index, site-quality, soil, soil-site

Site index of jack pine (*Pinus banksiana* Lamb) measured on 76 plots in northeastern Ontario was related to features of soil and topography using multiple regression. Site index at breast height age 50 years (SI_{BH50}) was used as the dependent variable, and 119 soil and topographic values were used as independent variables. Regression equations were imprecise using all 76 plots. When separate equations were computed for bedrock-moraine, glaciofluvial, and moraine landforms, precision was much greater with R^2 values of 0.78, 0.51 and 0.60, respectively.

The final bedrock-moraine equation consisted of slope percent, thickness of the B horizon, and percent stones in the top 25 cm of the soil profile. The glaciofluvial equation consisted of depth to average rooting, depth to moisture restricting layer, and percent silt in the B horizon. The moraine equation consisted of depth to maximum rooting, pore pattern, percent sand and percent silt in the BC horizon.

The northeastern Ontario plots were combined with Schmidt and Carmean's (1988) 131 plots. New regressions based on the pooled data had R^2 values of 0.84, 0.55, 0.37, 0.57, and 0.24 for bedrock-glaciofluvial, bedrock-moraine, glaciofluvial, lacustrine, and moraine landforms, respectively. These analyses produced valid jack pine soil-site equations for the combined bedrock and lacustrine landforms in northeastern and north central Ontario; but equations combining data for glaciofluvial and moraine landforms were imprecise.

The northeastern and north central Ontario plots were pooled with 16 plots from northwestern Ontario. New regressions based on the pooled data had R^2 values of 0.22, 0.47, and 0.17 for glaciofluvial, lacustrine, and moraine landforms, respectively. These analyses resulted in equations that had unacceptably low precision. The failure to compute acceptable soil-site equations was attributed to different soil and topographic variables influencing the height growth of jack pine in northwestern Ontario.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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INTRODUCTION

Forest management in Canada has changed dramatically in the last 100 years. The late 1800's were characterized by exploitation based on the viewpoint that the timber resource was inexhaustible. Pioneers viewed the forest as a barrier that must be removed and replaced by agricultural crops. In the 1920's, forests were recognized as having some commercial value, so fire suppression efforts were initiated. Forest management moved from exploitation to some extensive forest management in the 1950's. Regeneration of the second crop was given limited attention, and the reality of a finite timber resource was realized. Intensive management is now being considered for many sites with the recognition that advanced silvicultural practices will be needed for establishing and managing the most desirable tree species.

Today, almost all the commercial forest is allocated to wood-using industries. Forest Management Agreements (FMA's) base their harvest levels on regeneration levels and expected future yields. Other users of the forest demand alternative uses for the forest, resulting in a demand for Integrated Resource Management (IRM). Intensive forestry is now a reality and a necessity. However, there will never be enough money or personnel to manage all forest stands intensively. Thus, we must be selective and should concentrate management on the most productive sites and the most desirable tree species.

Intensive management should be concentrated on productive sites that will yield a return on the high-input investment needed for intensive management practices. Carmean (1993) stated five reasons for intensively managing productive sites:

1) productive sites produce a greater quantity of yield;
2) productive sites produce a better quality of yield;
3) productive sites produce larger trees sooner, thus shorter rotations are possible;
4) productive sites are best for species valued for sawlog and veneer log production; and
5) productive sites are more responsive to intensive management practices such as site preparation, release, and thinning.

Forest site-quality evaluation is an integral part of forest management (Figure 1). The various methods for site-quality evaluation provide the tools for identifying sites where growth and yield tables and models are applicable. Yield estimations are necessary for making forest management decisions regarding the intensity of forest management and which site-specific silvicultural practices to apply.

Commercially, jack pine is the second most important conifer species in Ontario after black spruce (*Picea mariana* (Mill.) B.S.P.) (Campbell 1990). Jack pine probably will increase in importance over time, due to ease and speed of artificial regeneration. Successful natural regeneration of jack pine varies, and is dependent on site-specific factors such as seed source, mineral soil exposure, and moisture levels. Jack pine is a management option on almost any site. It has a competitive advantage on dry infertile sites, grows vigorously and rapidly on moist, fertile sites, and can occupy wet mineral soils. Yields from jack pine stands are similar to yields for black spruce (Plonski 1984).

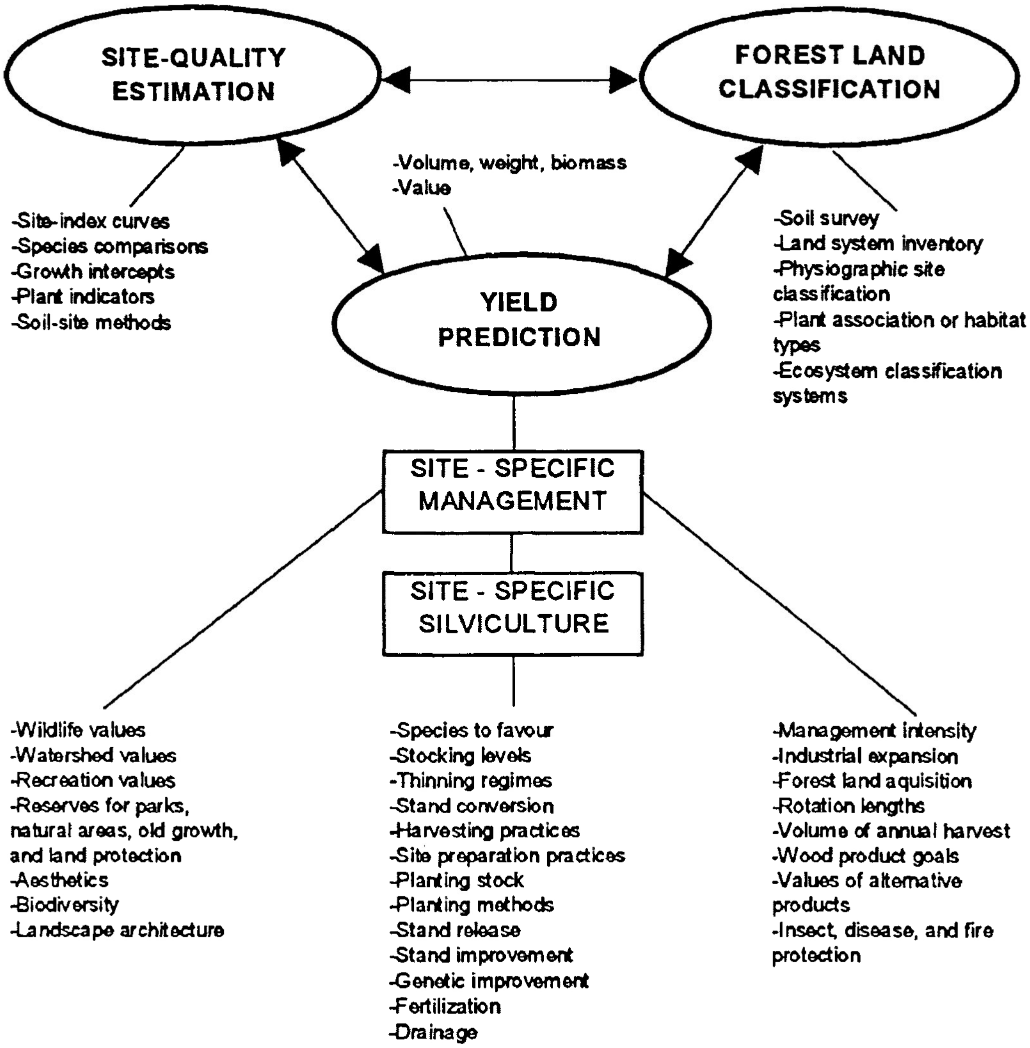


Figure 1. A complementary framework of site-quality estimation, yield prediction, and forest land classification is needed for decisions about site-specific management and silvicultural practices (Carmean 1994).

Soil-site relationships for jack pine were studied in north central Ontario by Schmidt (1986) and Schmidt and Carmean (1988), and in northwestern Ontario by Jackman (1990). However, no studies have been made in northeastern Ontario. Thus, this thesis provides information for northeastern Ontario, and also compares soil-site relationships between regions. The objectives of this thesis are to:

1) provide soil-site equations for jack pine in northeastern Ontario;
2) determine the soil features that are significantly related to the height growth of jack pine;
3) compare soil-site relations in northeastern Ontario with those produced by: a) Schmidt and Carmean (1988) in north central Ontario; and, b) Jackman (1990) in northwestern Ontario; and
4) determine if the comparison to other regions leads to the conclusion that the soil-site relations are essentially the same between regions. If so, new soil-site equations applicable to all areas of northern Ontario will be computed based on a pooled data set from all regions.

LITERATURE REVIEW

FOREST SITE-QUALITY

Forest site-quality is a measure of the ability of forest land to grow trees (Carmean 1975). Spurr and Barnes (1980) define forest site-quality as the sum total of all the factors affecting the capacity of the site to grow trees. These include climatic, soil, and biological factors.

HISTORY OF FOREST SITE-QUALITY

Site-Quality Evaluation in Europe

Site-quality was first used in agriculture in 234 B.C. (Tesch 1981). The Romans subjectively classified farm land on its ability to grow grapes. This practice of classifying land spread to the field of forestry in 1804, when German forests were subjectively ranked on a scale from 0 to 100 (Cotta 1804). Hartig (1795) subjectively delineated forest land into good, medium, and poor site classes, based on soils. Plant communities were used by Blomqvist (1872) to delineate levels of forest productivity.

Stand volume later became the most widely used system of site-quality evaluation in Europe. Baur (1876) measured stand volume at various ages for Norway spruce (*Picea abies* (L.) Karst.) in Germany; he plotted the data, then drew free-hand curves through the highest and lowest volumes, thus creating harmonized volume curves. Stand height replaced volume in an attempt to overcome the following problems: 1) arbitrary site classes based on volume may not represent actual differences in site-quality; 2) the curves are based on high and low extremes of volume; and 3) the volume curves were only applicable to 'normal' even-aged, pure, uniform stands.

Dominant tree height was assumed to be independent of stand density, leading Huber (1824) to develop a height index methodology for delineating site-quality. However, the harmonized height curves were only applicable to 'normal' even-aged, pure, uniform stands.

Site-Quality Evaluation in North America

Reviews of the history of forest site-quality evaluation in North America have been reported by Coile (1952), McLintock and Bickford (1957), Vincent (1961), Mader (1963), Jones (1969), Carmean (1975), Spurr and Barnes (1980), and Pritchett and Fisher (1987).

Three different methods of site evaluation divided the opinions of North American foresters from 1910 to 1925 (Mader 1963). Germany was currently using volume as the standard system (Bates 1918). Forest site types, as used by Cajander (1926) in Finland, was a second possibility. Height growth of dominant and codominant trees was strongly favoured by Graves (1906), Roth (1916, 1918), Watson (1917), Frothingham (1918, 1921), and Sterrett (1921).

Volume was a desirable measure, since it was recognized by the Society of American Foresters (SAF) as the most accurate measure of site-quality. However, the SAF did not commit to volume as a standard method of site-quality evaluation (Sparhawk *et al.* 1923). Volume was considered to be too dependent upon stand density, insect and disease damage to be reliable (Watson 1917). Moreover, in the 1920's, few volume tables had been developed for the major North American species.

Advocates for height growth asserted that height was independent of density, was simple to use, and could provide comparisons among tree species (Frothingham 1918, 1921). Over time, height growth was proven to be the superior method of estimating site-quality in North America. Site index based on the height growth of dominant and codominant trees is now the most widely accepted method for estimating site-quality (Carmean 1975, Carmean *et al.* 1989, Hagglund 1981).

Criticisms of site index have been presented by Mader (1963, 1968), Sammi (1965), and Cool (1965), re-iterating that volume is a more desirable measure than height growth. Inaccuracies of site index have been associated with older anamorphic site index curves, but polymorphic site index curves have recified this problem. Monserud (1984) gave valid criticisms about the <u>direct</u> estimation of site index working poorly in stands that are uneven-aged, of mixed species composition, damaged, or diseased. However, these stands can still be accurately estimated utilizing <u>indirect</u> site index estimation methods, such as soil-site methods.

HEIGHT GROWTH AS A STANDARD FOR ESTIMATING SITE-QUALITY

The use of height growth is logical, as height growth is more closely related to volume growth than any other measure (Carmean 1975). Spurr and Barnes (1980) emphasize this stating that "...the height of free-grown trees of a given species are more closely related to the capacity of a given site to produce wood than any other single measure". Height growth is also relatively unaffected by stand density or stocking (Rudolph 1951, Ralston 1953, Ware and Stahelin 1948, Lanner 1985).

USE OF BREAST HEIGHT AGE WITH HEIGHT GROWTH

Initial height growth of most tree species is slow and erratic, and has little relation to height growth above breast height (i.e. 1.3 m) and site-quality (Ferree *et al.* 1958, Day *et al.* 1960, Richards *et al.* 1962, Lenthall 1986, Thrower 1986, Carmean 1994). However, height growth above breast height is more rapid, consistent, and closely related to site-quality (Carmean 1994). Early height growth below breast height varies up to 10 years for many species (Carmean 1975), and greatly reduces the accuracy of site index curves based on total age. Thus, more accurate site index curves can be developed by using breast height age (Husch 1956, Carmean 1994), which eliminates much of the variability caused by erratic early growth below breast height.

Early erratic height growth is caused by many non-site factors including: weed and brush competition; frost damage; animal and insect injury; differences in stock quality; and planting stock and planting techniques (Carmean 1975).

Spurr and Barnes (1980) state that early erratic growth is caused by climate, topography, soil, moisture, and biological factors. Thus, eliminating this slow and erratic early height growth results in site index curves that more accurately express relationships between height growth and site-quality.

DIRECT ESTIMATION OF SITE-QUALITY

Carmean (1994) summarized site-quality evaluation methods to use, depending upon forest stand conditions (Table 1).

Table 1. The method to use for estimating site index depends upon forest stand conditions (Carmean 1994).

STAND CONDITION	METHOD FOR SITE-QUALITY EVALUATION
A. DIRECT ESTIMATION Undisturbed, even-aged, fully stocked stands	
-tree species present for which site estimation is needed, trees > 20 years of age	site index curves for species present in stand
-tree species present for which site estimation is needed, trees < 20 years of age	growth intercepts for species having recognizable internodes
-tree species not present for which site index estimation is needed, trees > 20 years of age	site index comparison graphs and equations
B. INDIRECT ESTIMATION Cutover lands, poorly stocked and uneven-aged stands, very young trees	soil-site methods; soil types, or ecosystem types can be used if they are closely related to site index

Site Index Curves

Height and age measurements from free-growing, uninjured, dominant or codominant trees in even-aged stands can be used directly for estimating site index. Site index curves specific to the tree species and geographic area are required. Carmean *et al.* (1989) summarized all site index curves in existence for eastern Canada and the eastern United States. Site index is defined as "a particular measure of site class based on the height of the dominant trees in a stand at an arbitrarily chosen age" (SAF 1983). Base ages for site index vary by species and by region. For most eastern species a total age of 50 years is favoured as a base age, but a total age of 100 years is used on the west coast; a base age of 25 years is used for plantations in the southern United States; a base age of 25 years is also gaining popularity in Canada, as plantations reach and exceed this age (Carmean 1994). Age from breast height is often used for species such as black and white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.), and red pine (*Pinus resinosa* Ait.) that have slow and erratic growth before reaching breast height.

Early site index curves in Ontario were developed from total height and total age tree measurements from temporary yield plots. These data were plotted, and fitted proportionally to an average guide curve (i.e. harmonized). These subjectively, graphically derived curves were used to define good, medium, and poor site classes (i.e. site classes one, two and three, respectively). A disadvantage of such harmonized site index curves is that the curves are not based on actual annual measurements of tree height growth. Harmonized curves were often in error, due to the guide curves being skewed when certain age classes had an abnormal distribution of site-quality. For example, high and low site index plots might not be normally distributed through all age classes. This situation could occur where young stands are mostly high site index stands due to early logging, while in contrast, older-aged stands may mostly occur on poor sites due to past logging that removed most of the older stands on good sites. Accordingly, the average guiding curve would over-estimate height growth for young ages, and under-estimate height growth for older ages (Carmean 1975). Harmonized curves also make the erroneous assumption that the pattern of tree height growth is the same for all site classes, localities, and soil conditions (Carmean 1975).

Anamorphic curves were usually constructed from a guide curve based on averaged total height and total age data using least squares regression methods. Proportional curves based on the guide curves had the same shape, regardless of site index level.

Periodic height measurements from permanent sample plots revealed a polymorphic height growth pattern different from those predicted by harmonized site index curves (Spurr 1956). The polymorphic pattern of tree height and growth also was demonstrated by both stem analyses and internode methods, beginning with Bull (1931). Polymorphic curves are now the current site index curve standard. Current polymorphic site index curves are based on stem analyses data, with annual height growth from each tree used in nonlinear regression models. Polymorphic curves can express different curve shapes for different levels of site index, and are much more accurate and useful than harmonized site index curves. Niznowski (1994) developed polymorphic site index curves for jack pine in northern Ontario (Figure 2) that were similar to the polymorphic curves developed by Lenthall (1986), Carmean and Lenthall (1989) for north central Ontario.

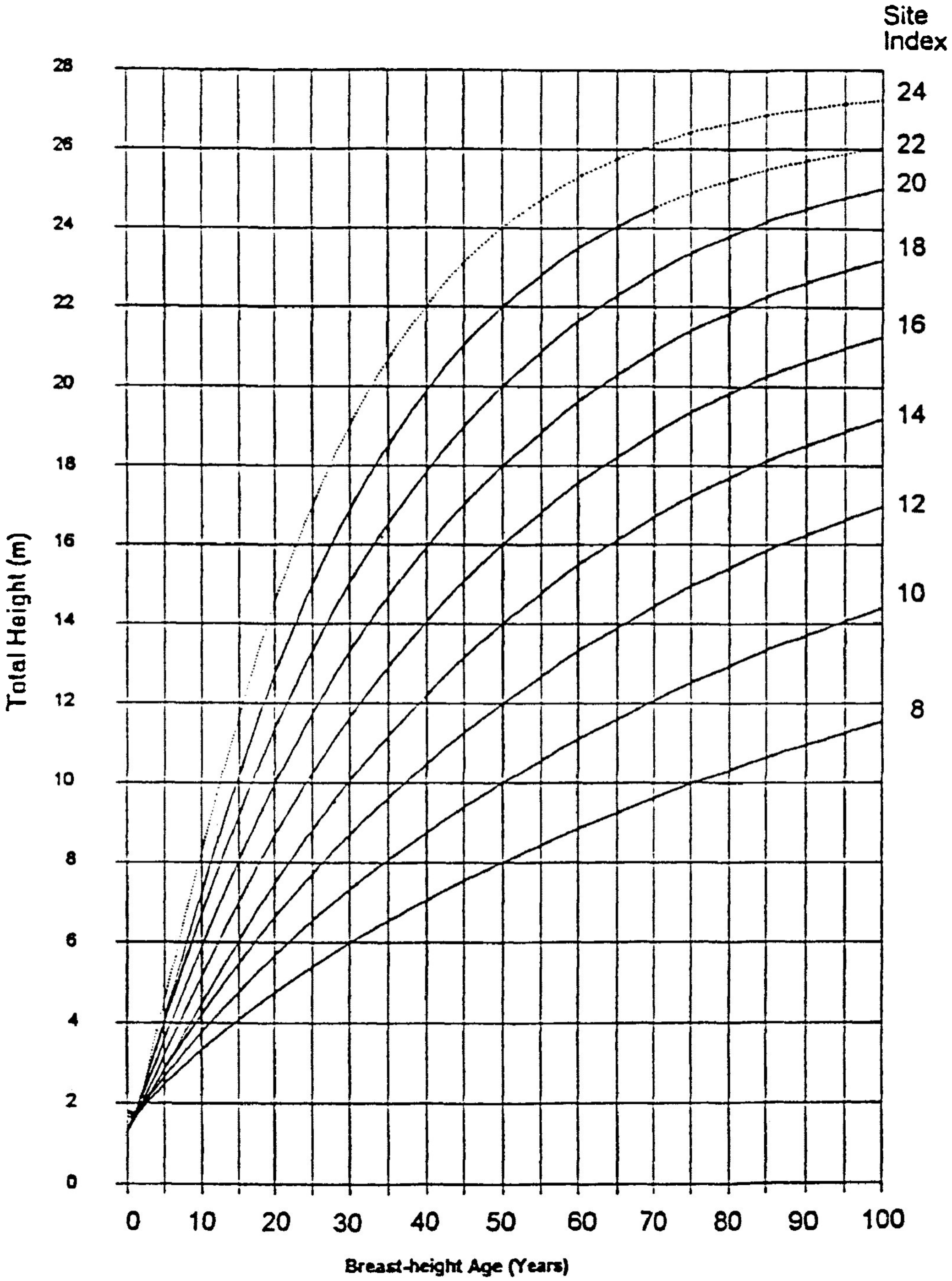


Figure 2. Polymorphic site index curves for jack pine in northern Ontario (Niznowski 1994).

Species Site Index Comparison

Species site index comparison is a method of direct site index estimation that uses measurements from tree species actually present in a stand as a means for estimating the site index of alternative tree species not present. This comparison of site index values, for different tree species on the same site, allows the most productive tree species for that site to be chosen. Thus, forest management decisions can be made not only for the tree species actually present in the stand, but also for alternative species that might be considered for future management on that site (Carmean 1994).

Site index comparison equations and graphs are constructed by measuring site index of several different tree species on the same plot. Stand and trees selected for measurement are still subject to conditions for measuring site index (i.e. even-aged and fully-stocked stands, uninjured, disease-free, dominant or codominant trees). Plots having paired site index measurements of two or more species (e.g. jack pine and aspen (*Populus tremuloides* Michx.)) are sampled across the full range of site index, soil, and climatic conditions. The site index comparison equations and graphs then are developed using regression analyses of the paired site index observations. One tree species is used as the dependent variable, and the other species is the independent variable. The resulting equations and graphs (Figure 3) can be used for selecting the most productive tree species for a given site.

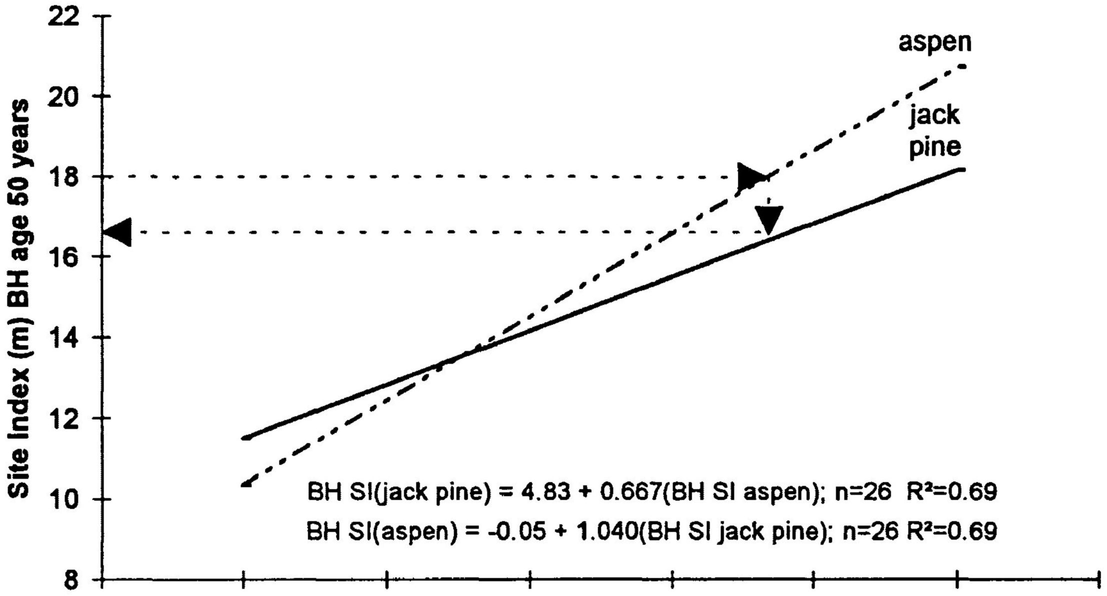


Figure 3. Site index comparison graph for jack pine and aspen in northwestern Ontario (Ortiz 1985, Carmean 1994). For example, aspen trees on a given stand have a site index value of 18 m, but there are no jack pine trees present. On the graph, begin at the 18 m mark on the Y-axis: 1) follow the horizontal hatched line straight across to the aspen line; 2) follow the line straight down to the jack pine line; 3) follow this line horizontally back to the Y-axis; and 4) read the estimated site index value (16.8 m) for jack pine.

Potential sources of error exist with species site index comparisons. If the site index estimations used in the analyses were based on older harmonized site index curves, the errors may be compounded in the resulting regression equations (Carmean 1975). This source of error can be eliminated if stem analyses is used to determine site index of each species on the study plots. A second possible source of error occurs when regression equations are solved backward, when they only should be solved forward; thus two alternate equations are provided for each species pair. Site index comparisons are merely comparisons of tree height at index age (usually 50 years); thus patterns of height growth before and after 50 years also must be considered. Many rapidly growing tree species may have slowed growth after 50 years, thus might be shorter in height when compared at 100 years.

Site index comparison graphs also can be misused by estimating site index of tree species that would not grow on certain soil types. Usually this occurs when one extrapolates beyond the graph's normal range. For example, one could measure the site index of black spruce on a wet organic soil, then use the graphs and equations to estimate the site index of jack pine. Jack pine would grow very poorly (if at all) on that site, and the true site index of jack pine on the organic soil would be much lower than the site index comparison graph would indicate. Common sense would prevent misuse of the comparison graphs.

Conversely, species comparisons are limited to the current range of species on given sites. For example, tamarack (*Larix laricina* (Du Roi) K. Koch) is generally only found on wet sites. Tamarack will grow well on both moist and dry sites (Sims *et al.* 1990a) that have a higher site index. Lack of sample plots with tamarack on moist and dry sites excludes the possibility of predicting site index of tamarack anywhere but wet sites.

Growth Intercepts

Growth intercepts can be used with uninodal tree species such as red pine, white pine (*Pinus strobus* L.), white spruce, and Douglas-fir (*Pseudotsuga* *menziesii* (Mirb.) Franco var. menziesii) that have recognizable internodes marking annual height growth (Carmean 1975). Growth intercepts directly estimate site index by measuring the distance between nodes or whorls for a selected period (usually three to five years) of early height growth. In contrast, site index curves express long-term height growth (usually 50 years). Usually, breast height (i.e. 1.3 m) is used as the starting point to measure the total distance of three to five internodes, yielding site index. However, Thrower (1986) found that more precise site index estimates could be obtained using a starting height of 1.5 m for red pine, and a starting height of 2.0 m for white spruce.

Advantages of the growth intercept method are:

1) total height is not measured, thus avoiding measurement errors associated with total height;

2) growth intercepts do not need age measurements, thus eliminating errors associated with counting annual rings (Wakeley and Marrero 1958, Carmean 1975);

3) errors from erratic early height growth are not measured, due to height growth being measured above breast height; and

4) growth intercepts can be used in very young plantations where site index curves cannot be used (Alban 1972).

Disadvantages of the growth intercept method include:

1) they are only applicable to tree species that have single, well-defined nodes or whorls marking annual height growth. Jack pine sometimes grows two whorls per year (Sims *et al.* 1990a), thus dependable growth intercepts cannot be recognized for jack pine;

2) the tree species chosen must have a strong relationship between juvenile height growth and mature height growth (Thrower 1986); and

3) the index age for site index estimated by growth intercepts is restricted from 15 to 25 years. Estimation errors occur when growth intercepts are extrapolated to older ages where polymorphic height growth patterns are much more pronounced (LaValley 1991).

INDIRECT MEASURES OF SITE-QUALITY

Indirect methods of site index estimation are required for forest stands that lack suitable trees for direct site index measurements. Conditions unsuitable for direct site index measurements include: uneven-aged stands; diseased stands; poorly-stocked stands; trees whose form is poor; recent cutovers and burns; stands less than 15 years old; and non-forested land.

There are various methods of indirectly estimating site index (Table 1). Commonly used methods utilize regression analyses to express relationships existing between site index and soil variables, topographic features, geomorphology, climatic variables, vegetation variables, or vegetation groups. These relationships are then used to predict site index when trees are not available for measurement.

Currently used measures of indirect site index estimation include plant indicators, physiographic site classification, ecosystem classification, soil surveys, and soil-site evaluation.

Plant Indicators

Phytosociology was pioneered in Europe. Cajander (1926) described five main vegetation communities in Finland that were useful for estimating site-quality of Scots pine (*Pinus sylvestris* L.) and Norway spruce.

Understory plant species are useful indicators or phytometers of forest site-quality in northern coniferous forests (Carmean 1975) where the plant communities are distinct and easily recognizable by the few understory plants that exist. An average site index value is then associated with each plant community. Vegetation can be a very sensitive site indicator (Killian 1984), but floristic systems such as ground vegetation types, plant communities, and forest cover types only give satisfactory results in natural or slightly altered forests.

Plant indicator methods are based on the premise that natural vegetation reflects the sum of all environmental factors important to plants (Major 1951, Mueller-Dombois and Ellenberg 1974, Daubenmire 1976). Plant variables measured to estimate site index include: presence; abundance; consistency of occurrence; and size of understory plants. There are also soil-site studies that have incorporated vegetation species into their regression equations (Foster 1959, MacLean and Bolsinger 1973, Corns and Pluth 1984, and Hamilton and Krause 1985).

A common methodology of plant indicator studies is to stratify the study area into areas of similar climate, landforms, and soils. Plant communities are then classified based on their productivity. Often both site index and mean annual increment (MAI) are used as measures of productivity in plant indicator studies. Tabular comparison is used for statistical analyses of the vegetation data.

Plant indicator studies reveal many plant community/site-quality relationships, but often the productivity variation among vegetation units is so great that plant indicators cannot be used as an accurate and reliable field method. Coile (1938) stated other disadvantages:

> 1) plant site types are often related to soil or topographic site types. Soil or topographic site types usually are more closely related to site-quality, and are a permanent site feature, and therefore should be used instead of plant site types;
>
> 2) species forming the forest canopy may affect the understory plant community;
>
> 3) trees growth is sometimes more dependent on deeper soil horizons, while understory plants are often affected only by a shallow surface layer of soil;
>
> 4) plant communities change with successional stages of the forest; and
>
> 5) understory plants only grow for several months each year, greatly reducing the field season for using plant indicators as a field method.

Vegetation alone is generally not adequate to estimate site-quality, but when combined with other environmental attributes, the approach becomes largely ecological (Schönau 1988).

Physiographic Site Classification

Physiographic site classification is based on the holistic concept of integrating all land and forest features (Burger 1972). Hills (1954) subjectively subdivided Ontario into areas of similar climate, moisture, and nutrient status (Figure 4). Such an approach provides a good framework for stratifying large forest regions into broad sub-divisions. However, landscape classification is unsuitable for site-quality estimation for two reasons: 1) physiographic site classification rarely includes any quantitative data on average site index, or even measures of site index variability within subdivisions (Carmean 1975); and 2) site-quality evaluation using site index is better suited for site-specific forest management. The mapping units used in site-specific forest management are forest stands approximately five to 200 ha. Physiographic site classification typically uses mapping units representing thousands of hectares, making this method suitable primarily for broad strategies and policy decisions, but unsuitable for site-specific forest management.

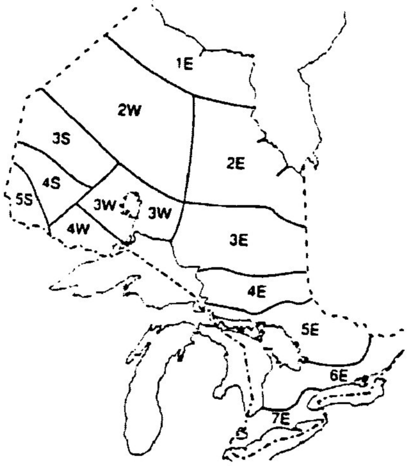


Figure 4. Hills' Site Regions of Ontario (Hills 1960).

Ecosystem Classification

Forest ecosystem classification is a method of logically grouping land units, derived from a combination of soils and vegetation. Climate is usually constant, as study areas for forest ecosystem classifications are chosen to have relatively homogenous climate. The general purpose of ecosystem classification is to:

1) classify and describe ecoregions (ecological zones) and their component ecosystems with regards to their floristic composition, soils, environmental characteristics, successional relationships, and forest productivity (Corns and Annas 1986);

2) provide a means for forest managers to describe ecosystems in the field;

3) produce small-scale maps of defined ecosystems; and

4) provide a framework for forest management interpretations for the described units.

Thorough reviews of forest ecosystem classification systems currently in use in each province of Canada have been given by Meades and Roberts (1992), Bowling and Zelazny (1992), Belanger *et al.* (1992), Bergeron *et al.* (1992), Sims and Uhlig (1992), Wells (1992), Corns (1992), Oswald (1992), and MacKinnon *et al.* (1992).

In Ontario, two forest ecosystem classifications have been completed, and a third is in progress (Figure 5). The Clay Belt region of northeastern Ontario was classified by Jones *et al.* (1983). This classification system defined 22 vegetation groups. Common combinations of vegetation and soil were combined into 14 operational groups. The NWO FEC (Northwestern Ontario Forest Ecosystem Classification) was developed by Sims *et al.* (1990b). It classified 38 vegetation types, and 22 soil types. Soils deeper than 100 cm were delineated as the deep soil group, while soils shallower than 100 cm were delineated as the shallow soil group. Management interpretations for potential forest management applications and interpretations such as productivity (site index), silviculture, and wildlife habitat were presented (Racey *et al.* 1989). Hierarchical keys for the vegetation and soils groups were presented for both systems. An ecosystem classification for eastern Ontario is currently in progress.

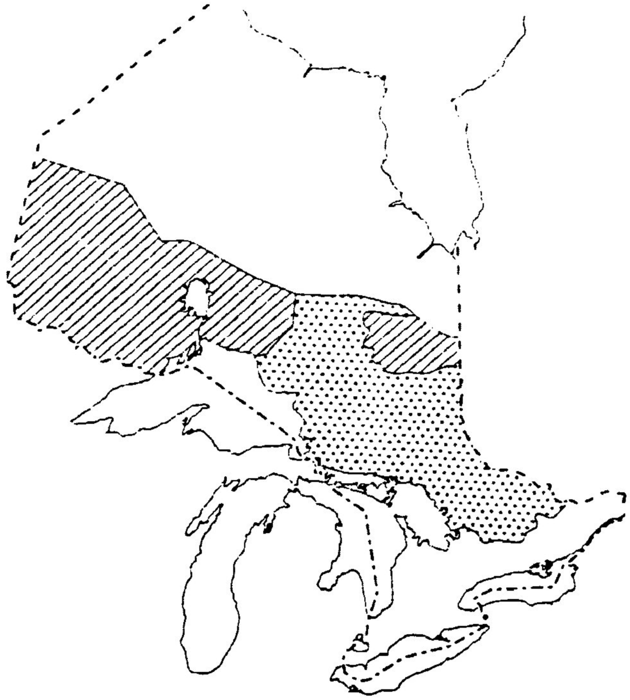


Figure 5. Forest ecosystem classification studies in Ontario (Sims 1992); *completed* (diagonal hatching) and *in progress* (dot pattern).

One objective for the NWO FEC is to define soil types that are closely related to site index for the major commercial tree species in northwestern Ontario. To achieve this goal, NWO FEC soil types should have little internal variation in site index, and each soil type should be significantly different from each other. Unfortunately, the relationship between NWO FEC soil types and site index is poor for:

1) jack pine (LeBlanc 1988, Buse and LeBlanc 1990);
2) black spruce (Fairbanks 1988, Buse and LeBlanc 1990, Buse and Baker 1991, and Buse and Towill 1991); and
3) trembling aspen (Li 1991).

Note that Buse and LeBlanc (1990) improved the relationship between NWO FEC soil types and site index by grouping soil types together. Jack pine site index variation (i.e. standard deviation) was reduced to an average of 0.3 m, while black spruce site index variation was reduced to an average of 1.7 m.

The solution to improving the relationship between NWO FEC soil types and site index is to identify the critical soil and topographic features that are related to the observed site index variation within soil types (Carmean 1994). Soil site studies by Schmidt and Carmean (1988), LaValley (1991), and Li (1991) have shown that depth to root restricting layer, coarse fragments, and glacial landform are closely related to site index. These soil features should be used for refining, redefining or phasing NWO FEC soil types.

Soil Surveys

Soil surveys have been made in Canada and the United States usually for agricultural purposes. Forest soils also have been surveyed in an attempt to find relationships between soil groups and productivity. Unfortunately, many studies show that soil taxonomic groups have a very wide range of site index and 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).

Soil-Site Evaluation

The soil-site method is the most popular and successful indirect method of site-quality evaluation. It uses soil physical, soil chemical, topographic, geomorphological, and climatic features to estimate site index indirectly. The soil-site method is applicable where no suitable stands and trees are available for direct measurement of site index. This method is required for non-forested land and stands that are uneven-aged, poorly stocked, partially cut, or completely harvested.

Soil-site equations are developed by establishing many temporary site plots that represent the range of site, soil, topography, geomorphology, and climate found within a designated study area (Carmean 1975). Soil and topographic conditions are measured on each plot, and site index estimated by stem analyses or by use of polymorphic site index curves. Multiple regression is then used to develop site index estimating equations based on the independent variables of soil, topography, and climate. Easily measurable site features should be used in favour of features that are difficult to measure in the field, even if the accuracy of the soil-site equation decreases slightly.

Soil-site work was first developed in Europe. Blomqvist (1872) related the productivity of soil to tree growth in Finland by defining three quality classes based on soil, exposure, and vegetation relationships. Soil scientists in North America began utilizing this technique in the 1920's. Haig (1929) made the first soil-site study in North America by observing that the site index of plantation red pine was closely related to the silt and clay content of the A horizon.

Coile (1948, 1952) did extensive soil-site work in the southern pine region of the United States from 1935 to 1960. Coile (1948) believed soil moisture was the most important factor in determining site index. He further postulated that slope steepness, aspect, and position influenced soil moisture, hence influencing tree growth. Coile (1952) also showed that soil texture affected site index by influencing soil moisture, rooting development, nutrient availability, and aeration. This led to the conclusion that aeration and rooting space influences water availability (Coile 1952, Doolittle 1963).

Early soil-site studies concentrated on soil physical features. Coile (1948) thought nutrient deficiencies were not as limiting as soil physical properties. Soil physical features, such as depth and texture, are directly or indirectly related to both soil water and nutrient availability (Carmean 1994). But soil-site studies usually use physical soil features because soil chemical properties are difficult to measure in the field.

Soil chemical factors received more attention later by workers such as Lutz and Chandler (1946). Some chemical factors were related to site index. Haig (1929) found total nitrogen content of the A horizon to be related to the site index of plantation red pine in Connecticut.

Comprehensive reviews of past soil-site studies are given by Coile (1948, 1952), Doolittle (1957), Della-Bianca and Olsen (1961), Rennie (1962), Ralston (1964), Van Dyne *et al.* (1968), Shrivastava and Ulrich (1976), and Carmean (1975, 1982).

SOIL-SITE STUDIES FOR JACK PINE

Many soil variables have been identified that are significantly related to the growth of jack pine. Table 2 lists these soil-site studies, the area studied, and the specific soil features found to be significant.

Table 2. List of soil variables that are significantly related to the growth of jack pine.

REFERENCE	AREA	SOIL VARIABLES SIGNIFICANTLY RELATED TO THE HEIGHT GROWTH OF JACK PINE
NATURAL JACK PINE		
Pawluk and Ameman (1961)	Minnesota	1) content of very fine sand, silt and clay in upper portion of soil; 2) soil moisture holding capacity; and 3) soil depth
Frissel and Hansen (1963)	Minnesota	1) moisture; and 2) nutrients

Table 2. (continued)

REFERENCE	AREA	SOIL VARIABLES SIGNIFICANTLY RELATED TO THE HEIGHT GROWTH OF JACK PINE
Chrosciewicz (1963)	Northern Ontario	1) moisture regime; 2) texture; and 3) macroclimate (i.e. Hills (1959) site regions)
Jameson (1965)	Saskatchewan	1) moisture regime; and 2) understory vegetation
Shetron (1969)	Wisconsin & Michigan	1) depth to fine sand or finer textured soil horizon
Hannah and Zahner (1970)	Wisconsin & Michigan	1) site index much greater on soils that are stratified by finer-textured lenses
Schmidt (1986), Schmidt and Carmean (1988)	North Central Ontario	soil features vary by landform as follows: 1) shallow to bedrock morainal soils - depth to bedrock, and coarse fragments in the A horizon; 2) deep morainal soils - depth to root restricting layer*, percent coarse fragments in the C horizon, and percent clay in the A horizon; 3) outwashed glacial sands - depth to root restricting layer**, and slope percent; and 4) glacial lacustrine soils - thickness of A horizon, and pH of BC horizon
PLANTATION JACK PINE		
Wilde *et al.* (1964)	Wisconsin	1) percent organic matter of soil; and 2) percent silt and clay
Shetron (1972)	Wisconsin & Michigan	1) amount of fine sand; and 2) thickness of B horizon
Hamilton and Krause (1985)	New Brunswick	1) soil drainage class; 2) depth of Ae horizon (deeper Ae reduces height growth); 3) depth of rooting; 4) presence or absence of *Kalmia* and *Vaccinium* (presence of bog laurel and blueberry indicates poor height growth for areas that are too wet or too dry)

*basal till, bedrock, mottles, gley, water table, till, or carbonates
**coarse sand, mottles, gley, and (or) water table

Northern Ontario

Chrosciewicz (1963) studied site-quality of jack pine in northern Ontario. He sampled 43 to 97 year old jack pine stands in Hills' Site Regions 4S, 3W, and 4E (i.e. north of Dryden, Longlac, and the area between Chapleau and Sudbury). This study found that soil moisture regime classes were significantly related to the growth of jack pine. Productivity (i.e. site index) increased as soil moisture regime (SMR; Ont. Instit. Ped. 1985) increased from zero to three, with SMR=3 being the most productive sites. As SMR exceeded three, height growth dropped dramatically. Soil texture had an effect on site index. Very fine sand had better height growth than fine or medium sand, with this effect being more pronounced on drier sites. Regional macroclimate (Hills' Site Regions) also was related to the height growth of jack pine. In order of most productive to least productive, the Site Regions are as follows: 4E (Sudbury), 4S (north of Dryden), and 3W (Longlac). This ranking shows that regional macroclimate influences the height growth of jack pine, since more northerly Site Regions have lower height growth.

North Central Ontario

Schmidt (1986), and Schmidt and Carmean (1988) made a soil-site study for jack pine in north central Ontario that identified relationships between jack pine site index and features of soil and topography. Their 99 site plots were stratified into four landforms: 1) shallow to bedrock morainal sites; 2) deep morainal soils; 3) outwashed glacial sands; and 4) glacial lacustrine soils. Different soil features were significant for each landform: 1) <u>shallow to bedrock</u> - depth to bedrock, and coarse fragment content of the A horizon; 2) <u>deep</u>

morainal - depth to root-restricting layer (e.g. basal till, coarse sandy subsoil, mottles, gley, water table, bedrock or carbonates), coarse fragment content of the C horizon, clay content of the A horizon; 3) outwash sands - depth to root-restricting layer (as above) and slope percent; and 4) glacial lacustrine - thickness of A horizon, and pH of the BC horizon (Figure 6).

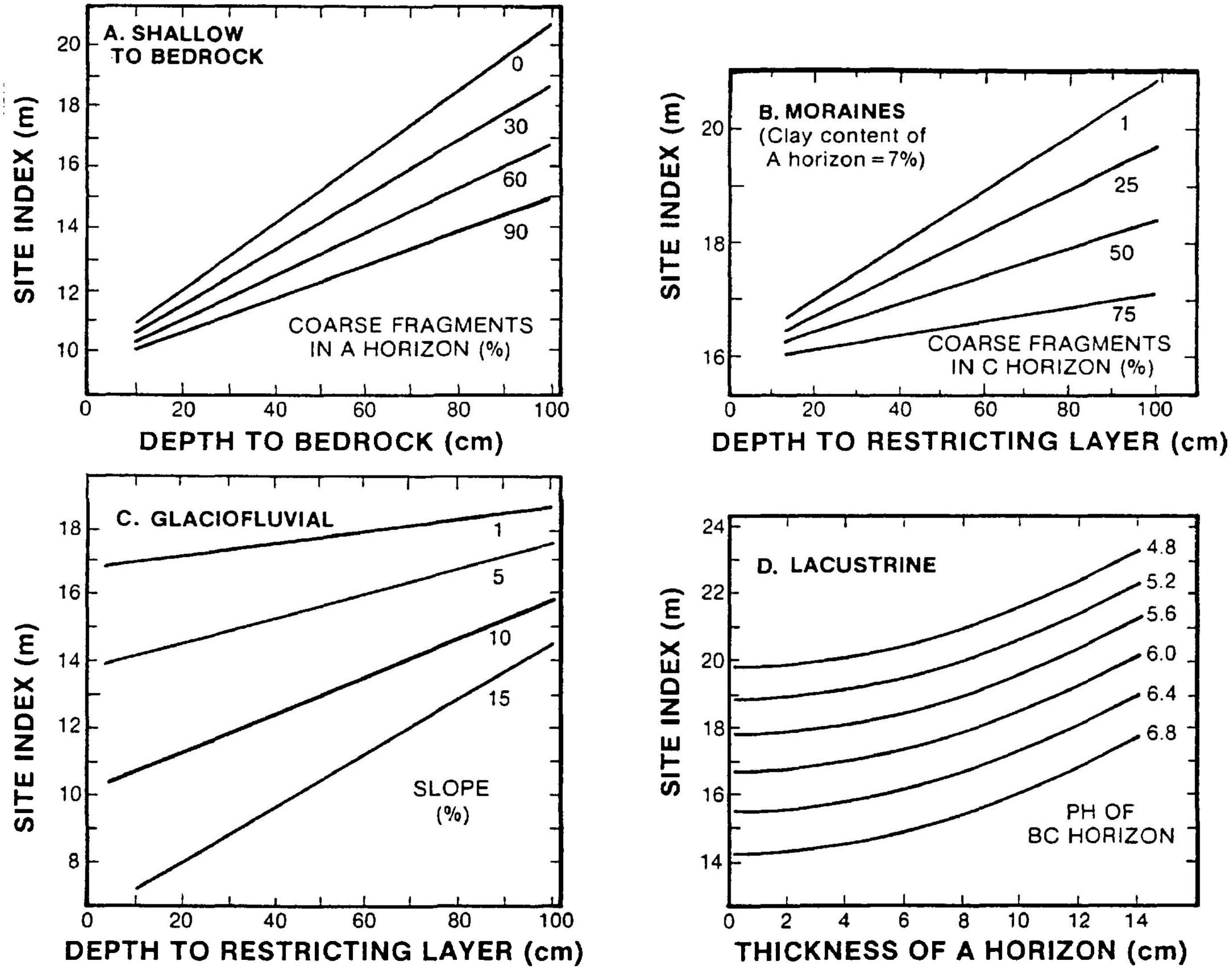


Figure 6. Trend graphs illustrating relationships between jack pine site index and features of soil and topography in north central Ontario (Schmidt 1986, Schmidt and Carmean 1988).

Jackman (1990) attempted to identify the relationship between jack pine site index and features of soil and topography in northwestern Ontario. This analyses proved inconclusive, due to a lack of soil profile data for depth to root restricting layers, and coarse fragment content. Site index curves were produced from the stem analyses trees.

Saskatchewan

Jameson (1965) related height growth curves of jack pine to site-quality in the Mixedwood Forest Section (B.18a forest section Rowe (1959)) of Saskatchewan. Before producing height curves, Jameson (1965) stratified sites into six ecologically defined sites:

A1: fresh soil moisture regime (SMR), loam to clay-loam tills, presence of *Corylus cornuta* Marsh (hazel) and *Alnus crispa* (Ait.) Pursh. (green alder);

A2: fresh SMR, sandy loam to loam soils of lacustrine or alluvial origin, lesser presence of hazel and green alder;

B: moist SMR, sandy glacial outwash or alluvial soils, presence of *Vaccinium angustifolium* Ait. (blueberry) and *Ledum groenlandicum* Oeder;

C: fresh SMR, sandy glacial outwash or alluvial soils, presence of *Aralia nudicaulis*, *Linnaea borealis*, and *Vaccinium Vitis-Idaea*;

D: dry SMR, sandy glacial outwash or alluvial soils, presence of *Arctostaphylos uva-ursi* (L.) Spreng. (bear berry) and blueberry;

E: very dry site on medium and fine sandy soils, presence of *Cladonia* spp. and bear berry.

This stratification of jack pine height growth shows how jack pine site-quality is related to soil moisture regime, landform, and understory vegetation.

New Brunswick

Hamilton and Krause (1985) studied relationships between site index of plantation jack pine and site variables. The study was based on 28 plots in plantations 6 to 16 years old. Multiple regression analyses showed that rooting depth, depth of an Ae horizon (leached horizon) and site occupancy of *Kalmia* spp. (bog laurel) and *Vaccinium* spp. (blueberry) could be used to predict site index. This study also showed that foliar nutrient levels could be used to predict site index of jack pine, but this is not a feasible field method because of the need for laboratory analyses of foliar samples. Correlation showed that the following site variables negatively affected the growth of jack pine: 1) depth of the Ae horizon; 2) clay content; 3) bulk density; and 4) drainage class. The authors warned that New Brunswick's climate is much wetter than for the continental climate of central North America, thus results are limited to the study area.

Minnesota

Pawluk and Arneman (1961) investigated the relationships between jack pine site index and soil characteristics. They sampled 18 plots on sites having similar slope, stand density, and past history. Site indices were determined from three dominant and two codominant trees from each plot. The investigators found that the site index of jack pine was related to: 1) the content of very fine sand, silt and clay in the upper portions of the soil; 2) moisture holding capacity; and 3) the depth of the soil. Chemical analyses was also performed, but this is not practical for field work. They summarized their study by stating that jack pine site index is related to characteristics of soil that influence available moisture holding capacity and fertility.

Pluth and Arneman (1963) found no relationship between synecological coordinates and site index for 38 plots in northern Minnesota. Frissel and Hansen (1965) compared jack pine site index to the synecological coordinates of moisture and nutrient regimes. They analyzed 83 plots using multiple regression analyses and revealed an R^2 value of 0.36.

Michigan and Wisconsin

Wilde *et al.* (1964) studied the site-quality of plantation jack pine. He sampled 16 to 30 year old plantations that had sandy and sandy loam soils. Multiple regression analyses showed that percent organic matter and percent silt and clay were closely related to site index of jack pine.

Shetron (1969) sampled 83 plots that were confined to glacial outwash soils. He found that growth of jack pine was related to the depth to fine sand, or to the depth to any soil with a finer texture than fine sand. This study found that site index of jack pine varied greatly for soil taxonomic units in northern Michigan. Shetron (1972) also studied soil-site relations for plantation jack pine in northern lower Michigan. He found that differences in the amount of fine sand accounted for most of the variation in the site index of jack pine, and that the thickness of the B horizon also was related to site index.

Hannah and Zahner (1970) studied the effects of soil stratification on the site index of jack pine, red pine, and bigtooth aspen (*Populus grandidentata* Michx.). Bands of finer-textured lenses occurring at infrequent intervals in outwashed glacial sands are referred to as "texture bands". Till-like lenses occurring in outwashed glacial sands are similar to texture bands, but their thickness is greater than five centimetres. Hannah and Zahner found that site index was increased from an average of 14.9 m (at age 50 years) to 16.8 m for sites which had soil texture bands, and to 19.8 m for sites with till-like lenses. They concluded that site index is much greater on sites with a high frequency of lenses or texture bands.

SITE FACTORS RELATED TO JACK PINE PRODUCTIVITY

Climate

Climatic variation has an undetermined effect on the growth of jack pine across Ontario. Within small geographic areas, climate varies insignificantly, except in areas of extremely irregular topography (Gaines 1949). Climate can be correlated to productivity if climatic information such as temperature, degree-days, precipitation, latitude, longitude, and altitude are measured. These climatic variables can then be used as independent variables, and used in the regression procedure.

Local microclimatic variation also can be measured. Gaines (1949), Hagglund (1981), and many others (Carmean 1975) have used aspect, slope position and shape, and upslope length to express the effects of local microclimatic variation.

Geomorphology

The analyses of site-quality may be simplified by stratification of data into parent material classes (Ralston 1964, Pritchett and Fisher 1987) in regions where soils differ greatly in parent material origin. In Ontario, a close relationship exists between glacial landforms and their soils (Sado and Carswell 1987). The soil types and topography within landforms affect moisture levels in the soil, which affects the growth of jack pine. Therefore, it is important to classify the landscape by landform. Landform stratification greatly aided soil-site work in northern Ontario (Schmidt and Carmean 1988, Buse and Towill 1991, LaValley 1991, and Li 1991). Even so, stratification into broad glacial landforms can be viewed as only an initial broad stratification because each glacial landform varies greatly in features closely related to site-quality such as depth of effective rooting and coarse fragment content (Schmidt and Carmean 1988).

Topography

Topography often is closely related to site-quality due to local modification of edaphic and microclimatic variables such as moisture, light, and temperature (Pritchett and Fisher 1987). Coile (1952) found that subsurface and surface movements of water were influenced by slope position, slope length, and slope percent. Mueller-Dombois (1964) developed a forest habitat type classification for southeastern Manitoba, using topography as one of several critical site features in this classification. Schmidt and Carmean (1988) found that slope percent was related to site index for jack pine on outwashed glacial sands. Buse and LeBlanc (1990) separated shallow soil FEC types based on telluric influence, thus expressing significant differences in the site index of jack pine. Microtopography (i.e. mounding) was related to the site index of black spruce (Buse and Towill 1991).

Aspect in hilly or mountainous regions has been successfully related to site index by several authors. Gaiser (1951) used a sine transformation of aspect, while Carmean (1964, 1965), Beers *et al.* (1966), Lloyd and Lemmon (1968), and Hartung and Lloyd (1969) used a cosine transformation to quantitatively relate aspect to site index. An interaction between aspect and slope steepness was used to express the site index of black oak in southeastern Ohio (Carmean 1965).

Soil Physical Characteristics

Coile (1948) considered that soil physical properties had more influence on site-quality than soil chemical properties. Often, soil physical properties that are related to site-quality are also closely related to soil chemical properties, thus significant features such as depth and texture express the combined effects of moisture availability, soil chemical relations, and soil aeration.

Moisture Availability

Moisture regime is a good indicator of moisture availability (LeBlanc and Towill 1989), since it is based on soil texture, depth to mottling, and depth to gley. Chrosciewicz (1963) found that soil moisture regime classes were significantly related to the growth of jack pine in northern Ontario. Productivity (i.e. site index) increased as moisture regime increased from zero to three, but as moisture regime exceeded three, height growth dropped dramatically. Mueller-Dombois (1964) found moisture regime to be a major characteristic in classifying jack pine habitat types in southeastern Manitoba. Less important characteristics were soil type and understory vegetation. Bella (1968) developed jack pine height over age curves and yield tables based on 365 permanent sample plots in southeastern Manitoba, using Mueller-Dombois' (1964) site type classification. He found that soil moisture regime was very closely related to the growth of jack pine, so separate height over age curves and yield tables were developed for each soil moisture class. Bella found that commercial jack pine sites were found on four habitat types and one subtype that was based on soil moisture as follows:

1) dry (d);
2) oligotrophic (nutritionally poor) fresh (of);
3) oligotrophic moist (om);
4) mesotrophic (nutritionally intermediate) fresh (mf); and
5) mesotrophic fresh-drier subtype (mf-).

Soil drainage is similar to soil moisture, as both ratings are related to soil texture, mottles, and gley, however soil drainage is a measure of the potential for a soil to drain, while moisture regime is a measure of available mosture. Gaines (1949) found drainage to be related to site-quality, as did LaValley (1991) and Li (1991).

Soil texture has been found to have a curvilinear relationship to site-quality (Ralston 1964). Gaines (1949), Coile (1952), Pritchett and Fisher (1987) also have found soil texture to be related to site-quality. Fine textured soils retain more moisture, benefiting tree growth. In contrast, coarse textured soil is rapidly drained and retains only small amounts of moisture, thus site-quality is reduced.

Coarse fragments affect soil moisture and aeration. Too many coarse fragments cause a reduction in the volume of available soil, thus reducing available moisture, which reduces site-quality. A moderate amount of coarse fragments in fine-textured soils benefits tree growth through increased aeration and penetration of surface water (Ralston 1964).

Soil Depth

Soil depth determines the volume of soil available for rooting, thus influencing tree growth (Coile 1952, Pritchett and Fisher 1987). Ralston (1964) and Schmidt and Carmean (1988) found that tree growth response to increased rooting space was curvilinear. Various measures of soil depth, such as total depth, depth to bedrock, and depth to silt bands are related to tree growth (Coile 1935, Gaines 1949, Pawluk and Arneman 1961, Ralston 1964, Stratton and Struchtemeyer 1968, Spurr and Barnes 1980).

Soil depth can be defined as 'effective' soil depth. Effective depth is defined as depth to any root restricting layer such as bedrock, claypan, hardpan, water table, seepage, grey gley, mottling, or carbonates (Ralston 1964, Schmidt and Carmean 1988). LaValley (1991) and Li (1991) both found effective rooting depth to be a significant independent variable in soil-site equations for white spruce and trembling aspen, respectively.

Effective soil depth is decreased by presence of coarse fragments in the soil profile due to the decrease in fine soil volume that the coarse fragments occupy (Childs and Flint 1990). These coarse fragments decrease productivity (Viro 1947, Steinbrenner 1979), due to a decreased soil volume for nutrient supply. However, a small coarse fragment percentage in the soil profile may increase productivity (Viro 1947).

Soil Chemical Properties

Soil chemical properties are related to site-quality (Doolittle 1963, Ralston 1964). Major classes of soil chemical properties are nutrients, organic matter, and pH. Foliar nutrient analyses also can be used for estimating soil nutrient levels (Spurr and Barnes 1980). Nutrients found to influence tree growth are nitrogen, phosphorus, potassium, calcium, and magnesium (Carmean 1975, Pritchett and Fisher 1987). However, soil chemical and foliar analyses of nutrient levels are rarely done in soil-site studies, due to their prohibitive expense.

Soil organic matter has been found to influence site-quality (Ralston 1964). Depth of an Ah horizon, humus form, and thickness of L, F, and H horizons are indirect measurements of soil organic matter. Direct measurements of soil organic matter require laboratory analyses. Higher levels of organic matter increase the amount of available water (Coile 1952), and increase nutrient supply.

Soil pH influences nutrient availability (Pritchett and Fisher 1987), but has little influence on tree growth since most trees have a wide pH tolerance (Lutz and Chandler 1946). However, Schmidt and Carmean (1988) found that pH was related to site-quality of jack pine on glacial lacustrine soils, but this relationship was considered only as a means for separating acid red clays from more calcareous grey silty clays.

METHODS

DATA COLLECTION

Study Area

The study area is in northeastern Ontario, Canada extending from the town of White River to the Ontario/Quebec border, north to the tree line, and south to the city of Sudbury. The study area spans portions of both the northern and northeastern Ontario Ministry of Natural Resources (OMNR) administrative regions. This area was selected because soil-site studies for jack pine had not previously been completed in northeastern Ontario. Soil-site equations exist for a portion of north central Ontario (Schmidt and Carmean 1988), and Jackman (1990) attempted a limited site-quality study in northwestern Ontario. Accordingly, this soil-site study for northeastern Ontario provided an opportunity to compare my results with previous results obtained for north central and northwestern Ontario (Schmidt and Carmean 1988, Jackman 1990).

The continental climate of the study area is characterized by very cold winters, and hot summers. Lake Superior locally influences climate by cooling adjacent land in the summer, and warming it in the winter.

The physiography of the region reflects bedrock geology (Sado and Carswell 1987). Two main geographic areas are the Precambrian Shield and the Hudson Bay Lowland. A wide variety of surficial glacial deposits are found in northeastern Ontario. These deposits include glaciolacustrine and glaciomarine deep water deposits, glaciofluvial deposits, deep glacial moraine deposits, and shallow to bedrock areas having thin glacial sediments. Organic deposits are scattered throughout the region in areas having poor drainage. Many esker formations run north and south in the study area. Major moraine systems include: Chapleau I, II, and III; Pinard; and Cartier I, II, and III moraine systems. Less common formations include wind-blown dunes, drumlins, and beach forms.

Plot Selection

Plots were located in undisturbed, fully-stocked, natural jack pine stands. The stands were a minimum of 50 years old (breast-height age), were even-aged (i.e. maximum of 10 years spread), and had dominant or codominant trees that were free-growing, uninjured, and unforked. Both pure and mixedwood jack pine stands were sampled. Plots were located in areas where the local topography and soil conditions were relatively homogeneous; each plot location was evaluated for soil horizon, texture, and coarse fragment homogeneity by using a soil auger to determine soil characteristics. Efforts were made to establish plots in areas representing the full range of site-quality, soil, and topographic conditions found in the study area.

Plots were established no further than 0.5 km from roads, because of the need to carry equipment to the plot, and to carry soil samples and tree sections from the plot. Plots were not randomly located, but were chosen to represent each of the four landforms (i.e. bedrock, glaciofluvial, lacustrine, and moraine), and as wide a range of soils, topography, site-quality, and geographic range as possible (Figure 7).

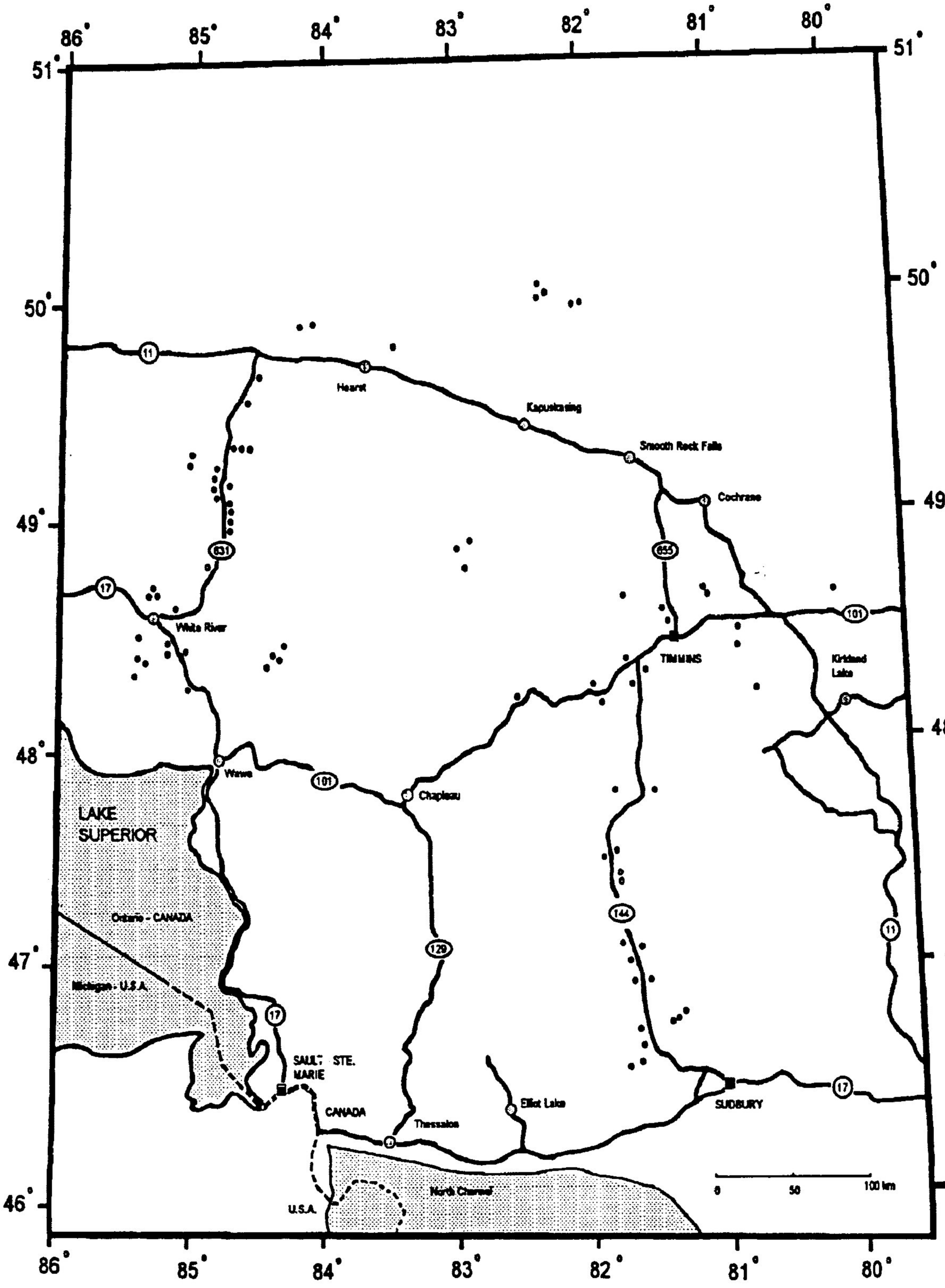


Figure 7. Location of 79 study plots in northeastern Ontario.

Stem Analyses

The plots used in this study were established during the summer of 1990 by Glen Niznowski and the author. Niznowski determined site index by felling and sectioning three dominant or codominant trees per plot, as data for his M.Sc.F. thesis (Niznowski 1994). Sections from each tree were taken at 0.1, 0.5, 1.0, 1.3, 2.0 m, and every 1.0 m thereafter, until 13.0 m, where section lengths were taken at 0.5 m intervals. The sections were labeled, bagged, and transported to Thunder Bay for analyses.

Annual ring counts were made for each section of each tree using the OMNR Tree Ring Increment Measure (TRIM) system (MacIver *et al.* 1985). These data were used to plot separate height-age curves for each of the three trees on each plot. Trees on all the plots were visually screened for erroneous data. Individual-tree height curves were corrected if erroneous values were observed; in a few cases trees were discarded if plotted curves indicated past suppression or top breakage. The individual height growth curves for each plot were then averaged into a single average height-age curve. Average tree height at 50 years (breast-height age) observed on the average plot curve was used as the site index value for each plot.

Soil and Site Measurements

A 1.2 m^3 soil pit (1.0 m by 1.0 m) was dug to a depth of 120 cm, or until bedrock was reached. At each plot, the pit was centrally located (approximately equidistant) to all of the trees used for stem analysis; pits were also located to avoid windthrows and stumps, or other local disturbances. At the bottom of each pit, a soil auger was used to auger to a depth of 2.0 m, whenever possible. Soil profile descriptions for each plot were made following standard Ontario procedures (Ontario Institute Pedology 1985). Soil samples of approximately 0.5 kg were taken from each major horizon for laboratory analyses.

Descriptions were made of the Clay Belt vegetation, soil and operational groups (Jones *et al.* 1983); NWO FEC vegetation and soil types (Sims *et al.* 1990b); stand composition; understory vegetation; topography; and landform. The NWO FEC system is not applicable in northeastern Ontario, even so the NWO soil and vegetation units still were recorded to test the potential for extrapolation to northeastern Ontario. Dependent and independent variables (Table 3) were recorded on a tally sheet (Appendix I) according to standard Canadian methods (Canada Soil Survey Committee 1978) and utilizing MUNSELL soil colour charts (Munsell Colour Company, Inc. 1971).

Plot topography was described by measuring aspect, percent slope, upslope length from the soil pit to the top of the slope, down slope length from the soil pit, site position, surface shape, and microtopography. Each plot was assigned to a landform class and the data recorded on a tally sheet.

Table 3. List of dependent and independent variables.

DEPENDENT VARIABLE	
SI	Average height (m) of three dominant and codominant trees at breast-height age 50 years (SI_{BH50})
INDEPENDENT VARIABLES	
1) Soil Depth Variables	
PSD	depth to particle size discontinuity
BR	depth to bedrock
WATERTAB	depth to water table
SEEPAGE	depth to water seepage
CARB	depth to carbonates
FMOTT	depth to faint mottles
DMOTT	depth to distinct mottles
PMOTT	depth to prominent mottles
GLEY	depth to gley
DMRL	depth to moisture restricting layer (i.e. coarse sandy subsoil, mottles, gley, water table, bedrock, carbonates or basal till)
AVGROOT	average depth of rooting
MAXROOT	depth to deepest root
2) Soil Horizon Variables (for A, B, BC, and C horizons)	
DEPTH	depth of soil horizon boundary
THICK	thickness of soil horizon
CHROMA	chroma of the soil horizon
VALUE	value of the soil horizon
MOT_CHR	chroma of mottles (if present)
MOT_VAL	value of mottles (if present)
MOT_AB	percent mottling abundance
MOT_SIZ	size of mottles
CONS1	soil consistency when wet
CONS2	soil plasticity
CONS3	soil consistency when moist
CFTOTAL	total coarse fragment percent (gravel, cobbles, and stones)
CFGRAVEL	coarse fragment percent of gravel

Table 3. (continued)

CFCOBBL	coarse fragment percent of cobbles
CFSTONE	coarse fragment percent of stones
PGRVCOB	percent gravel and cobbles
PCOBSTON	percent cobbles and stones
ROOTAB	percent rooting abundance
ROOTSIZ	root size
<u>3) Soil Horizon Laboratory Analyses Variables (for A, B, BC, and C horizons)</u>	
GRAVEL	percent gravel as determined by laboratory analysis
PH	pH (reaction) of soil
%SAND	percent sand as determined by particle size analysis
%SILT	percent silt as determined by particle size analysis
%CLAY	percent clay as determined by particle size analysis
%SICLAY	percent silt and clay
OM	percent organic matter
<u>4) Profile Coarse Fragment Variables</u>	
S_STON	percent surface stones
S_BR	percent surface bedrock
%COBBTOP	percent cobbles in the top of the pit (0-25 cm)
%COBBBOTT	percent cobbles in the bottom of the pit (26-120 cm)
%COBBTOT	percent cobbles in the entire pit (0-120 cm)
%STONTOP	percent stones in the top of the pit (0-25 cm)
%STONBOTT	percent stones in the bottom of the pit (26-120 cm)
%STONTOT	percent stones in the entire pit (0-120 cm)
<u>5) Litter Layer Variables</u>	
LDEPTH	depth of litter (L) organic horizon
LTHICK	thickness of litter (L) organic horizon
FDEPTH	depth of fibric (F) organic horizon
FTHICK	thickness of fibric (L) organic horizon
HDEPTH	depth of humus (H) organic horizon
FHTHICK	thickness of fibric and humus organic horizons
H_FORM	humus form (8= fibrimor; 9=humifibrimor; 10=fibrihumimor)
<u>6) Topographic Variables</u>	
SLOPEL	length of slope
UPSLOPEL	length of slope upwards from plot
SLOPE%	percent slope
ASPECT	aspect in degrees
COSASPECT	cosine of aspect in degrees

Table 3. (continued)

SINASPECT	sine of aspect in degrees
S_SHP	surface shape (1=convex, 2=straight, 3=concave)
S_POS	site position (1=crest, 2=upper, 3=middle, 4=lower, 5=toe, 6=depression, 7=level)
M_TOPO	microtopography
7) Soil Moisture Variables	
MR	moisture regime
D_CLS	drainage class
P_PAT	pore pattern
8) Categorical Variables	
REGION	OMNR Administrative Region
SPPCOMP	stand species composition
MODE	mode of deposition
MODE2	second mode of deposition (if any)
FPS	family particle size
STRAT	soil stratified (subjective - psd better)
CFECSOIL	Clay Belt FEC soil classification
FECSOIL	NWO FEC soil classification
CFECVEG	Clay Belt FEC vegetation classification
FECVEG	NWO FEC vegetation classification
OG	Clay Belt FEC Operational Group
HORIZON	soil horizon
HORIZON2	simplified soil horizon (A, B, BC, and C)

LABORATORY ANALYSES

Sample Preparation

Soil samples from each horizon from each plot were air-dried. Roots and other organic material in the soil were removed and discarded. Fine textured soil that had soil aggregates were crushed with a mortar and pestle. The soil samples were then sieved through a 2 mm sieve to separate the gravel (> 2.0 mm) from the fine earth (<2.0 mm) fraction. Percent gravel content by weight was determined using the formula:

$$\%\ gravel\ (by\ weight) = \frac{weight\ of\ gravel\ (g)}{weight\ of\ gravel\ and\ fine\ earth\ (g)} \times 100$$

pH Measurements

The pH methodology described by Shelrick (1984) was used to determine reaction of the soil. A glass electrode pH meter was calibrated using pH 7.0 and pH 4.0 solutions. A 20.0 g sample of soil was weighed and placed in a 50 ml beaker, and 40.0 ml of distilled water was added. The suspension was then stirred with a clean glass rod. The suspension was allowed to settle for 30 minutes. The pH meter was used to measure pH to one decimal place.

Particle-Size Analysis

The hydrometer method (Bouyoucos 1962) was used to estimate the sand, silt, and clay textural fractions from each of the soil samples. Soil samples of 100.0 g were weighed for sandy soils; 50.0 g sample were weighed for clay soils. The soil samples were placed in a dispersing cup with 100.0 ml of distilled water and 10.0 ml of Calgon solution (50.0 g Calgon dissolved in 1.0 litre of water). The solution was stirred, then allowed to soak for 15 minutes. The dispersing cup was placed on an electric soil mixer, and stirred for 5 minutes.

The mixed solution was transferred to a settling cylinder. A calibrated hydrometer was placed in the cylinder, then distilled water added until there was exactly 1.0 litres of solution. The cylinder's solution was mixed by inverting and shaking, the cylinder then was allowed to settle. The hydrometer was quickly suspended, and readings taken at 40 seconds (silt and clay in suspension) and after two hours (clay content in suspension) of sedimentation. The temperature of the water was recorded for each reading and used to adjust the hydrometer readings.

Sand content was calculated by this formula: 100% - corrected hydrometer reading at 40 seconds. Clay content was the corrected hydrometer reading at two hours. Silt content was calculated as the residual (i.e. 100% - (% sand + % clay).

Organic Matter Content

A modified Walkey-Black wet combustion method was used to determine organic matter content in the A and B horizons (McKeage 1978). A 1.0 g soil sample was digested in a 500 ml Erlenmyer flask with 10 ml of 1.0 normal (i.e one gram equivalent of solute per litre) $K_2Cr_2O_7$; 20 ml of 95% H_2SO_4 was added to the solution under a fume hood, and the solution was swirled for one minute. The solution was then left to stand for 30 minutes.

200 ml of distilled water, 10 ml H_3PO_4 and 1.0 ml of barium diphenylaminesulphonate indicator solution were mixed into the flask. The solution was then titrated by adding $FeSO_4$ until the colour of the solution flashed to green. Percent organic matter was calculated using the formula:

$$\%\,organic\,matter = \frac{[(10\ ml\ K_2Cr_2O_7\ -\ ml\ of\ FeSO_4\ required\ for\ titration) \times 0.5] \times 0.40}{1.0\ g\ of\ soil}$$

DATA ANALYSES

Data were analyzed for northeastern Ontario alone, and by combining the northeastern data with north central and northwestern Ontario data (Figure x). The main headings and sub-headings in Figure 8 are used to show the sequence of aggregations and subsequent analyses in the methods, results, and discussion sections.

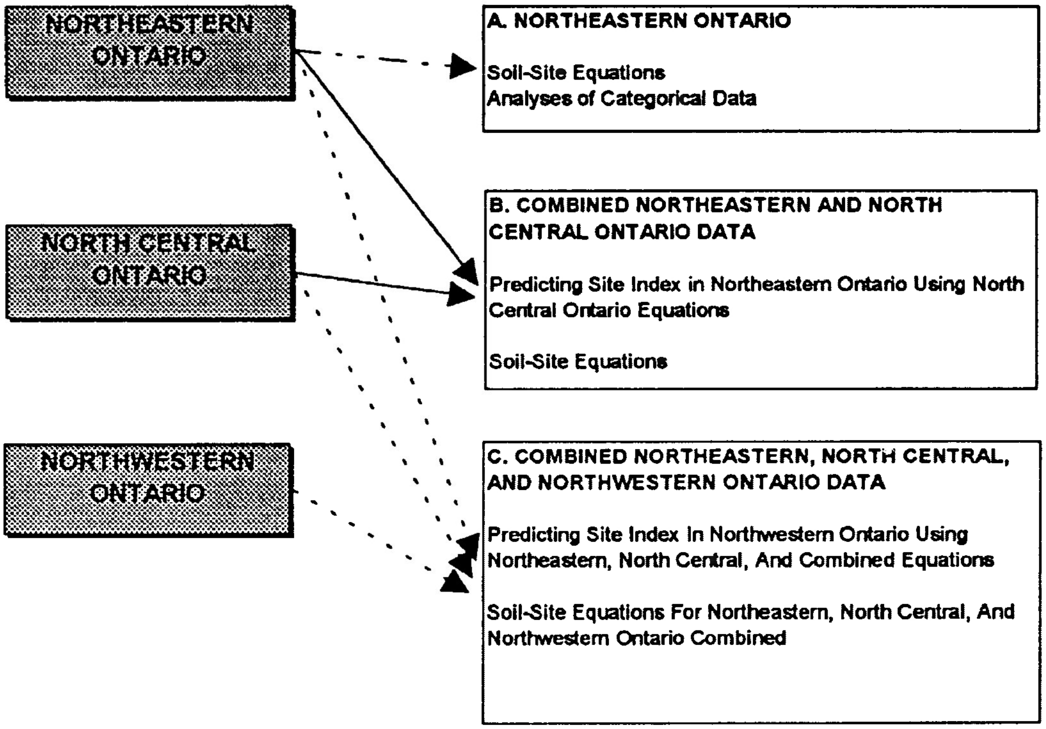


Figure 8. Sequence of aggregations of data and subsequent analyses for northeastern, north central, and northwestern Ontario.

A. NORTHEASTERN ONTARIO

All data were entered into a dBase IV (Ashton-Tate 1991) data base on a Compaq 386/25e DOS-based personal computer. The data were printed, and the output compared to the original tally sheets to verify that no data entry errors occurred. The SAS version 6.04 statistical software (SAS Institute Inc. 1988) was used for the statistical analyses.

Data Preparation

Plot Screening

The original 79 plots were closely examined for anomalies. This led to the exclusion of three plots, reducing the data set to 76 plots. Plot 50 was not included in the analyses, because stem analyses showed that the three tree height growth curves were too erratic, due to tree top breakage; plot 58 was excluded because it was an organic soil; plot 61 was excluded because the soil was a boulder pavement, which is an unusual soil condition.

Plot Stratification

The data were stratified into five landform classes (Sado and Carswell 1987, Schmidt and Carmean 1988):

1) bedrock-moraine - soils with less than one metre of moraine soil above bedrock and containing > 10% coarse fragments (15 plots);

2) bedrock-glaciofluvial - soils with less than one metre of glaciofluvial soil above bedrock and containing < 10% coarse fragments (four plots);

3) glaciofluvial sands - soils whose parent material (i.e. sand) was of glaciofluvial, fluvial or aeolian origin (33 plots);

4) lacustrine - heavy-textured soils whose parent material was of glaciofluvial or glaciolacustrine origin (lake bottom clay); and the fine earth fraction was less than 50% sand (six plots); and

5) moraine - soils whose parent material was of glacial moraine origin (unsorted till); and contained > 10% coarse fragments (18 plots).

Averaging Soil Horizon Data

Soil horizon data for each plot was combined into four major horizons (A, B, BC, and C), except bedrock landforms, which usually only have A and B horizons. If the soil profile consisted of more than four horizons, values for the minor horizons were averaged with the major horizon. For example, if a Bfj horizon and a Bm horizon were present in the profile, the data from these layers were averaged to form a single generic B horizon. If the soil profile consisted of less than four horizons, the horizon above was averaged with the horizon below to calculate the values of the missing horizon (e.g. often there was no BC horizon).

Preliminary Screening and Data Analyses

Simple Correlations

Pearson product-moment correlation coefficients (r) of site index (SI_{BH50}) with each independent variable were computed for all 119 variables using site index as the dependent variable. Correlations were calculated for the combined data set and separately for each landform. Ten candidate independent variables were selected for the combined data set and for each landform data set. The selected candidates had a high simple correlation with site index, and also were not highly correlated with other independent variables. Backward stepwise multiple regression was used as a second method to screen variables.

Independent Variable Screening

119 independent variables were available for model building (Table 3). Screening was required to eliminate soil variables that had little or no relationship to site index. Each variable had to meet all four of Schmidt's (1986) criteria as follows:

1) a value for the variable is available for each plot;
2) the variable is not greatly affected by site disturbances;
3) the variable could 'reasonably' be expected to be related to site index; and
4) the variable either can be measured in the field or can be obtained through simple laboratory analyses.

The ten candidate independent variables, previously chosen from simple correlations, were tested for curvilinearity for each equation. The curvilinear form of the independent variable was used in the analyses if any of the variables were found to have a statistically significant improvement. This procedure was repeated using the following variable transformations: 1) natural logarithm; 2) square root; 3) inverse; and 4) quadratic.

Summary Statistics and Scatterplots

Summary statistics including the mean, standard deviation, minimum and maximum values for the dependent and independent variables were computed for all landforms combined. Graphs of the dependent variable (i.e. site index) were plotted against each of the ten screened independent variables.

Preliminary Equations

Backward stepwise multiple regression was used to compute a preliminary equation for the combined data set, and for three of the five landforms. Equations were not calculated for the bedrock-glaciofluvial and lacustrine landforms, due to their small sample size (i.e. four and six plots, respectively).

A poor relationship existed for the combined data set of 76 plots that combined all five landforms. Therefore, future computations were restricted to separate analyses for the bedrock-moraine, glaciofluvial, and moraine landforms.

The residuals for the three preliminary equations were examined to determine if the assumptions of regression had been violated, as follows:

1) the errors belonged to the population (i.e. no outliers; Weisberg 1980); and,

2) the error terms were random (i.e. no heteroscedasticity; Chatterjee and Price 1977).

Bonferroni's t-test at $P < 0.05$ was used to test each preliminary equation for outliers. Scatterplots of the residuals versus the predicted values for each equation were examined to detect heteroscedasticity.

A standard error (S_b), number of observations (N), R^2 value, R^2 value adjusted for sample size (R^2adj), and standard error of the estimate (SEE) was calculated for each equation.

Final Analyses

Check Plots

Twenty percent of the plots were randomly chosen for check plots. These check plots were separated from the original computational plots. No check plots were used in the bedrock-moraine or moraine landform, since these two landforms were only represented by 15 and 18 plots, respectively.

Model Building

A four-variable limit was placed on the multiple regression equations. This constraint was enforced to minimize the number of independent variables needed to predict site index in the field. Backward stepwise regression and 'all possible subsets' regression was used simultaneously to create a four-variable multiple regression equation.

Each model was constrained to three independent variables, and the regression procedure was repeated. An F-test was then used to test if the four-variable model statistically explained more variation than the three-variable model, at $P < 0.05$. The four-variable model was used for further analyses if the test passed, and a three-variable model was used for further analyses if the test failed.

Interactions

All possible two-way interactions were computed for each equation. The regression procedure was repeated, utilizing the interactions as additional independent variables. Additional interactions based on all ten independent variables were calculated and included in the regression procedure in an attempt to improve the equation.

Site Index Prediction Tables, Residuals, and Trend Graphs

Site index prediction tables were generated from the final equation for each landform. Table headings were created from the independent variables from each final equation. The range of observed values defined the upper and lower limits for each independent variable. This range was sub-divided into appropriate multiples, to obtain a discrete number of rows and columns for each table. The mid-point value of each row and column heading was inputted into the final equation, and the cells within the table populated with site index values. Site index values higher or lower than the observed maximum and minimum site index within each landform were deleted from the table.

The final equation for each landform was used to compare predicted site index values against actual site index values. These graphs displayed residuals for each landform.

Site index trend graphs were plotted, based on the final equation for each landform. Lines on each graph were not plotted above maximum observed site index, or below the lowest observed site index value for each landform.

ANALYSES OF CATEGORICAL DATA

One-way ANOVA's were calculated for each categorical variable (e.g. Clay Belt Operational Group, humus form, and soil texture) using site index as the response variable. ANOVA's were calculated in an attempt to find meaningful stratifications that yielded statistically different groups. Independent variables which were statistically significantly different at $P < 0.05$ were further explored by using SNK (Student-Newman-Keul's) multiple range test (Steel and Torrie 1980) to identify statistically significant groups. Independent variables were grouped together based on their mean site index, and the SNK tests re-computed in an attempt to improve the identification of statistically significant groups. The variable grouping and re-computing of the SNK test were sometimes repeated.

B. COMBINED NORTHEASTERN AND NORTH CENTRAL ONTARIO DATA

PREDICTING SITE INDEX IN NORTHEASTERN ONTARIO USING NORTH CENTRAL ONTARIO EQUATIONS

Schmidt and Carmean's (1988) equations developed in north central Ontario were used to predict site index for 62 of the 76 plots from the northern and northeastern regions. Fourteen northeastern plots were not included with this analyses, since values for their soil variables exceeded the range defined by the north central equations. For example, the glaciofluvial equation for north central Ontario contains percent slope as an independent variable. The largest percent slope observed in north central Ontario was 15%, therefore, all glaciofluvial northeastern plots whose slope exceeded 15% were excluded from the analyses. Actual site index for each plot was compared to predicted site index, using Pearson's correlation coefficient at $P < 0.05$, for the 62 northeastern plots.

SOIL-SITE EQUATIONS FOR NORTHEASTERN AND NORTH CENTRAL ONTARIO COMBINED

The northeastern data were combined with north central data from two sources:

1) 131 plots from north central Ontario (Schmidt 1986); and
2) 12 plots in north central Ontario. Niznowski (1993) and the author collected soils data from additional Lenthall (1986) jack pine stem analyses plots not included in Schmidt's (1986) analyses.

New soil-site equations were developed using the same methodology as the northeastern soil-site equations, but using the combined data set.

C. COMBINED NORTHEASTERN, NORTH CENTRAL, AND NORTHWESTERN ONTARIO DATA

Supplemental soils and jack pine site index data were obtained from various sources as follows:

1) 59 plots in northwestern Ontario (Jackman 1990); and
2) Niznowski (1993) and the author collected soils and stem analyses data on 16 plots near Red Lake.

PREDICTING SITE INDEX IN NORTHWESTERN ONTARIO USING NORTHEASTERN, NORTH CENTRAL ONTARIO AND COMBINED EQUATIONS

The northwestern Ontario data were used to predict site index with northeastern, north central, and combined northeastern / north central Ontario site index prediction equations. Actual site index for each plot was compared to predicted site index, using Pearson's correlation coefficient at $P < 0.05$.

SOIL-SITE EQUATIONS FOR NORTHEASTERN, NORTH CENTRAL AND NORTHWESTERN ONTARIO COMBINED

Schmidt's (1986) north central Ontario data were pooled with the northeastern Ontario data. New soil-site equations were developed using the same methodology as the northeastern soil-site equations.

Jackman's (1990) northwestern Ontario data were examined and found to be lacking in many important soil variables. This was due to NWO FEC soil cards being utilized for soils descriptions. The NWO FEC soil cards contained only 59 independent variables, many of which were not soil variables found to be important by Schmidt and Carmean (1988), LaValley (1991), or Li (1991). In contrast, important features such as depth to root restricting layers and coarse fragment content were not included in the soil descriptions for the NWO FEC plots.

RESULTS

A. NORTHEASTERN ONTARIO

SOIL-SITE EQUATIONS

Summary Statistics

Summary statistics including the mean, standard deviation, minimum and maximum values of the site index values for each landform were computed (Table 4).

Table 4. Summary statistics of site index values for each landform.

Landform	Number of plots	Average SI (m)	Minimum SI (m)	Maximum SI (m)	Range of SI (m)	Standard deviation (m)
Bedrock-glaciofluvial	4	15.9	13.5	19.6	6.1	3.0
Bedrock-moraine	15	15.5	10.4	19.7	9.3	3.0
Glaciofluvial	33	17.4	12.9	22.4	9.5	2.3
Lacustrine	6	16.9	13.3	20.7	7.4	2.9
Moraine	18	17.8	13.5	20.4	6.9	1.7
TOTAL	76					

where SI = site index (SI_{BH50}) is total height of dominant and codominant trees at breast height age 50 years.

Independent Variable Screening

Pearson product-moment correlation coefficients (r) for site index with each independent variable were computed by landform. Simple correlations and backward stepwise multiple regression were used to choose 10 'best' independent variables for each landform (Table 5). No correlations were attempted for the bedrock-glaciofluvial and lacustrine landforms because these landforms were only represented by four and six plots, respectively (Table 4).

Table 5. Simple correlations with site index (SI_{BH50}) by landform.

Independent Variable Category	Variable	Bedrock-Moraine (r)	Glaciofluvial (r)	Moraine (r)
SOIL DEPTH	BR	0.463		
	AVGROOT		0.546**	
	DMRL		0.379	
SOIL HORIZON	BTHICK	0.552*		
	ACONS3	0.434		
	AROOTSIZ		0.321	
	BC CHROMA		0.346	-0.293
SOIL HORIZON LABORATORY ANALYSES	A%SILT		0.422*	
	B%SILT		0.503**	
	BC%SAND		-0.399*	-0.349
	BC%SILT		0.478*	0.331
	BC%SICLAY		0.397*	0.349
PROFILE COARSE FRAGMENT	A%COBBL	-0.601*		
	A%GRVCOB	-0.539*		
	%STONETOP	-0.421		-0.350
	A%COBST			-0.319
	B%STONE			-0.335
	A%STONE			-0.398
	ACFTOTAL			-0.295
TOPOGRAPHY	SINASPECT	0.574*		
	SLOPE%	-0.530*		-0.382
SOIL MOISTURE	D_CLS	0.483	0.429*	
	MR	0.464		

* statistically significant at $P < 0.05$ * *statistically significant at $P < 0.01$

Note: Bedrock-glaciofluvial and lacustrine landforms had too few plots to be included in this table.

Preliminary Equations

The ten variables for each landform were used to compute preliminary equations (Table 6), unstratified and stratified by landform.

Table 6. Preliminary multiple regression equations for the combined data, and for each landform.

Landform	Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
Combined	A1	SI = 13.47+ 0.5829 (D_CLS) - 0.0130 (BR) + 0.0554 (AVGROOT) + 0.0164 (DMRL)	0.212 0.011 0.022 0.010	76	0.228	0.185	2.13
Bedrock-Moraine	BRM1	SI = 12.51 + 0.0067(SINASPECT) - 0.2174 (SLOPE%) + 0.2152 (%STONTOP) + 0.1405 (BTHICK)	 0.007 0.060 0.096 0.041	15	0.776	0.686	1.66
Glacio-fluvial	GF1	SI = 10.74 + 0.6069 (D_CLS) + 0.0981 (AVGROOT) + 0.0242 (DMRL) + 0.0702 (B%SILT)	0.291 0.030 0.008 0.018	27*	0.727	0.678	1.38
Moraine	M1	SI = 64.70 - 0.0321 (MAXROOT) - 0.9974 (P_PAT) - 0.4357 (BC%SAND) - 0.4174 (BC%SILT)	 0.012 0.316 0.171 0.179	18	0.584	0.456	1.26

*does not include six plots which were randomly selected for check plots

Bedrock-Moraine Final Equations

A four-variable model (equation BRM1) and a three-variable model (equation BRM2) were computed using backward stepwise regression and 'all possible subsets' regression simultaneously (Table 7). An F-test was then used to test if the four-variable model statistically explained more variation than the three-variable model, at $P < 0.05$. Equation BRM2 was chosen over equation BRM1 because it passed the F-test.

Table 7. Multiple regression equations for the bedrock-moraine landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
BRM1	SI = 12.51 + 0.0067 (SINASPECT) - 0.2174 (SLOPE%) + 0.2152 (%STONTOP) + 0.1405 (BTHICK)	0.007 0.060 0.096 0.041	15	0.776	0.686	1.66
BRM2	SI = 12.64 - 0.2370 (SLOPE%) + 0.2391 (%STONTOP) + 0.1598 (BTHICK)	0.055 0.091 0.035	15	0.757	0.691	1.65
BRM3	SI = 13.61 - 0.1877 (SLOPE%) + 0.0066 $(\%STONTOP)^2$ + 0.1353 (BTHICK)	0.041 0.002 0.029	15	0.762	0.697	1.63
BRM4 (final equation)	SI = 14.50 - 0.2943 (SLOPE%) + 0.4588 (BTHICK) - 0.0094 [(35-%STONTOP) x BTHICK]	0.054 0.097 0.003	15	0.827	0.780	1.39

Each independent variable was tested to see if a quadratic transformation improved the R^2. The independent variable $(\%STONTOP)^2$ was found to improve the regression equation significantly, and was thus included in equation BRM3.

Interaction terms were created using all independent variables. Backward stepwise regression and 'all possible subsets' regression were used simultaneously to determine which interactions should be included in the final model. This computation showed that equation BRM4 greatly improved precision using an interaction [(35 - %STONTOP) X Bthick]. Equation BRM4 was selected as the final equation for the bedrock-moraine landform.

Equation BRM4 was used to calculate site index values for the observed range of slope percent, B thickness, and percent stones (0 - 25 cm). These site index values were compared to actual site index values for each plot (Figure 9), and used in a site index prediction table for field estimation of site index (Table 8). Equation BRM4 was also used to construct trend graphs, showing the relationship between site index and slope percent, B thickness, and percent stone (Figure 10).

Table 8. Site index prediction table for the bedrock-moraine landform using equation BRM4.

	B Thickness (cm)											
	0 - 20			20 - 40			40 - 60			60 - 80		
	% Stone (0-25 cm)											
slope %	0 - 10	10 - 20	20 - 30	0 - 10	10 - 20	20 - 30	0 - 10	10 - 20	20 - 30	0 - 10	10 - 20	20 - 30
0 - 10	14.8	15.7	16.7	18.3								
10 - 20	11.9	12.8	13.7	15.4	18.2		18.9					
20 - 30			10.8	12.4	15.3	18.1	16.0			19.5		
30 - 40					12.3	15.1	13.0	17.7		16.6		
40 - 50						12.2		14.8	19.5	13.6		

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; B thickness = thickness of the B horizon; % Stone (0-25cm) = percent stones in the top of the soil pit (0 to 25 cm); Slope % = percent slope.

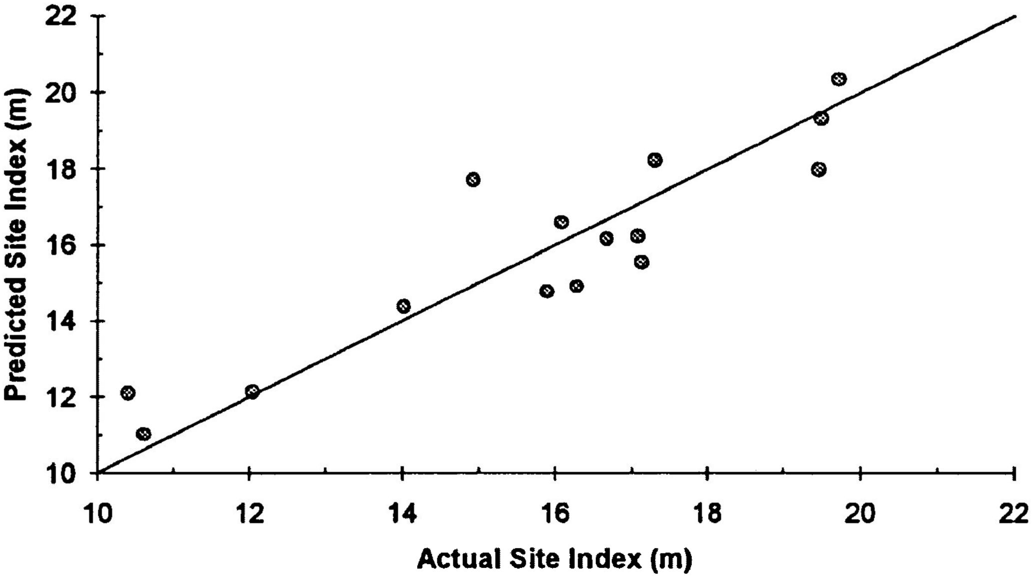


Figure 9. Residuals showing differences between predicted and measured site index for plots established on bedrock-moraine soils, using equation BRM4.

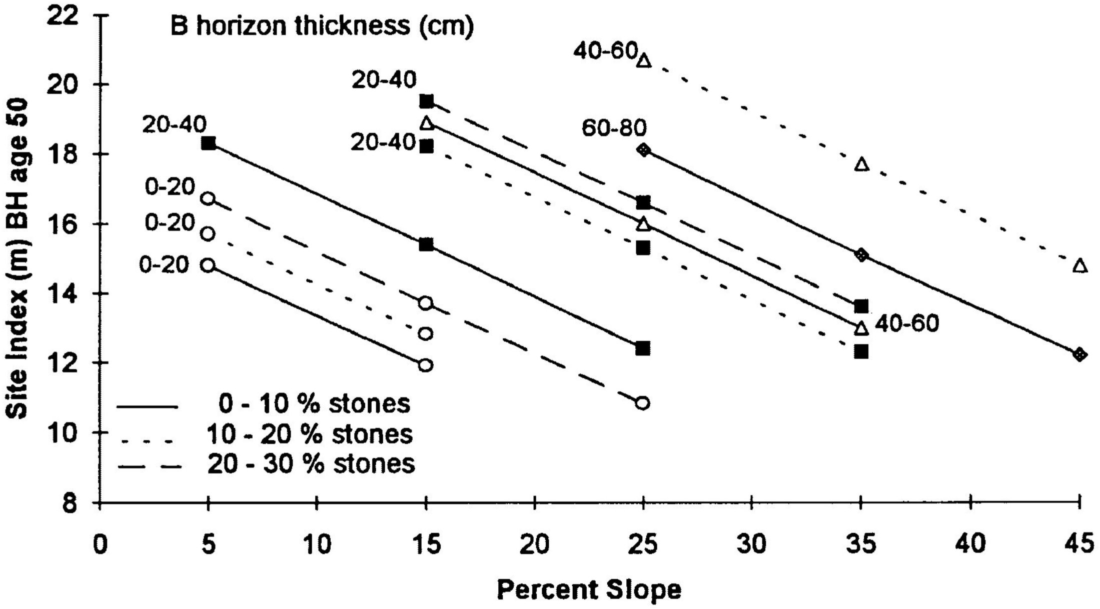


Figure 10. Site index trend graphs for the bedrock-moraine landform, using equation BRM4.

Glaciofluvial Final Equations

Six of the 33 plots were randomly chosen and used as check plots. The remaining 27 computational plots were used to compute a four-variable model (equation GF1) and three-variable model (equation GF2), using backward stepwise regression and 'all possible subsets' regression simultaneously (Table 9). An F-test was then used to test if the four-variable model statistically explained more variation than the three-variable model, at $P < 0.05$. Equation GF2 was chosen over equation GF1 because it passed the F-test, even though equation GF2 was less precise than equation GF1.

Table 9. Multiple regression equations for the glaciofluvial landform.

Eqn #	SI Equation	S_h	N	R^2	R^2 (adj)	SEE (m)
GF1	SI = 10.74 + 0.6069 (D_CLS) + 0.0981 (AVGROOT) + 0.0242 (DMRL) + 0.0702 (B%SILT)	0.291 0.030 0.008 0.018	27	0.727	0.678	1.38
GF2	SI = 12.08 + 0.0921 (AVGROOT) + 0.0267 (DMRL) + 0.08509 (B%SILT)	0.031 0.008 0.017	27	0.673	0.631	1.47
GF3	SI = 12.75 + 0.0879 (AVGROOT) + 0.0193 (DMRL) + 0.0016 (DMRL x B%SILT)	0.032 0.008 0.0003	27	0.658	0.613	1.51
GF4	SI = 12.26 + 0.1029 (AVGROOT) + 0.0237 (DMRL) + 0.0614 (B%SILT)	0.032 0.010 0.017	33	0.520	0.470	1.70
GF5 (final equation)	SI = 12.77 + 0.0937 (AVGROOT) + 0.0183 (DMRL) + 0.0014 (DMRL x B%SILT)	0.032 0.009 0.0003	33	0.558	0.512	1.62

Each independent variable was tested to see if a quadratic transformation improved the R^2 of equation GF2. No independent variables were found for which the model was improved significantly by a quadratic transformation.

Interaction terms were created using all independent variables. Backward stepwise regression and 'all possible subsets' regression were used simultaneously to choose which interactions should be included in the model. The interaction term (DMRL X B%Silt) in equation GF3 somewhat decreased R^2, thus equation GF2 was considered superior.

An attempt was made to increase the accuracy of the final regression equation by combining the six check plots with the 27 computation plots. The 33 plots were then used with equation GF2 to compute equation GF4. Addition of the six check plots into equation GF2 resulted in a decrease in R^2, from 0.63 to 0.47. The six check plots were added into the previously rejected equation GF3, to create equation GF5. Equation GF5 had a decrease in R^2, from 0.61 to 0.51. Although addition of the check plots decreased R^2, equation GF5 was still chosen as the final equation, since its R^2 value was higher than equation GF4.

Equation GF5 was used to calculate site index values for the range of DMRL, depth to average rooting, and percent silt in the B horizon. These site index values were compared to actual site index values (Figure 11), and used in a site index prediction table for field estimation of site index (Table 10). Equation GF5 also was used to construct trend graphs, showing the relationship between site index and depth to moisture restricting layer, depth to average rooting, and B% silt (Figure 12).

Table 10. Site index prediction table for the glaciofluvial landform using equation GF5.

	Depth to Average Rooting (cm)											
	0 - 10			**10 - 20**			**20 - 30**			**30 - 40**		
	B % Silt											
DMRL (cm)	**0 -15**	**15-30**	**30-45**	**0 -15**	**15-30**	**30-45**	**0 -15**	**15-30**	**30-45**	**0 -15**	**15-30**	**30-45**
0 - 25	13.6	13.9	14.1	14.5	14.8	15.1	15.5	15.7	16.0	16.4	16.7	16.9
25 - 50	14.3	15.1	15.9	15.3	16.0	16.8	16.2	17.0	17.8	17.1	17.9	18.7
50 - 75	15.0	16.4	17.7	16.0	17.3	18.6	16.9	18.2	19.5	17.9	19.2	20.5
75 - 100	15.8	17.6	19.4	16.7	18.5	20.4	17.6	19.5	21.3	18.6	20.4	22.2
100 -125	16.5	18.8	21.2	17.4	19.8	22.1	18.4	20.7		19.3	21.7	

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; depth to Average Rooting = average depth of rooting. B % Silt = percent silt in the B horizon; DMRL = depth to moisture restricting layer (i.e. coarse sandy subsoil, mottles, gley, water table, bedrock, carbonates or basal till).

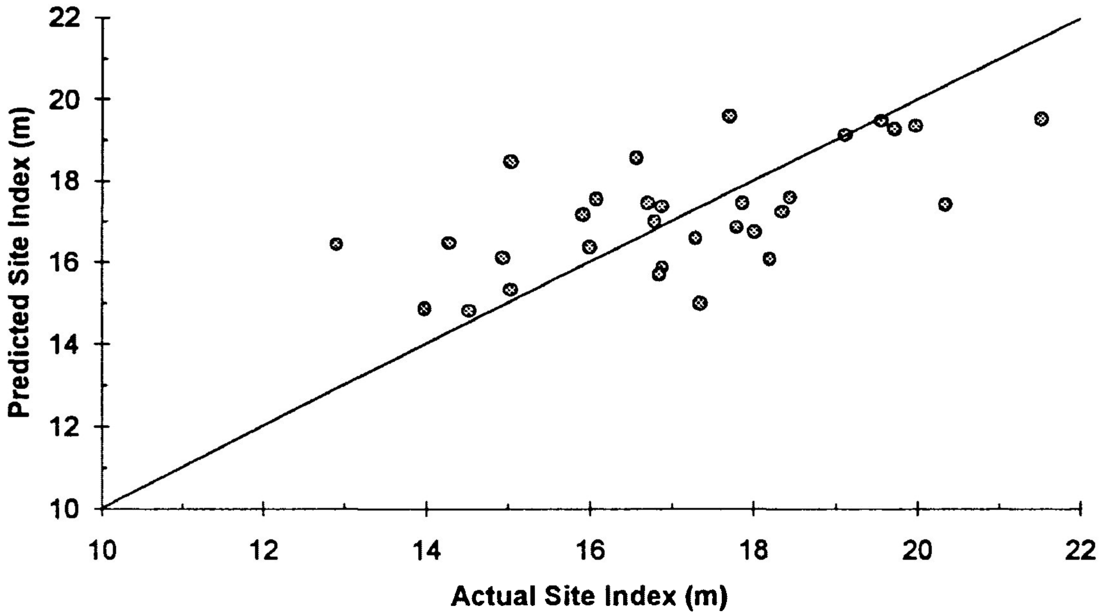


Figure 11. Residuals showing differences between predicted and measured site index for plots established on glaciofluvial soils, using equation GF5.

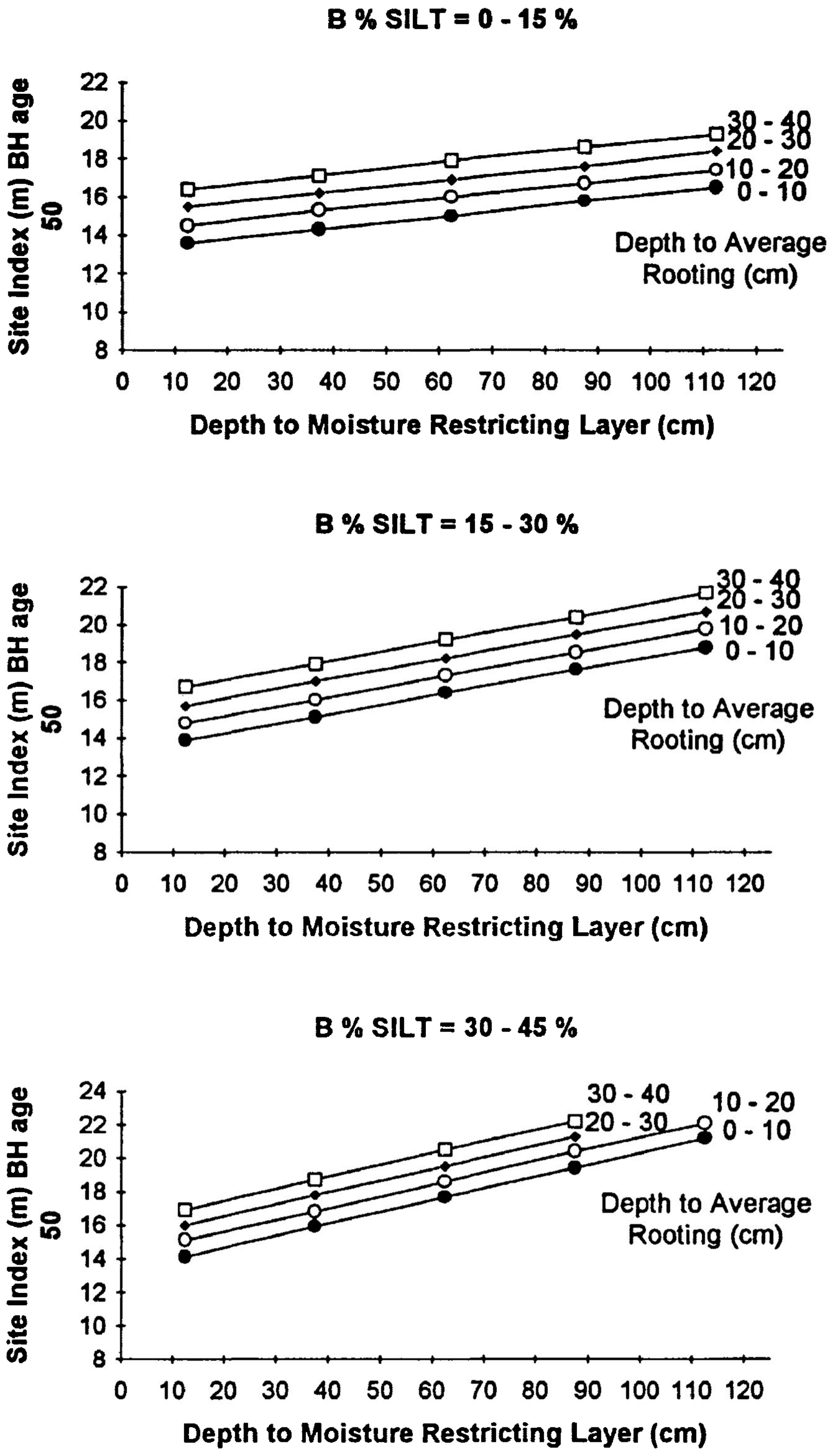


Figure 12. Site index trend graphs for the glaciofluvial landform using equation GF5.

Moraine Final Equations

A four-variable model (equation M1) and a three-variable model (equation M2) were computed using backward stepwise regression and 'all possible subsets' regression simultaneously (Table 11). An F-test was then used to test if the four-variable model statistically explained more variation than the three-variable model, at $P < 0.05$. Equation M2 failed the F-test, and equation M1, which was statistically superior, was used for the next phase of equation development.

Each independent variable was tested to see if a quadratic transformation improved the R^2. None of these quadratic transformations were found to improve the precision of equation M1 significantly.

Table 11. Multiple regression equations for the moraine landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
M1	SI = 64.70 - 0.0321 (MAXROOT) - 0.9974 (P_PAT) - 0.4357 (BC%SAND) - 0.4174 (BC%SILT)	0.012 0.316 0.171 0.179	18	0.584	0.456	1.26
M2	SI = 14.16 + 0.4499 (AROOTAB) + 1.7148 (S_SHP) - 0.1386 (BCFSTONE)	0.206 0.642 0.061	18	0.484	0.373	1.27
M3 (final equation)	SI = 19.93 + 0.6125 (MAXROOT) - 0.0145 (MAXROOT x P_PAT) - 0.0063 (MAXROOT x BC %SAND) - 0.0061 (MAXROOT x BC %SILT)	0.029 0.004 0.0003 0.0003	18	0.691	0.595	1.09

Interaction terms were created using all independent variables. Backward stepwise regression and 'all possible subsets' regression was used simultaneously to choose which interactions should be included in the final model, resulting in the final equation M3. These computations showed that precision was statistically improved using three interaction terms: (MAXROOT x P_PAT); (MAXROOT x BC %SAND); and (MAXROOT X BC %SILT).

Equation M3 was used to calculate site index values for the range of maxroot, pore pattern, BC %sand, and BC %silt. These site index values were used to compare actual site index values (Figure 13), and in a site index prediction table for field estimation of site index (Table 12). The table was divided into two sections to prevent erroneous combinations of BC %sand and BC %silt, since percent sand, silt and clay in any horizon cannot exceed 100%. Thus, the table with BC % sand equal to 90%, shows only the BC % silt content of 10%. Equation M3 also was used to construct trend graphs, showing the relationship between site index and depth to maximum rooting, pore pattern, BC %sand, and BC %silt (Figure 14).

Table 12. Site index prediction table for the moraine landform using equation M3.

	Pore Pattern							
	0		1		2		3	
	BC %SAND							
	70	50	70	50	70	50	70	50
	BC % Silt							
Maxroot (cm)	20-40	40-60	20-40	40-60	20-40	40-60	20-40	40-60
30 - 50	19.5	19.6	18.9	19.1	18.3	18.5	17.7	17.9
50 - 70	19.2	19.5	18.4	18.6	17.5	17.7	16.6	16.9
70 - 90	19.0	19.3	17.9	18.2	16.7	17.0	15.5	15.9
90 - 110	18.8	19.2	17.3	17.7	15.9	16.3	14.4	14.8
110 -130	18.6	19.0	16.8	17.3	15.1	15.6		13.8

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; BC% Sand = percent sand in the BC horizon; BC% Silt = percent silt in the BC horizon; maxroot = depth to maximum rooting.

BC %sand = 90% (BC %silt = 10% by default)

	Pore Pattern			
Maxroot (cm)	0	1	2	3
30 - 50	19.3	18.7	18.2	17.6
50 - 70	19.0	18.1	17.3	16.4
70 - 90	18.7	17.5	16.4	15.2
90 - 110	18.4	16.9	15.5	14.0
110 -130	18.1	16.3	14.6	

where SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; maxroot = depth to maximum rooting.

Equation M3 was also used to construct a trend graph, displaying the relationship between site index and depth to maximum rooting, pore pattern, BC% sand, and BC% silt (Figure 13).

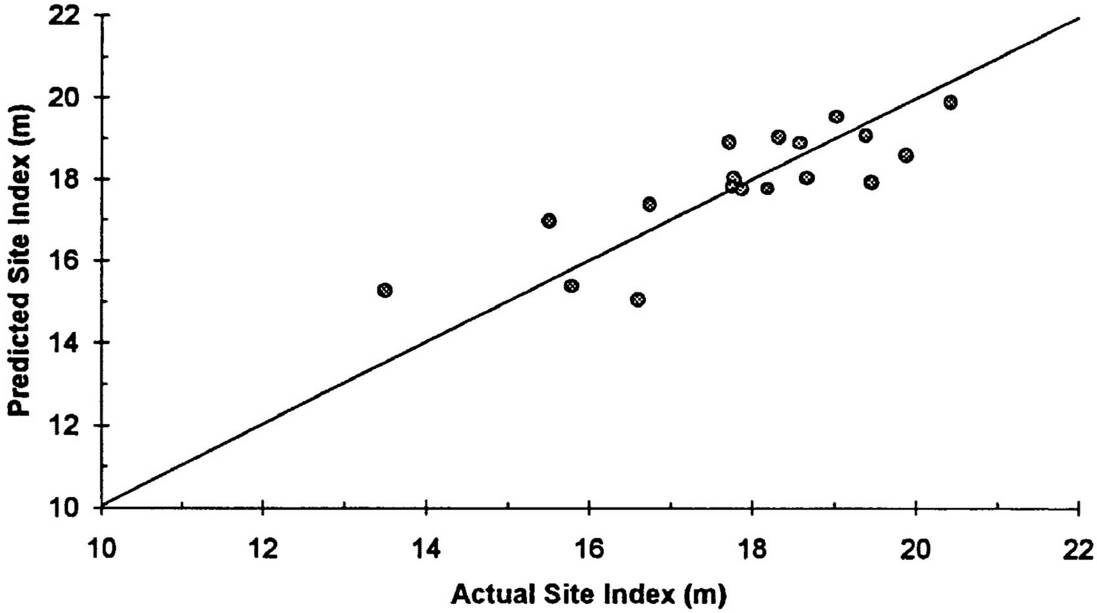
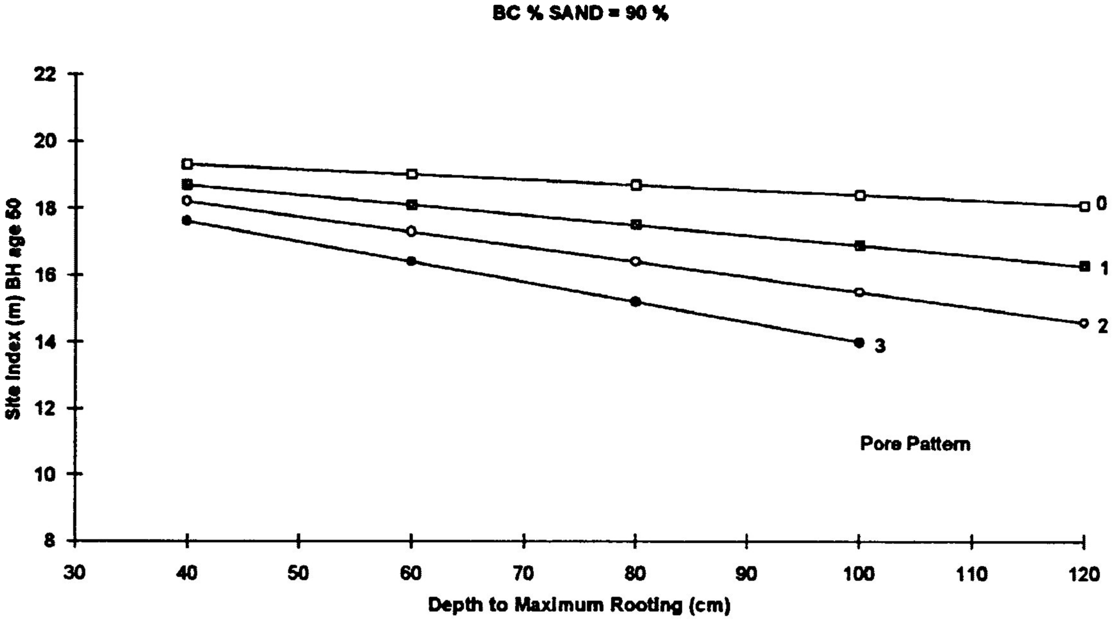


Figure 13. Residuals showing differences between predicted and measured site index for plots established on moraine soils, using equation M3.



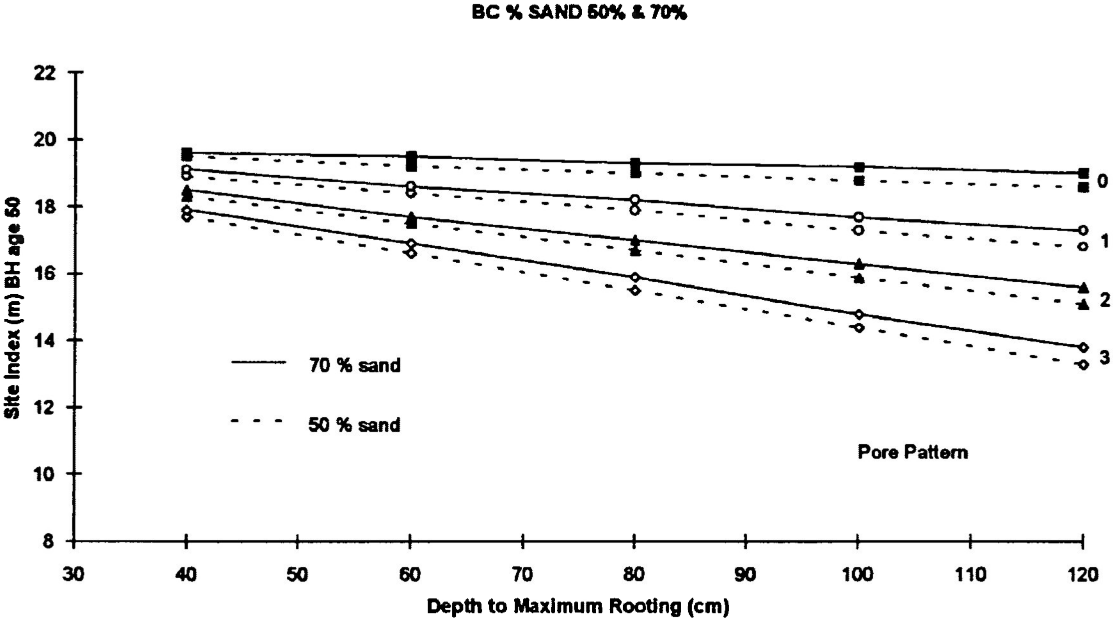


Figure 14. Site index trend graphs for the moraine landform using equation M3.

ANALYSES OF CATEGORICAL DATA

One-way ANOVA's were calculated for each categorical variable using site index as the response variable, in an attempt to find meaningful stratifications that yielded statistically different groups. These ANOVA's showed that only a few categorical variables had statistically significant differences (Table 13). The moraine landform had no variables that were statistically different.

Table 13. ANOVA results of categorical variables by landform, using site index as the response variable.

	COMBINED LANDFORMS	BEDROCK-MORAINE	GLACIO-FLUVIAL	MORAINE
VARIABLE	P(F)	P(F)	P(F)	P(F)
REGION	0.5250	n/a	0.8877	0.6675
SPPCOMP	0.1004	0.2678	0.1288	0.7015
S_SHP	0.9792	0.4824	0.0102*	0.5061
S_POS	0.1360	0.5198	0.3405	0.7331
MR	0.3803	0.4004	0.6536	0.4664
D_CLS	0.1865	0.3694	0.0947	0.3238
P_PAT	0.4634	0.7799	0.8711	0.5392
FPS	0.5744	0.7799	0.7696	0.3603
H_FORM	0.0196*	0.1899	0.0067**	0.7879
STRAT	0.0237*	0.2097	0.3897	0.6382
CFECSOIL	0.0058**	0.0300*	0.6367	0.3826
FECSOIL	0.0212*	0.1116	0.6392	0.4323
CFECVEG	0.0329*	0.0597	0.3975	0.3277
FECVEG	0.0037**	0.0190*	0.0383*	0.9461
OG	0.0001**	0.0027**	0.5380	0.3388

* statistically significant at $P < 0.05$
* *statistically significant at $P < 0.01$

Independent variables which were significant at $P < 0.05$ were further explored by using Student-Newman-Keul's (SNK) multiple range tests to identify statistically significant groupings of FEC soil, vegetation and operational groups; groupings of slope shape and humus types also were considered. The SNK procedure identifies each classification (e.g. convex, flat, concave) within a variable (e.g. surface shape) as group A, B, or C. If all classifications within a variable are identified as group A, then there is no statistically significant difference among the classifications. If some classifications are group A, and the remainder is group B, then there are two statistically significantly different groups within the given variable. Note that overlap can occur, and a single classification could belong to both groups A and B.

Independent variables were grouped together based on their mean site index, and the SNK tests recomputed in an attempt to improve the identification of statistically significant groups (Tables 14 to 21). The variable grouping and recomputing of the SNK test was sometimes repeated. These groupings are shown for all landforms combined (Tables 14 to 20) and for glaciofluvial soils (Table 21). No groupings are given for the moraine soils because none of the categorical variables showed a significant relation to site index (Table 13). Also, no groupings are given for bedrock-moraine soils, since all landforms have been combined.

Initial ANOVA of the humus form classification shows that there was a significant difference between humus types, but the SNK test lumped all humus types into the same statistical group 'A'. After grouping the humifibrimor and fibrihumimor humus forms together, the mean site index of group 'A' was statistically significantly different from group 'B' (Table 14).

Table 14. Student-Newman-Keul's groupings of humus form classification for all landforms combined.

SNK Grouping	Mean SI	N	$P(F>F_c) = 0.0049$
A	17.89	37	9 (humifibrimor)
B	16.32	39	8, 10 (fibrimor and fibrihumimor)

Initial SNK analysis of soil stratification shows that stratified soils have a statistically significantly higher site index than unstratified soils (Table 15). However, the SNK test does not separate stratified and unstratified soils into two separate statistical groups.

Table 15. Student-Newman-Keul's groupings of soil stratification for all landforms combined.

SNK Grouping	Mean SI	N	$P(F>F_c) = 0.0237$
A	17.97	26	Y (Stratified soil layers)
A	16.62	50	N (Homogeneous soil layers)

Initial SNK analysis of Clay Belt FEC soil types showed that there were two overlapping statistical groups 'A' and 'B'. Subjectively grouping the soil types into five groups failed to adequately stratify soil types, but further grouping was possible. Therefore, three groups were formed (Table 16), which delineated statistically different soil groups 'A' and 'B'. Group 'A' consists of two soil type groupings with means of 18.22 m and 16.84 m. Group 'B' consists of three plots, all in Clay Belt soil group S1, has a mean site index of 12.07 m, and is statistically significantly different from group 'A'.

Table 16. Student-Newman-Keul's groupings of Clay Belt FEC soil classification for all landforms combined.

SNK Grouping	Mean SI	N	$P(F>F_c) = 0.0001$
A	18.22	24	S3, S4, S8
A	16.84	49	S2, S5, S6, S7, S9, S10
B	12.07	3	S1

Initial SNK analysis of NWO FEC soil types showed that there were statistically significant differences between soil types, but the SNK test did not stratify the soil types into distinct statistical groups. After subjectively grouping the soil types into five groups, then reiterating with three groups, two statistically significantly different groups (A and B) were delineated (Table 17). Group 'A' has two soil type groupings with means of 18.18 m and 17.52 m. Group 'B' has a mean site index of 14.81 m.

Table 17. Student-Newman-Keul's groupings of NWO FEC soil classification for all landforms combined.

SNK Grouping	Mean SI	N	$P(F>F_c) = 0.0001$
A	18.18	16	SS5, S3, S5
A	17.52	44	S1, S2, SS6, SS8
B	14.81	16	SS3, SS7, S7, S8, S10

Initial SNK analysis of the Clay Belt FEC vegetation types shows that there were significant differences between vegetation types, but the SNK test grouped all vegetation types into one statistical group 'A'. After subjectively grouping the vegetation types into three groups, then reiterating with two groups, the mean site index of group 'A' was statistically significantly different from group 'B' (Table 18).

Table 18. Student-Newman-Keul's groupings of Clay Belt FEC vegetation classification for all landforms combined.

SNK Grouping	Mean SI	N	$P(F>F_c) = 0.0001$
A	18.42	29	V3, V4, V6
B	16.29	47	V1, V2, V5, V7, V23

Initial SNK analysis of the NWO FEC vegetation types shows that there were significant differences between vegetation types, but the SNK test did not stratify the vegetation types into distinct statistical groups; all vegetation types belonged to the same statistical group 'A'. However, after subjectively grouping the vegetation types into four groups, and reiterating with three groups, three statistically significantly different groups (A, B and C) were formed (Table 19). The mean site index of group 'A' was 18.09 m, and did not overlap with groups 'B' or 'C', whose mean site index values were 15.99 m, and 13.80 m, respectively.

Table 19. Student-Newman-Keul's groupings of NWO FEC vegetation classification for all landforms combined.

SNK Grouping	Mean SI	N	$P(F>F_c) = 0.0001$
A	18.09	44	V7, V16, V17, V18, V28, V34
B	15.99	28	V29, V31, V32
C	13.80	4	V30

Initial SNK analysis of the Clay Belt FEC operational groups (OG's) shows that there was a significant difference between OG's. However, there was much overlap between these two groups. After grouping the soil types into three groups, the mean site index of group 'A' was statistically significantly different from group 'B' (Table 20). Group 'A' consists of 73 out of 76 plots, which shows that OG's stratify productivity of jack pine poorly.

Table 20. Student-Newman-Keul's groupings of the Clay Belt FEC operational group classification for all landforms combined.

SNK Grouping	Mean SI	N	$P(F>F_c) = 0.0001$
A	18.38	30	OG3, OG4
A	16.54	43	OG2, OG5, OG6
B	12.07	3	OG1

Initial SNK analysis of the surface shape classification for the glaciofluvial landform shows that threre were significant differences and some overlap between surface shapes (Table 21). Both the concave and convex surface shapes belong to statistical group 'A'. Both the flat and convex surface shapes belong to statistical group 'B', showing that the convex surface shape overlaps into both groups.

Table 21. Student-Newman-Keul's groupings of the surface shape classification for the glaciofluvial landform.

SNK Grouping	Mean SI	N	$P(F>F_c) = 0.0102$
A	20.17	4	3 (concave)
A, B	18.94	3	1 (convex)
B	16.85	26	2 (flat)

Most of the categorical variables did not have statistically significantly different groups. After combining classifications within a variable, groups with a statistically significantly different average site index were achieved. Variables such as surface shape could not be grouped, because there were less than four classifications within each variable.

B. COMBINED NORTHEASTERN AND NORTH CENTRAL ONTARIO DATA

The northeastern and north central Ontario data were tested for compatibility. Soil-site equations were then developed using the combined data.

PREDICTING SITE INDEX IN NORTHEASTERN ONTARIO USING NORTH CENTRAL ONTARIO EQUATIONS

Schmidt and Carmean's (1988) bedrock, glaciofluvial, lacustrine, and moraine equations developed in north central Ontario were used to predict site index on each of the 76 plots located in northeastern Ontario. Actual site index for each plot was compared to predicted site index, using the Schmidt and Carmean (1988) equations (Tables 22 to 25; Figures 15 to 18).

Bedrock-Moraine

Schmidt and Carmean's (1988) bedrock-moraine equation contained two independent variables (i.e. depth to bedrock and coarse fragments in the A horizon) found to be significantly related to site index in north central Ontario. In contrast, the northeastern bedrock-moraine equation contained three independent variables: slope percent; thickness of the B horizon; and percent stones in the top 25 cm of the soil profile. B horizon thickness is very similar to depth to bedrock, except that the A horizon is not included. Often on bedrock-moraine soils in northeastern Ontario, the A horizon is usually less than 5 cm thick, so B horizon thickness would be a slightly smaller number than depth to bedrock.

Schmidt and Carmean's (1988) bedrock-moraine equation did not predict site index at $P < 0.05$ (Table 22) for the northeastern bedrock-moraine data. The equation under-estimates site index, as many plots are below the 45° line of perfect correlation (Figure 15).

Table 22. Pearson's correlation coefficient for northeastern data with Schmidt and Carmean's (1988) north central data for the bedrock-moraine landform.

Plot No.	Actual SI	Predicted SI	Residual
1	19.47	14.40	-5.07
6	10.41	14.63	4.22
7	19.73	14.66	-5.07
8	12.05	12.04	-0.01
16	17.08	17.34	0.26
18	12.28	13.59	1.31
51	19.69	18.57	-1.12
55	16.09	13.72	-2.37
57	16.29	15.04	-1.25
65	10.62	11.14	0.52
66	14.03	16.15	2.12
67	16.67	12.13	-4.54
70	15.90	14.79	-1.11
77	17.10	13.10	-4.00
78	17.31	15.56	-1.75
			r = 0.503 P = 0.056

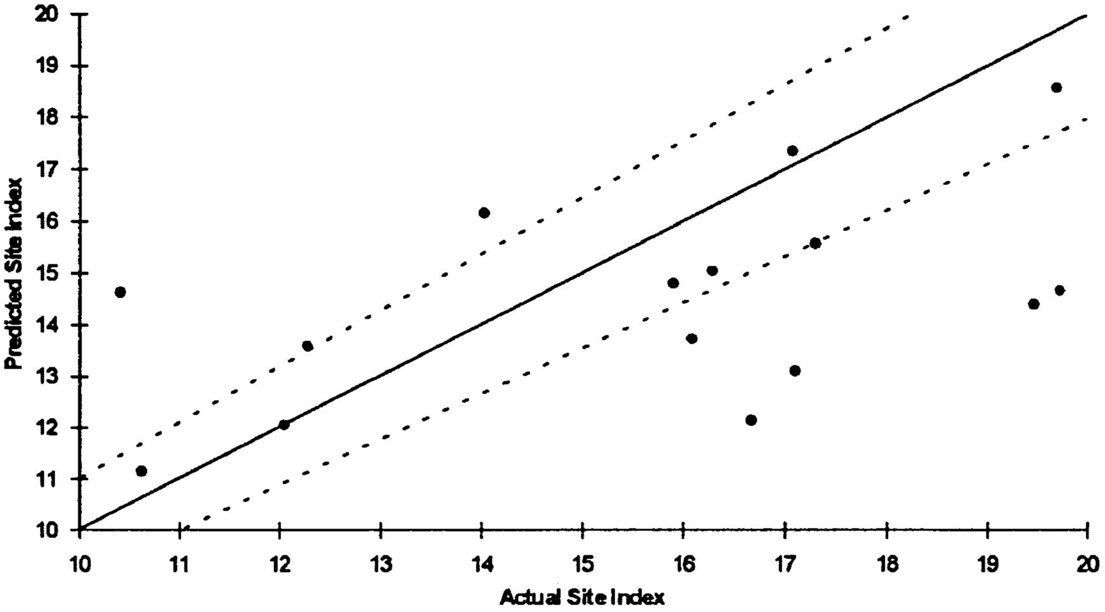


Figure 15. Predicted versus actual site index for 15 northeastern Ontario data, using Schmidt and Carmean's (1988) bedrock-moraine equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

Glaciofluvial

Only 23 of the 33 available northeastern Ontario plots were used for comparisons with the Schmidt and Carmean's (1988) glaciofluvial north central Ontario equation. The north central Ontario plots had a maximum slope of 12%; and ten of the northeastern Ontario plots exceeded 12% slope, causing unrealistic site index values to be predicted. Therefore, these ten plots were excluded form the comparison.

Schmidt and Carmean's (1988) glaciofluvial equation contained two independent variables (depth to root restricting layer and percent slope) found to be significantly related to site index. The northeastern glaciofluvial equation contained three independent variables: depth to moisture restricting layer, depth to average rooting, and percent silt in the B horizon. Schmidt and Carmean's

(1988) glaciofluvial equation did not predict site index at $P < 0.05$ for the northeastern glaciofluvial data (Table 23). The equation over-estimates site index, as many plots are above the 45° line of perfect correlation (Figure 16). This figure also shows the poor relationship between predicted and actual site index, as indicated by the many plots outside the 10% range.

Table 23. Pearson's correlation coefficient for northeastern data with Schmidt and Carmean's (1988) north central data for the glaciofluvial landform.

Plot No.	Actual SI	Predicted SI	Residual
2	18.75	18.39	-0.36
11	17.80	19.00	1.20
21	14.53	19.00	4.47
24	17.86	18.17	0.31
25	16.79	16.77	-0.02
26	15.92	19.00	3.08
30	18.21	16.48	-1.73
31	15.04	17.59	2.55
32	14.94	18.57	3.63
34	22.39	18.19	-4.20
36	13.99	17.18	3.19
37	16.00	18.39	2.39
40	18.36	16.89	-1.47
41	19.97	18.05	-1.92
42	15.57	15.38	-0.19
45	17.71	18.21	0.50
52	21.52	13.78	-7.74
53	16.07	15.44	-0.63
56	16.88	11.46	-5.42
63	15.04	18.60	3.56
71	19.71	18.19	-1.52
75	12.91	17.74	4.83
76	14.29	17.18	2.89
			r = 0.124
			P = 0.574

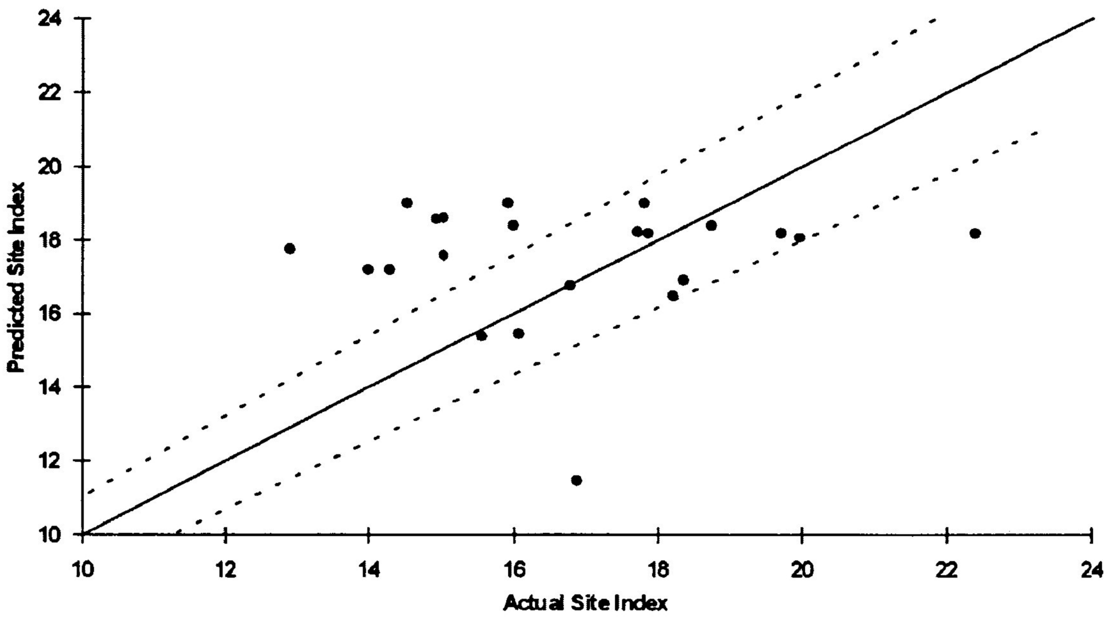


Figure 16. Predicted versus actual site index for 23 northeastern Ontario data, using Schmidt and Carmean's (1988) glaciofluvial equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

Lacustrine

Schmidt and Carmean's (1988) lacustrine equation for north central Ontario contained two independent variables (thickness of the A horizon and pH of BC horizon) found to be significantly related to site index. The northeastern lacustrine data contained only six plots, preventing any regression analyses computations. Schmidt and Carmean's (1988) lacustrine equation predicted site index adequately for the northeastern lacustrine data (Table 24). The equation estimates site index erratically, since plots are either above or below the 45° line of perfect correlation (Figure 17), and few plots are within the 10% range.

Table 24. Pearson's correlation coefficient for northeastern data with Schmidt and Carmean's (1988) north central data for the lacustrine landform.

Plot No.	Actual SI	Predicted SI	Residual
23	13.34	16.15	2.81
27	13.27	12.24	-1.03
28	15.79	13.28	-2.51
39	20.68	16.50	-4.18
44	13.83	18.45	4.62
74	14.33	22.40	8.07
			r = 0.012 P = 0.976

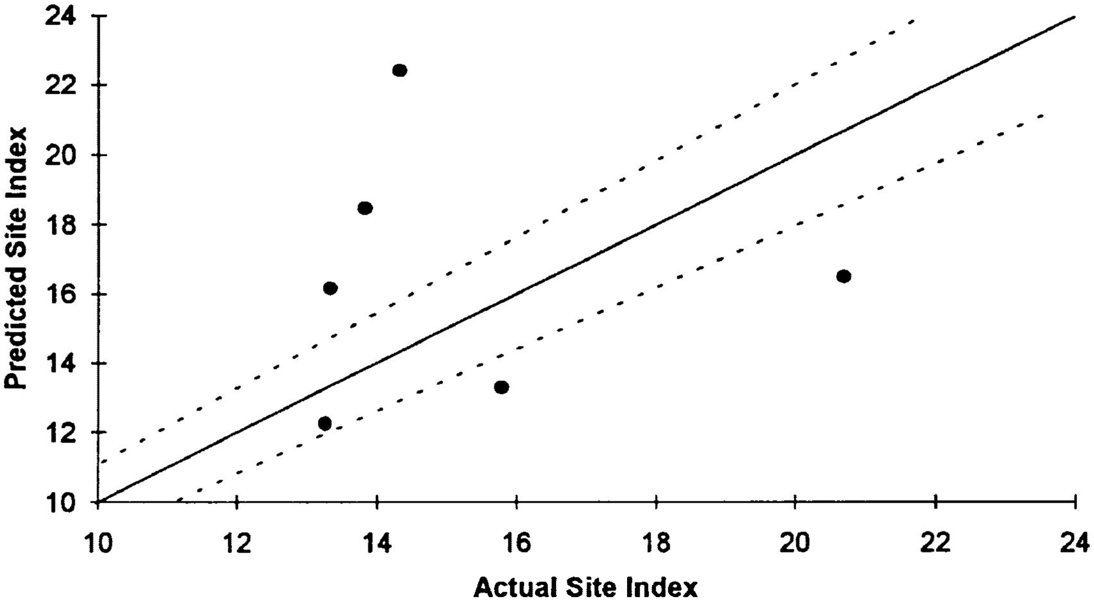


Figure 17. Predicted versus actual site index for six northeastern Ontario data, using Schmidt and Carmean's (1988) lacustrine equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

Moraine

Schmidt and Carmean's (1988) moraine equation for north central Ontario contained three independent variables: depth to root restricting layer; percent coarse fragments in the C horizon; and percent clay in the A horizon found to be significantly related to site index. The northeastern moraine equation contained four independent variables: depth to maximum rooting; pore pattern; percent sand in the BC horizon; and percent silt in the BC horizon. Even though there were no variables common to both equations, Schmidt and Carmean's (1988) moraine equation predicted site index poorly for the northeastern moraine data (Table 25). The equation under-estimates site index, as many plots are below the 45° line of perfect correlation (Figure 15). This figure also shows the poor relationship between predicted and actual site index, since most plots are outside the 10% range.

Table 25. Pearson's correlation coefficient for northeastern data with Schmidt and Carmean's (1988) north central data for the moraine landform.

Plot No.	Actual SI	Predicted SI	Residual
3	18.19	15.49	-2.71
12	18.59	13.50	-5.09
13	15.79	15.38	-0.41
19	18.37	13.70	-4.67
20	19.03	13.55	-5.48
29	15.51	17.54	2.03
35	19.37	14.52	-4.85
46	17.54	16.73	-0.81
47	18.33	14.26	-4.07
48	17.77	17.46	-0.31
49	19.88	17.63	-2.25
54	17.87	15.59	-2.28
59	20.42	17.78	-2.64
60	17.75	13.55	-4.20
62	13.51	15.33	1.82
69	16.60	13.96	-2.65
72	16.74	13.55	-3.19
73	19.45	14.67	-4.78
			r = 0.040 P = 0.873

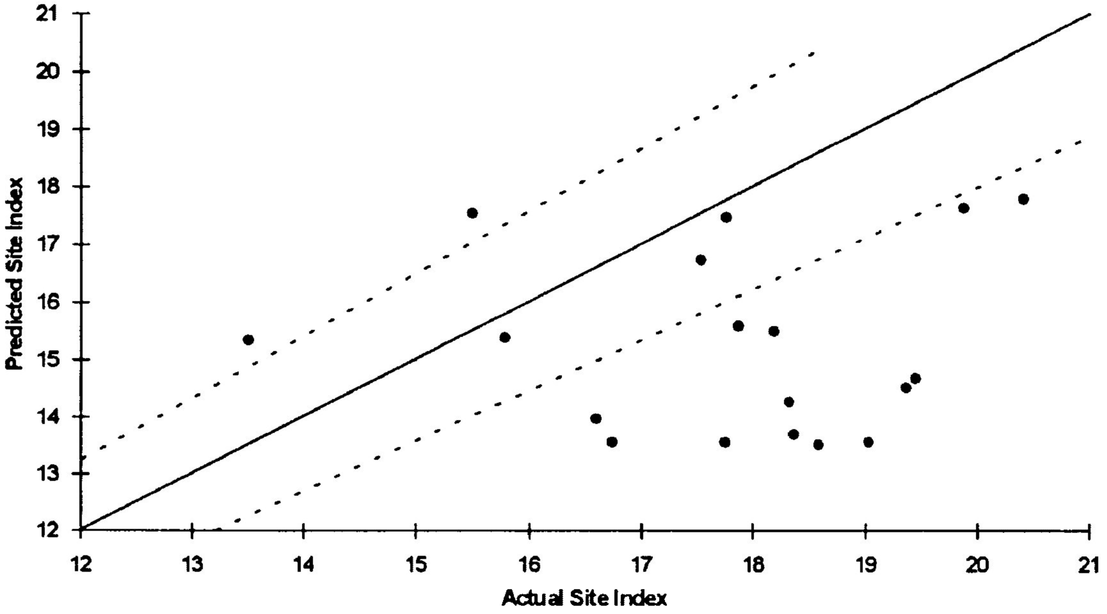


Figure 18. Predicted versus actual site index for 18 northeastern Ontario data, using Schmidt and Carmean's (1988) moraine equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

SOIL-SITE EQUATIONS FOR NORTHEASTERN AND NORTH CENTRAL ONTARIO COMBINED

Schmidt and Carmean's (1988) data were combined with data from north central Ontario, since their equations predicted site index adequately for the northeastern data. The northwestern Ontario data is also included (Table 26), although this data were combined in the next major section (after the northeastern and north central data were tested, combined, and soil-site equations developed. The combined data set greatly increased the number of plots in each landform for all of northern Ontario.

Table 26. Source of combined data by landform and geographic region.

Landform	North eastern Ontario	North eastern Ontario (extras)	North central Ontario (Schmidt 1986)	North central Ontario (extras)	North western Ontario*	Total number of plots
Bedrock - Glaciofluvial	4	0	11	3	0	**18**
Bedrock - Moraine	15	0	11	1	0	**27**
Glaciofluvial	33	1	45	1	3	**83**
Lacustrine	6	0	19	0	7	**32**
Moraine	18	1	36	5	6	**66**
TOTAL	**76**	**2**	**122**	**10**	**16**	**226**

*Northwestern Ontario data is not included with the analyses in section B (Comparison of Northeastern Ontario and North Central Ontario), but is included with the analyses in section C (Combined Northeastern, North Central, and Northwestern Ontario Data).

Summary Statistics

Summary statistics including the mean, standard deviation, minimum and maximum values of the site index values for each landform were computed (Table 27).

Table 27. Summary statistics of site index values for each landform of the combined northeastern and north central data.

Landform	Number of plots	Average SI (m)	Minimum SI (m)	Maximum SI (m)	Range of SI (m)	Standard deviation (m)
Bedrock-glaciofluvial	18	13.3	9.3	19.6	10.3	3.44
Bedrock-moraine	27	15.6	10.4	19.7	9.3	2.68
Glaciofluvial	80	17.6	11.9	22.4	10.5	2.01
Lacustrine	25	17.9	13.3	20.1	7.5	2.24
Moraine	60	17.6	13.4	21.6	8.2	1.91
TOTAL	210					

where SI = site index (SI_{BH50}) is total height of dominant and codominant trees at breast height age 50 years.

Independent Variable Screening

Pearson product-moment correlation coefficients (r) for site index with each independent variable was computed by landform. Simple correlations and backward stepwise multiple regression were used to select the 10 'best' independent variables for each landform (Table 28).

Table 28. Simple correlations with site index (SI_{BH50}) by landform for the combined northern Ontario data.

Independent Variable Category	Variable	Bedrock-Glaciofluvial (r)	Bedrock-Moraine (r)	Glaciofluvial (r)	Lacustrine (r)	Moraine (r)
SOIL DEPTH	BR	0.824**	0.493**			
	AVGROOT	0.746		0.431**		
	DMRL	0.676**		0.245		
	MAXROOT	0.720**	0.332			
SOIL HORIZON	AROOTAB	-0.704*				
	BCROOTAB				-0.494*	
	B+BCTHICK					0.243
	AROOTSIZ					-0.222
	BROOTSIZ					-0.246
SOIL HORIZON LAB ANALYSES	A%CLAY	-0.589*			0.630**	-0.349*
	B%SAND	0.538*	0.317			
	A%SILT			0.250*		
	B%SILT			0.250*		
	B%SICLAY			0.222		
	A%SAND				-0.464*	
PROFILE COARSE FRAGMENT	ACFGRVEL	-0.511*			-0.537**	
	BCFCOBST	0.547*			-0.523**	-0.208
	COBBTOT		-0.332			
	CFTOTAL		-0.377		-0.636**	
	CFCOBBL		-0.497**			
	APGRVCOB		-0.503**		-0.660**	
	STONBOTT			-0.264*		
	AGRAVEL				-0.478*	
	BC%COBBL				-0.479*	
	BCFTOTAL					-0.226
	ECFTOTAL					-0.238
	BCFSTONE					-0.263*
	ECFSTONE					-0.317*
	BC%COBST					-0.277*
TOPO-GRAPHY	SLOPEL		0.347	-0.245		
	SLOPEP		0.320			
	SINASP		0.452*			
	COSASP			0.476**		
	S_SHP			0.288*		
	S_POS			0.348**		
SOIL MOISTURE	P_PAT	-0.573*			0.596**	

* statistically significant at $P < 0.05$

* *statistically significant at $P < 0.01$

Combined Bedrock-Glaciofluvial

The combined bedrock-glaciofluvial data set consists of 14 plots from north central Ontario, and four plots from northeastern Ontario (Table 26). Schmidt and Carmean (1988) did not make a regression analyses for bedrock-glaciofluvial soils, because of an insufficient number of plots. But when the author's four plots for northeastern Ontario were combined with the 14 plots in north central Ontario, the sample size was adequate for regression analyses. These 18 plots were enough to complete a soil-site equation, but not enough plots to verify the equation using check plots.

A four-variable model (equation BRGF1) and a three-variable model (equation BRGF2) were computed using backward stepwise regression and 'all possible subsets' regression simultaneously (Table 29). An F-test showed that the four-variable model did not explain a significantly greater amount of variation than the three-variable model, at $P < 0.05$. Hence, equation BRGF2 was chosen over equation BRGF1.

Each independent variable was tested to see if a quadratic transformation improved the R^2. None of these transformations significantly improved the precision of equation BRGF2. Therefore, a second three-variable equation was computed (equation BRGF3).

Table 29. Multiple regression equations for the combined bedrock-glaciofluvial landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
BRGF1	SI = 12.65 - 0.1796 (AVGROOT) + 0.1444 (MAXROOT) + 0.1797 (BCFCOBST) - 0.0894 (AROOTAB)	0.040 0.021 0.038 0.037	18	0.911	0.883	1.18
BRGF2	SI = 16.26 + 0.1303 (BR) - 0.1363 (AVGROOT) - 1.6218 (P_PAT)	0.018 0.042 0.571	18	0.872	0.844	1.36
BRGF3 (final equation)	SI = 10.76 - 0.1868 (AVGROOT) + 0.1660 (MAXROOT) + 0.2127 (BCFCOBST)	0.046 0.022 0.041	18	0.871	0.843	1.36
BRGF4	SI = 10.02 - 0.0055 (DMRL X AVGROOT) + 0.0044 [ABTHICK X (26 - AROOTAB)] + 0.0732 [MAXROOT X (5 - P_PAT)]	0.001 0.001 0.008	18	0.936	0.923	0.96

Interaction terms were created using all independent variables. Backward stepwise regression and 'all possible subsets' regression was used simultaneously to determine which interactions should be included in the model. This computation showed that equation BRGF4 improved precision using the three interactions (DMRL X AVGROOT), [ABTHICK X (26 - AROOTAB)], and [MAXROOT X (5 - POREPAT)].

Equation BRGF3 was selected as the final equation, since it had acceptable precision and relatively few independent variables. Equation BRGF3 was then used to calculate site index values for the range of depth to average rooting, depth to maximum rooting, and percent cobbles and stones in the B horizon. These predicted site index values were used for comparisons with actual site index values (Figure 16), and also were listed in a site index prediction table for field estimation of site index (Table 30). Equation BRGF3 was also used to construct trend graphs, illustrating the relationship between site index and depth to bedrock, depth to average rooting, and pore pattern (Figure 20).

Table 30. Site index prediction table for the combined bedrock-glaciofluvial landform using equation BRGF3.

	AVGROOT (cm)								
	0 - 10			**10 - 20**			**20 - 30**		
	B cf% Cobbles + Stones								
Maxroot (cm)	**0 - 10**	**10 - 20**	**20 - 30**	**0 - 10**	**10 - 20**	**20 - 30**	**0 - 10**	**10 - 20**	**20 - 30**
15	13.4	15.5	17.6	11.5	13.6	15.8	9.6	11.8	13.9
30	15.9	18.0		14.0	16.1	18.3	12.1	14.3	16.4
45	18.4			16.5	18.6		14.6	16.8	18.9
60				19.0			17.1	19.2	
75							19.6		

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; maxroot = depth to maximum rooting; avgroot = depth to average rooting; B cf % Cobbles + Stones = percent cobbles and stones in the B horizon.

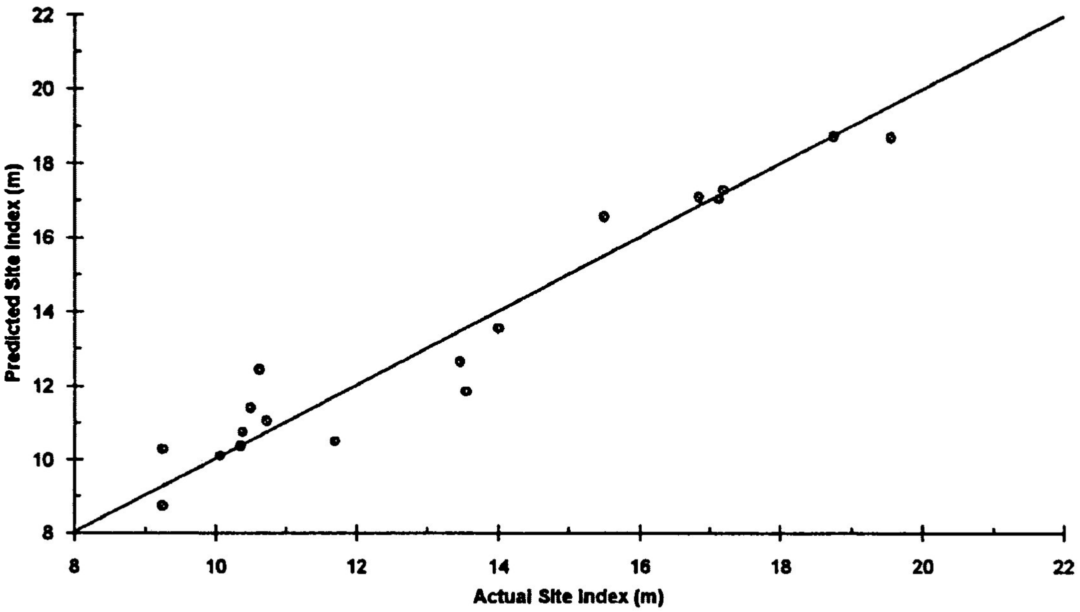


Figure 19. Residuals showing differences between predicted and measured site index for plots established on bedrock-glaciofluvial soils, using equation BRGF3.

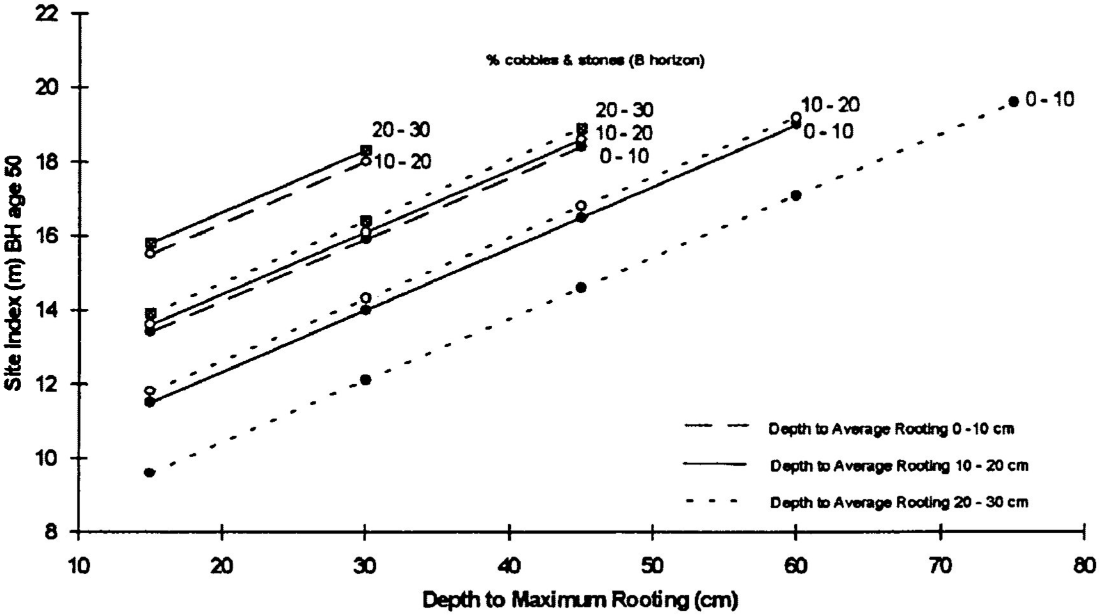


Figure 20. Site index trend graphs for the combined bedrock-glaciofluvial landform, using equation BRGF3.

Combined Bedrock-Moraine

The combined bedrock-moraine data set consists of 12 plots from north central Ontario, and 15 plots from northeastern Ontario (Table 26). A three-variable model (equation BRM1) was computed using backward stepwise regression and 'all possible subsets' regression simultaneously (Table 31). No four-variable model was tested, because there were no valid four-variable models.

Six of the 27 plots were randomly chosen as check plots. The remaining 21 plots were used to compute equation BRM1. Bonferroni's t-test and a scatterplot of the residuals of equation BRM1 showed that there was one outlier. This outlier was identified as plot number 9154. Soil on this plot consisted of 60 cm of organic soil over bedrock with no mineral soil, thus this plot was deemed not to be part of the bedrock-moraine population. This plot was deleted from the data set, leaving a total of 20 computation plots. The model was recomputed, resulting in equation BRM2 (Table 31).

Table 31. Multiple regression equations for the combined bedrock-moraine landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
BRM1	SI = 15.18 + 0.0837 (BR) - 0.0855 (SLOPE%) - 0.1324 (A%GRVCOB)	0.019 0.034 0.032	21	0.691	0.636	1.99
BRM2	SI = 16.93 + 0.0591 (BR) - 0.1156 (SLOPE%) - 0.1188 (A%GRVCOB)	0.019 0.031 0.028	20	0.737	0.688	1.68
BRM3 (final equation)	SI = 15.91 + 0.0559 (BR) - 0.0768 (SLOPE%) - 0.1091 (A%GRVCOB)	0.019 0.029 0.028	26	0.608	0.554	1.79

Each independent variable was tested to see if a quadratic transformation improved the R^2. None of these transformations significantly improved the precision of BRM2.

All variables (including the original 'best' ten variables) were included in interaction terms. Backward stepwise regression and 'all possible subsets' regression were used simultaneously to determine which interactions should be included in the final model. However. including interactions in the BRM2 equation did not increase equation precision.

An attempt was made to increase the accuracy of the final regression equation by combining the six check plots with the 20 computation plots. The 26 plots were then used with equation BRM2 to compute equation BRM3 (Table 31). Results show a marked drop in precision when these six check plots were added to the original 20 computation plots. Equation BRM3 had the lowest standard estimate of error, even with the decrease in R^2, and was adopted as the final equation.

Equation BRM3 was used to calculate site index values for the range of depth to bedrock, slope percent, and percent gravel and cobbles in the A horizon. These predicted site index values were compared to actual site index values (Figure 21), and were used in a site index prediction table for field estimation of site index (Table 32). Equation BRM3 was also used to construct trend graphs, showing the relationship between depth to bedrock, percent slope, and percent gravel and cobbles in the A horizon (Figure 22).

Table 32. Site index prediction table for the combined bedrock-moraine landform using equation BRM3.

BR (cm)	% SLOPE														
	0 - 10			10 - 20			20 - 30			30 - 40			40 - 50		
	A% gravel+cobbles														
	0 - 20	20 - 40	40 - 60	0 - 20	20 - 40	40 - 60	0 - 20	20 - 40	40 - 60	0 - 20	20 - 40	40 - 60	0 - 20	20 - 40	40 - 60
0 - 15	14.9	12.7	10.5	14.1	11.9		13.3	11.1		12.5	10.4		11.8	9.6	
15 - 30	15.7	13.5	11.3	14.9	12.7	10.6	14.2	12.0		13.4	11.2		12.6	10.4	
30 - 45	16.5	14.3	12.2	15.8	13.6	11.4	15.0	12.8	10.6	14.2	12.0		13.5	11.3	
45 - 60	17.4	15.2	13.0	16.6	14.4	12.2	15.8	13.6	11.5	15.1	12.9	10.7	14.3	12.1	
60 - 75	18.2	16.0	13.8	17.4	15.3	13.1	16.7	14.5	12.3	15.9	13.7	11.5	15.1	12.9	10.8
75 - 90	19.0	16.9	14.7	18.3	16.1	13.9	17.5	15.3	13.1	16.7	14.6	12.4	16.0	13.8	11.6

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; slope % = percent slope; A% gravel+cobbles = percent gravel plus percent cobbles in the A horizon; BR = depth to bedrock (cm).

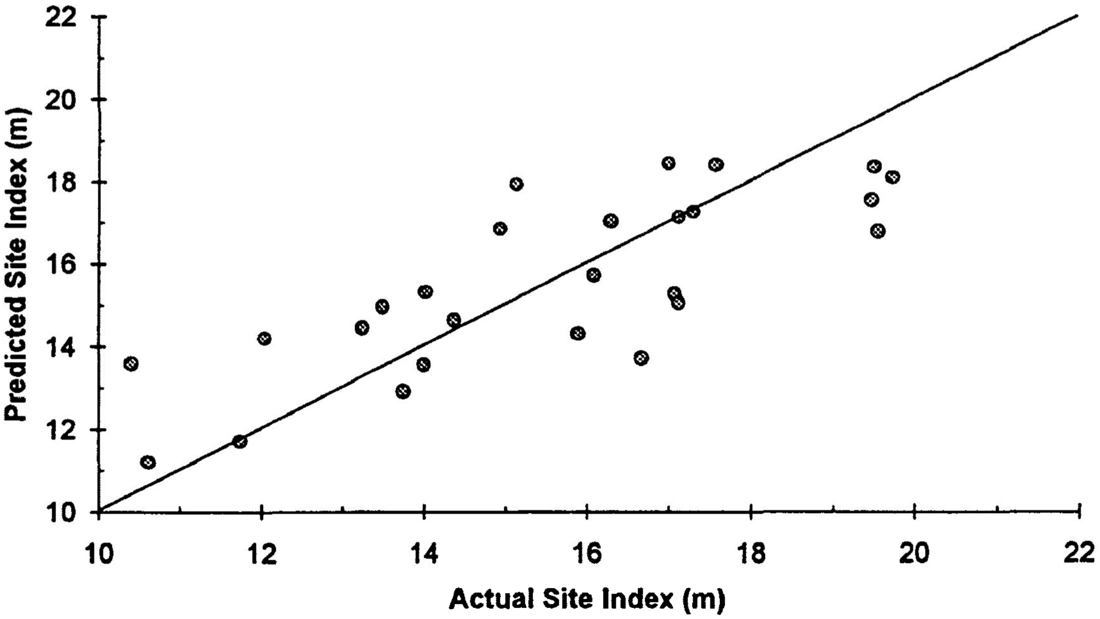


Figure 21. Residuals showing differences between predicted and measured site index for plots established on bedrock-moraine soils, using equation BRM3.

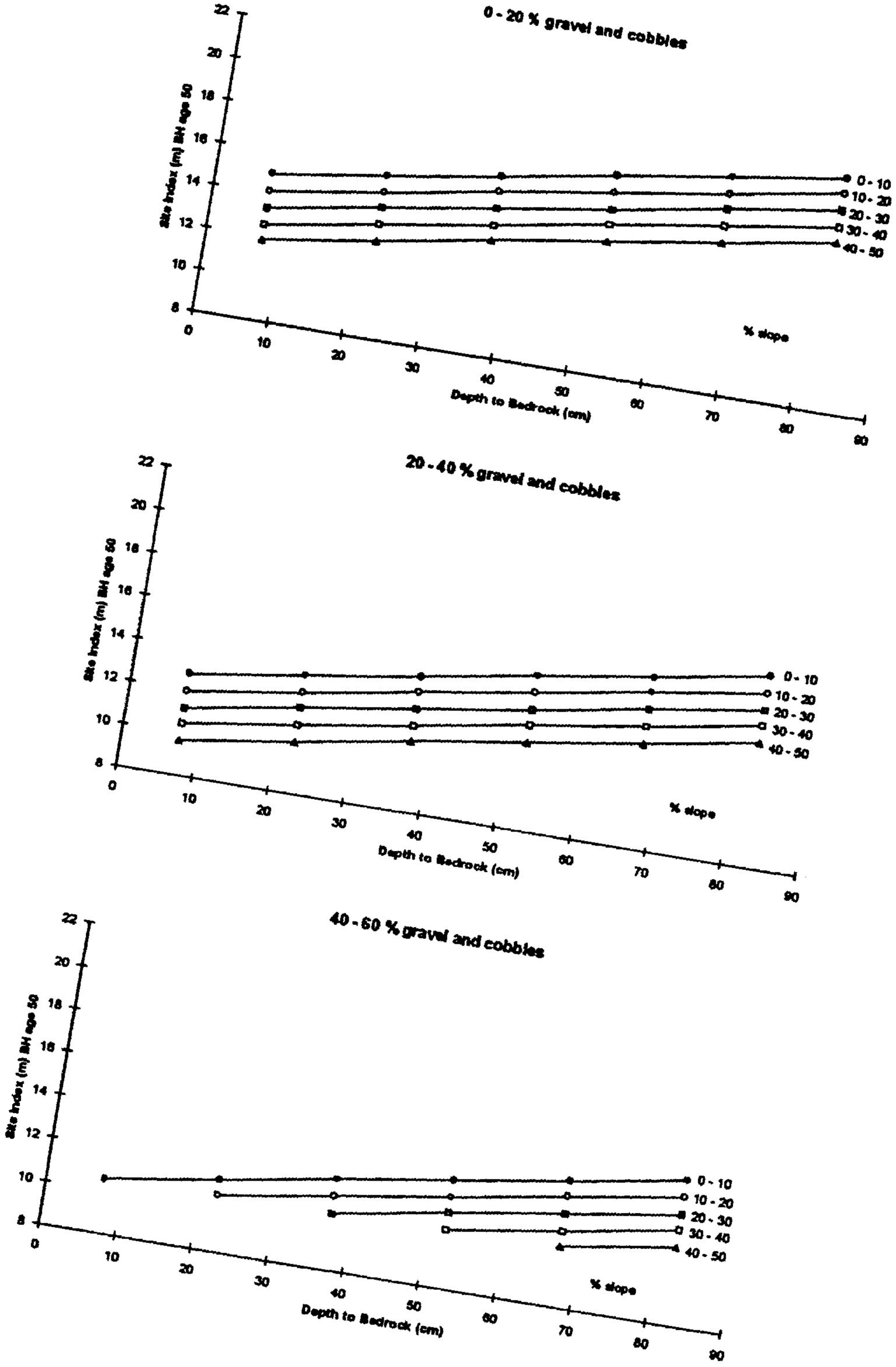


Figure 22. Site index trend graphs for the combined bedrock-moraine landform using equation BRM3.

Combined Glaciofluvial

The combined glaciofluvial data set consists of 46 plots from north central Ontario and 34 plots from northeastern Ontario, for a combined total of 80 plots (Table 26). Sixteen of the 80 plots were randomly selected as check plots, leaving 64 computational plots. Four out of five outliers were removed from the computational plots. Two plots (plots 9100 & 9101) were discarded, because their mode of deposition was eolian, and not glaciofluvial; plot 34 was deleted, since it had a very anomalous white Ae horizon; plot 17 was also an outlier, but there was no justification for deletion, so it was retained in the data set. Plot 9086 was deleted because its coarse fragment content exceeded the 10% maximum set for glaciofluvial soils. Deletion of outliers reduced the computational data set from 64 plots to 60 plots.

Initially, there were no valid three or four-variable models. A two-variable model (equation GF1) was computed instead (Table 33). A four-variable model (equation GF2) was computed using backward stepwise regression and 'all possible subsets' regression simultaneously. An F-test showed that equation GF2 statistically explained more variation than the two-variable model (equation GF1), at $P < 0.05$.

Each independent variable was tested to see if a quadratic transformation improved the R^2. None of these transformations significantly improved the precision of equation GF2.

Table 33. Multiple regression equations for the combined glaciofluvial landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
GF1	SI = 13.00 + 0.0159 (COSASPECT) + 0.0744 (AVGROOT)	0.004 0.019	60	0.289	0.259	2.07
GF2	SI = 12.64 + 0.0107 (COSASPECT) + 0.0173 (S_SHP) + 0.2326 (A%SILT) - 0.1813 (A%SICLAY)	0.003 0.452 0.087 0.076	60	0.438	0.397	1.52
GF3	SI = 12.60 + 0.0127 (COSASPECT) + 1.3543 (S_SHP) + 0.0476 (A%SILT) - 0.2193 (A%CLAY)	0.003 0.452 0.016 0.090	60	0.440	0.399	1.52
GF4	SI = 13.68 + 0.0003 [(110 - SLOPEL) X AVGROOT] + 0.1165 [S_SHP X (10 - A%CLAY)] + 0.0013 (B%SAND x B%SILT)	0.0001 0.030 0.0002	60	0.485	0.457	1.44
GF5	SI = 13.04 + 0.0101 (COSASP) + 1.2070 (S_SHP) + 0.0431 (A%SILT) - 0.1287 (A%CLAY)	0.003 0.464 0.015 0.082	76	0.313	0.274	1.71
GF6 (final equation)	SI = 14.13 + 0.0004 [(110-SLOPEL) X AVGROOT] + 0.0788 [S_SHP X (10 - A%CLAY)] + 0.0013 (B%SAND X B%SILT)	0.0001 0.027 0.0003	76	0.400	0.371	1.59

Equation GF2 contains two related independent variables: 1) A %silt; and, 2) A %silt and clay. Therefore, a new equation (GF3) was computed using the same independent variables as equation GF2, but changing the variable A %silt and clay to just A% clay. These computations resulted in equation GF3. This equation was tested to determine if interactions improved the model. All variables (including the original 'best' ten variables) were included in interaction terms. Backward stepwise regression and 'all possible subsets' regression was used simultaneously to determine which interactions should be included in the model. This computation showed that equation GF4 slightly increased precision using the interactions [(110 - SLOPEL) X AVGROOT], [S_SHP X (10 - A%CLAY)], and (B%SAND X B%SILT). The interaction terms in equation GF4 did not improve R^2 significantly more than equation GF3.

An attempt was made to increase the accuracy of the final regression equation by combining the 16 check plots with the 60 computation plots. The 76 plots were then used to calculate equations GF5 and GF6, which are based on equations GF3 and GF4, respectively. Equation GF6 was selected as the final model, since equation GF5 was not statistically significant at $P < 0.05$.

Valid soil-site regression equations must have a minimum R^2 value of 0.55 (Carmean 1975). Therefore, no site index prediction table was developed for equation GF6.

Combined Lacustrine

The combined lacustrine data set consists of 19 plots from north central Ontario and six plots from northeastern Ontario, for a combined total of 25 plots (Table 26). Five of the 25 plots were randomly selected as check plots, leaving 20 computational plots.

A two-variable model (equation L1) and three-variable model (equation L2) were computed using backward stepwise regression and 'all possible subsets' regression simultaneously. An F-test showed that the three-variable model did not statistically explain more variation than the two-variable model, at $P < 0.05$.

A second three-variable equation (equation L3) was computed, due to the high standard error of the estimate (SEE) of equation L2. Equation L3 was used for further analyses, because its SEE was acceptable (Table 34).

Table 34. Multiple regression equations for the combined lacustrine landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
L1	SI = 19.69 - 0.0330 (BCTHICK) - 9.6268 (BCROOTSIZ)	0.009 2.694	20	0.587	0.538	1.65
L2	SI = 14.69 + 1.0104 (P_PAT) - 0.0235 (ABETHICK) - 0.7205 (BCROOTSIZ)	0.462 0.009 2.633	20	0.660	0.596	1.55
L3	SI = 21.07 - 0.0318 (ABETHICK) - 0.1533 (BRTAB) - 9.0691 (BCROOTSIZ)	0.008 0.071 2.607	20	0.657	0.592	1.55
L4	SI = 19.60 - 0.0327 (BCTHICK) - 8.777 (BCROOTSIZ)	0.008 2.259	25	0.585	0.548	1.51
L5 (final equation)	SI = 20.83 - 0.0308 (ABETHICK) - 0.1385 (BRTAB) - 8.4398 (BCROOTSIZ)	0.008 0.066 2.255	25	0.627	0.573	1.46

Each independent variable was tested to see if a quadratic transformation improved the R^2. None of these transformations significantly improved the precision of equation L3.

Interaction terms were created using all independent variables. Backward stepwise regression and 'all possible subsets' regression was used simultaneously to determine which interactions should be included in the model. These interactions did not significantly increase R^2 of equation L3.

An attempt was made to increase the accuracy of the final regression equation by combining the five check plots with the 20 computation plots. These 25 plots were used with equations L1 and L3 to compute equations L4 and L5, respectively. Addition of the five check plots into equation L1 resulted in an increase in R^2 from 0.54 to 0.58. Addition of the five check plots into equation L3 resulted in a small decrease in R^2 from 0.59 to 0.57. Equation L5 was selected as the final model, since equation L5 has greater precision than equation L4 (Table 34).

Equation L5 was used to calculate site index values for the range of thickness of the A, B, and BC horizons, rooting abundance in the B horizon, and root size in the BC horizon. These predicted site index values were compared to actual site index values (Figure 23), and were used in a site index prediction table for field estimation of site index (Table 35). Equation L5 also was used to construct a trend graph, showing the relationship between site index and coarse fragment content in the A horizon, cobbles and stones content in the BC horizon, and rooting abundance in the BC horizon (Figure 24).

Table 35. Site index prediction table for the combined lacustrine landform using equation L5.

	B % rooting abundance								
	0 - 7.5			7.5 - 15			15 - 22.5		
	BC Root Size (cm)								
Depth to C horizon (cm)	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
0 - 50	18.7	17.0	15.3	17.7	16.0	14.3	16.6	14.9	13.2
50 - 100	17.2	15.5	13.8	16.1	14.4		15.1	13.4	
100 - 150	15.6	13.9		14.6			13.5		
150 - 200	14.1								

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; B % rooting abundance = percentage of roots in the B horizon; BC root size = size of roots (cm) in the BC horizon; depth to C horizon = depth of soil above C horizon.

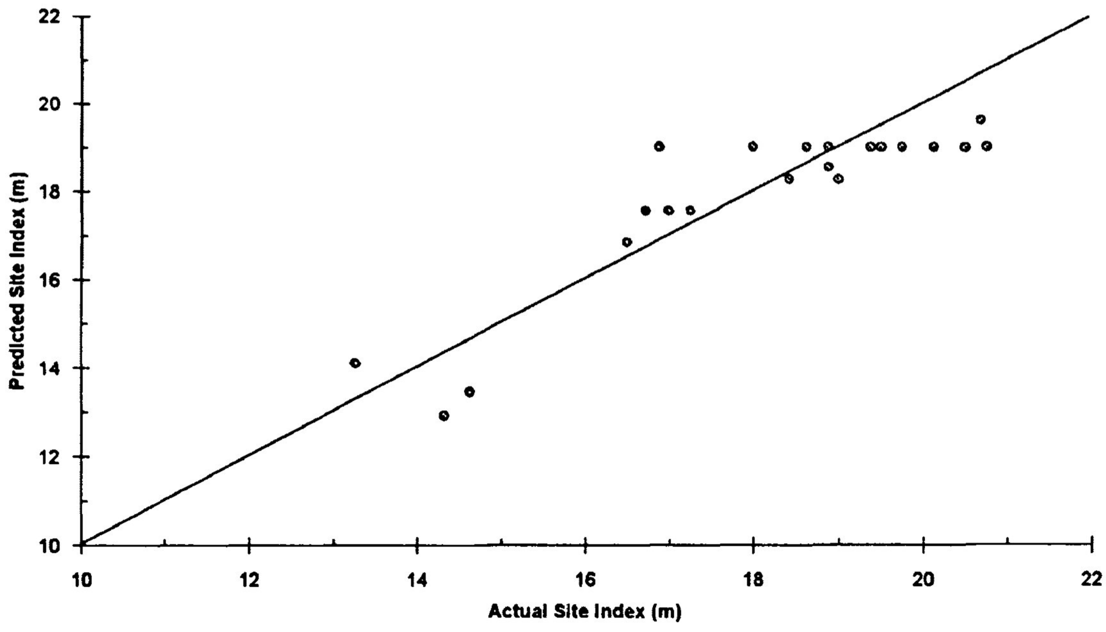


Figure 23. Residuals showing differences between predicted and measured site index for plots established on lacustrine soils, using equation L5.

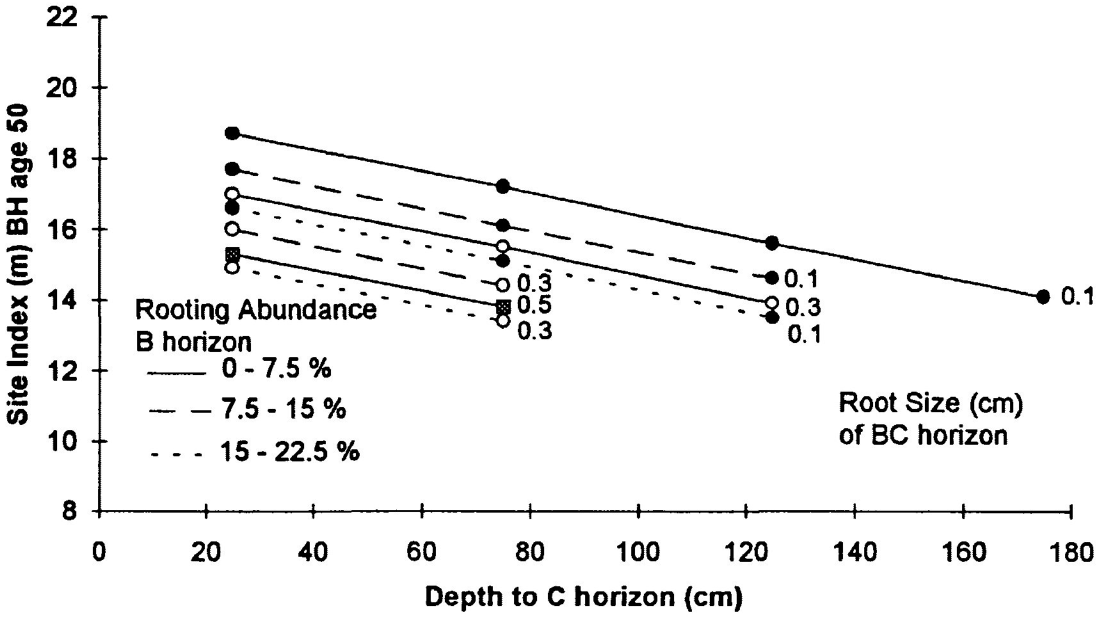


Figure 24. Site index trend graphs for the combined lacustrine landform using equation L5.

Combined Moraine

The combined moraine data set consists of 41 plots from north central Ontario and 19 plots from northeastern Ontario, for a combined total of 60 plots (Table 26). Twelve of the 60 plots were randomly selected as check plots, leaving 48 computational plots.

There were no valid three or four-variable models. Instead, a two-variable model (equation M1) was computed (Table 36), using backward stepwise regression and 'all possible subsets' regression simultaneously.

Table 36. Multiple regression equations for the combined moraine landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
M1	SI = 19.50 - 0.2386 (A%CLAY) - 0.0386 (BC%COBST)	0.081 0.013	48	0.260	0.227	1.89
M2	SI = 17.27 - 0.0411 (BC%COBST) + 0.0035 [(11 -A%CLAY) X B+BCTHICK]	0.013 0.001	48	0.276	0.244	1.86
M3	SI = 19.55 - 0.2601 (A%CLAY) - 0.0328 (BC%COBST)	0.074 0.011	60	0.240	0.213	1.82
M4 (final equation)	SI = 17.08 - 0.0356 (BC%COBST) + 0.0039 [(11 -A%CLAY) X B+BCTHICK]	0.011 0.001	60	0.266	0.241	1.79

Each independent variable was tested to see if a quadratic transformation improved the R^2. None of these transformations significantly improved the precision of equation M1.

Interaction terms were created using all independent variables. Backward stepwise regression and 'all possible subsets' regression was used simultaneously to choose which interactions should be included, resulting in equation M2.

An attempt was made to increase the accuracy of equations M1 and M2 by combining the 12 check plots with the 48 computation plots. The 60 plots were then used with equations M1 and M2 to compute equations M3 and M4. Addition of the check plots into both equations resulted in a small decrease in R^2.

Tests of both equations M3 and M4 showed the same two outliers, plots 62 and 9090. No valid reason could be found for the deletion of these two plots, therefore they remained in the data set. Equation M4 was selected as the final model for the moraine landform (Table 36).

Valid soil-site regression equations must have a minimum R^2 value of 0.55 (Carmean 1975). Therefore, no site index prediction table was developed for equation M4.

C. COMBINED NORTHEASTERN, NORTH CENTRAL, AND NORTHWESTERN ONTARIO DATA

Computations were not possible from Jackman's (1990) data for northwestern Ontario because soils data were incomplete and lacked many important soil variables, such as depth to moisture restricting layer and percent coarse fragments. Lack of common soil variables precluded any comparison between the northwestern, north central and northeastern Ontario data. Other supplementary data which had NWO FEC soil card information also was discontinued.

Niznowski (1994) and the author collected data on 16 plots in northwestern Ontario to supplement Jackman's (1990) lack of plots in moraine and lacustrine soils (Table 26). This data were compatible with the author's and Schmidt's (1986) data, and allowed testing and combining of northwestern data with northeastern and north central Ontario site index equations.

PREDICTING SITE INDEX IN NORTHWESTERN ONTARIO USING NORTHEASTERN, NORTH CENTRAL ONTARIO, AND COMBINED EQUATIONS

The 16 plots from northwestern Ontario were used to test the validity of the following equations for use in northwestern Ontario:

1) Schmidt and Carmean's (1988) equations for north central Ontario;
2) northeastern Ontario equations; and
3) combined northeastern and north central Ontario equations .

The applicable site index prediction equations (i.e. equations whose R^2 value was greater than 0.55) from north central and northeastern Ontario were used to predict site index on each of the 16 northwestern Ontario plots. Actual site index for each plot was compared to predicted site index, using Pearson's correlation coefficient at $P < 0.05$ (Tables 37 to 41).

Glaciofluvial

The three northwestern Ontario plots were used to test Schmidt and Carmean's (1988) north central Ontario glaciofluvial equation. The north central equation did not estimate site index adequately for the three northwestern Ontario plots (Table 37; Figure 25). The northeastern Ontario equation (equation GF5; Table 9), based on 33 plots, and the combined northeastern / north central equation (equation GF6; Table 33) based on 76 plots, were not evaluated due to their poor precision.

Table 37. Pearson's correlation coefficient for three northwestern data with Schmidt and Carmean's (1988) glaciofluvial equation for north central Ontario.

Plot No.	Actual SI	Predicted SI	Residual
83	16.02	16.05	0.03
85	10.19	17.56	7.37
88	15.59	17.56	1.97
			r = 0.556 P = 0.625

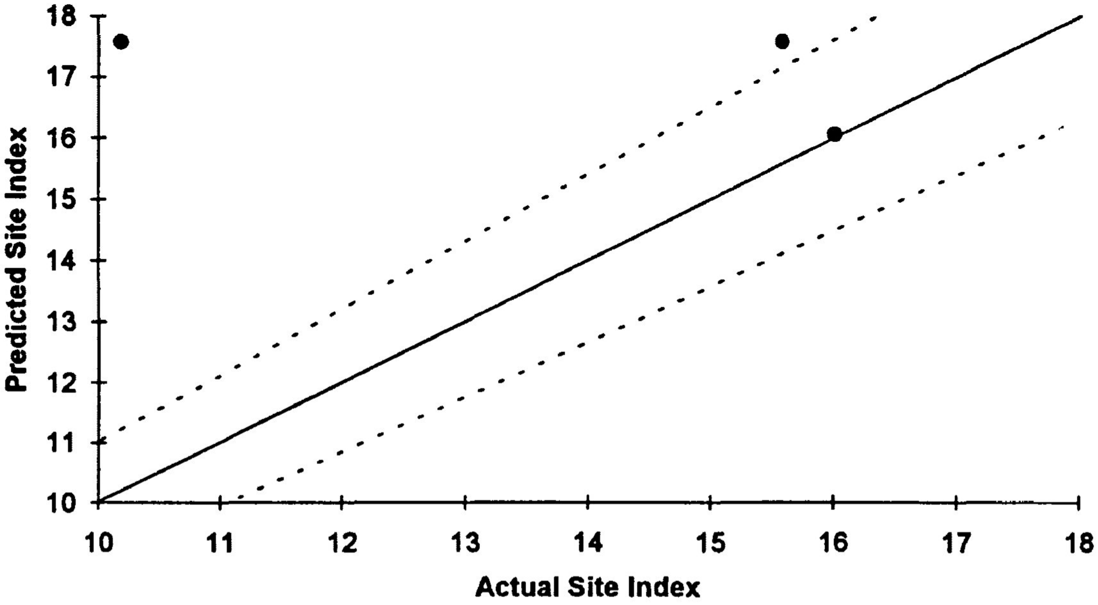


Figure 25. Predicted versus actual site index for three northwestern Ontario data, using Schmidt and Carmean's (1988) glaciofluvial equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

Lacustrine

Seven lacustrine plots were sampled in northwestern Ontario (Table 26). Schmidt and Carmean's (1988) lacustrine equation for north central Ontario did not predict site index adequately for these plots (Table 38). The combined northeastern and north central Ontario lacustrine equation (equation L4; Table 34) also did not predict site index adequately for the seven northwestern Ontario plots (Table 38). Both equations over-estimated site index (Figures 26 and 27), as many plots are below the 45° line of perfect correlation. Northeastern Ontario did not have a lacustrine equation, because only six lacustrine plots were established in this area (Table 4).

Table 38. Pearson's correlation coefficient for seven northwestern data with: a) Schmidt and Carmean's (1988) lacustrine equation for north central Ontario; and b) with the combined northeastern / north central Ontario lacustrine equation.

Plot No.	Actual SI	Predicted SI	Residual
a)			
80	18.38	19.38	1.00
81	15.25	17.58	2.33
82	15.19	18.78	3.59
84	13.93	21.21	7.28
92	16.48	18.78	2.30
93	14.20	19.00	4.80
96	18.50	20.44	1.94
			r = 0.081 P = 0.862
b)			
80	18.38	18.99	0.61
81	15.25	20.33	5.08
82	15.19	20.33	5.14
84	13.93	18.99	5.06
92	16.48	20.33	3.85
93	14.20	22.12	7.92
96	18.50	20.33	1.83
			r = 0.309 P = 0.501

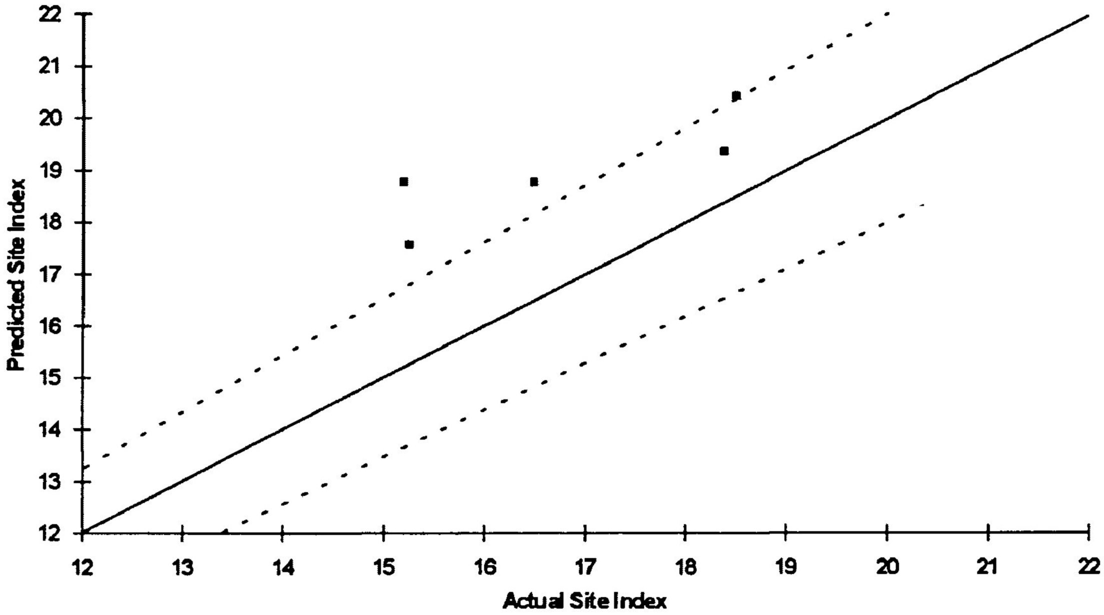


Figure 26. Predicted versus actual site index for seven northwestern Ontario data, using Schmidt and Carmean's (1988) lacustrine equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

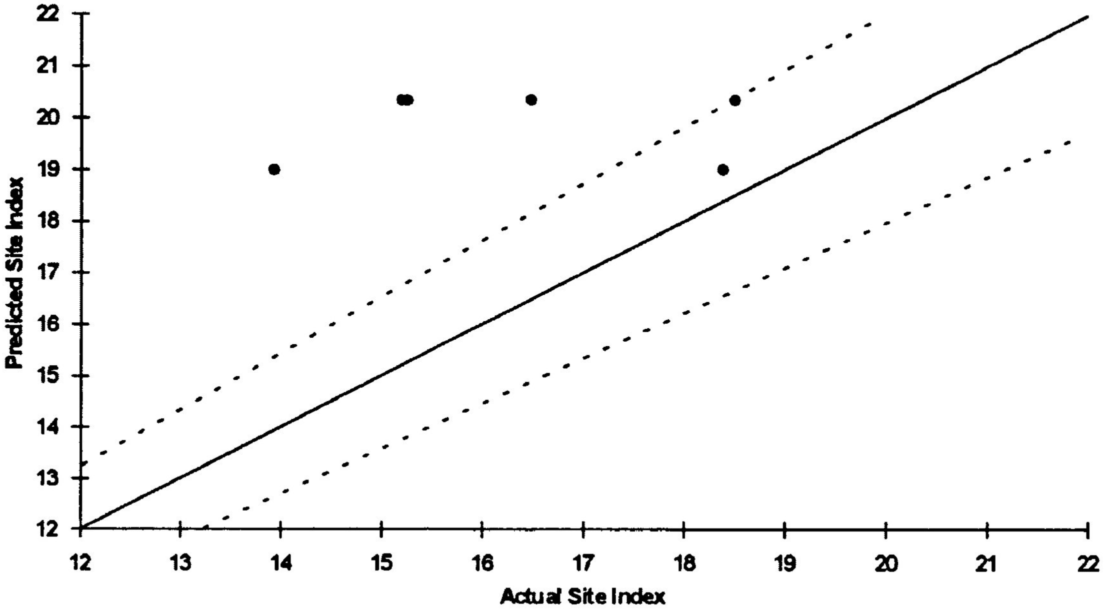


Figure 27. Predicted versus actual site index for seven northwestern Ontario data, using the combined northeastern / north central lacustrine equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

Moraine

Six moraine plots were sampled in northwestern Ontario (Table 26). Moraine equations for north central Ontario (Schmidt and Carmean 1988), and northeastern Ontario both predicted site index poorly for these plots (Table 39). The northeastern Ontario equation predicted site index better than Schmidt and Carmean's (1988) equation, but it is still unuseable. Both equations overestimate site index (Figures 28 and 29), as many plots are above the 45° line of perfect correlation. These figures also show the poor relationship between predicted and actual site index, since most plots are outside the 10% range.

The combined northeastern / north central moraine equation (equation M4; Table 36) based on 60 plots, was not evaluated due to its poor precision.

Table 39. Pearson's correlation coefficient for six northwestern data with: a) Schmidt and Carmean's (1988) moraine equation for north central Ontario; and b) northeastern Ontario moraine equation.

Plot No.	Actual SI	Predicted SI	Residual
a)			
87	18.38	18.88	0.50
89	15.25	17.08	1.83
90	15.19	20.43	5.24
91	13.93	19.40	5.47
94	16.48	22.98	6.50
95	14.20	22.93	8.73
			r = 0.001 P = 0.999
b)			
87	18.38	18.59	0.21
89	15.25	18.59	3.34
90	15.19	19.42	4.23
91	13.93	18.63	4.70
94	16.48	16.93	0.45
95	14.20	14.42	0.22
			r = 0.103 P = 0.846

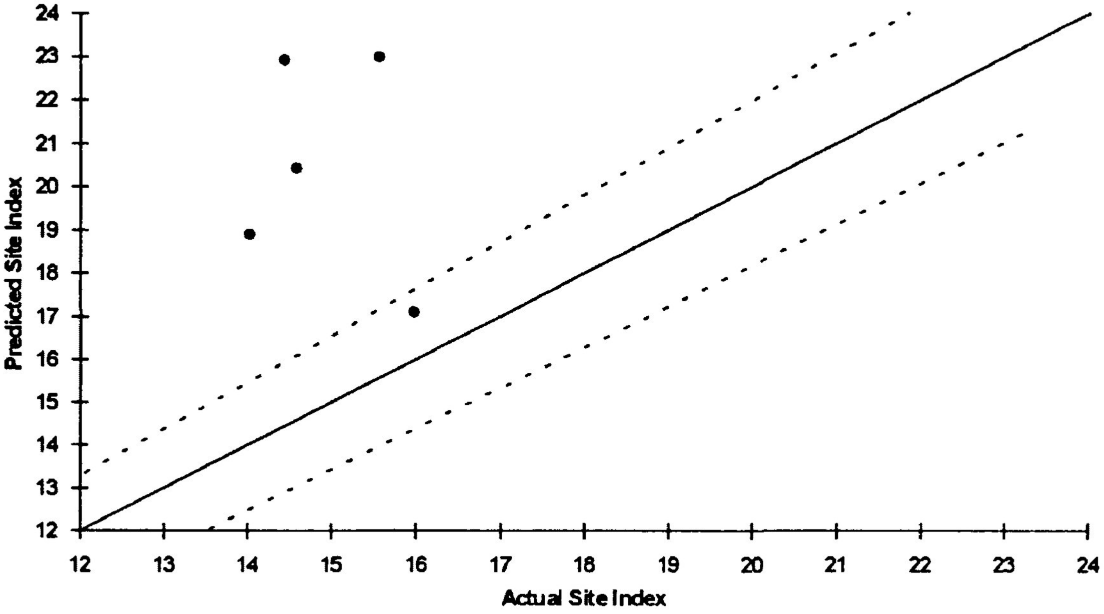


Figure 28. Predicted versus actual site index for six northwestern Ontario data, using Schmidt and Carmean's (1988) moraine equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

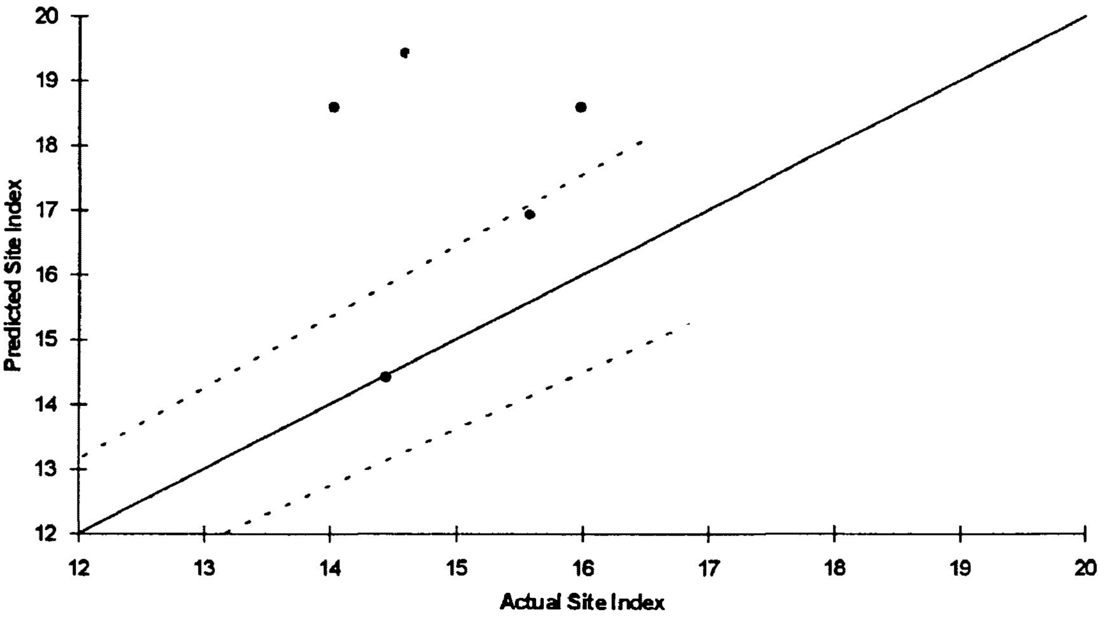


Figure 29. Predicted versus actual site index for six northwestern Ontario data, using the northeastern Ontario moraine equation. Solid line denotes perfect correlation, while dashed lines indicate upper and lower 10% range.

SOIL-SITE EQUATIONS FOR NORTHEASTERN, NORTH CENTRAL, AND NORTHWESTERN ONTARIO COMBINED

Glaciofluvial

The pooled glaciofluvial data set consists of 46 plots from north central Ontario, 34 plots from northeastern Ontario, and the three plots from northwestern Ontario, for a combined total of 83 plots (Table 26). Sixteen of the 83 plots were randomly selected as check plots, leaving 67 computational plots. Four out of five outliers were removed from the computational plots. Two plots (plots 9100 & 9101) were discarded, because their mode of deposition was eolian, and not glaciofluvial; plot 34 was deleted, since it had a very anomalous white Ae horizon; plot 17 was also an outlier, but there was no justification for deletion, so it was retained in the data set. Plot 9086 was deleted because its coarse fragment content exceeded the 10% maximum set for glaciofluvial soils. Deletion of outliers reduced the computational data set from 67 plots to 63 plots.

The combined glaciofluvial data set was used to compute a two-variable model (equation GF1), since there were no valid three or four-variable models (Table 40). Equation GF1 was computed using backward stepwise regression and 'all possible subsets' regression simultaneously.

Both independent variables (i.e. SLOPEL and COSASPECT) were tested to see if a quadratic transformation improved the R^2. None of these transformations significantly improved the precision of equation GF1. This combined equation was less precise than equation GF1.

Table 40. Multiple regression equations for the pooled glaciofluvial landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
GF1	SI = 16.30 - 0.0207 (SLOPEL) + 0.0109 (COSASPECT)	0.007 0.004	63	0.329	0.306	1.91
GF2 (final equation)	SI = 16.02 - 0.0116 (SLOPEL) + 0.0115 (COSASPECT)	0.006 0.004	79	0.243	0.223	1.90

An attempt was made to increase the accuracy of the final regression equation by combining the 16 check plots with the 63 computation plots. The 79 plots were then used to calculate equation GF2, which used the same independent variables as equation GF1.

Valid soil-site regression equations must have a minimum R^2 value of 0.55 (Carmean 1975). Therefore, no site index prediction table was developed for equation GF2.

Lacustrine

The pooled lacustrine data set consists of 19 plots from north central Ontario, six plots from northeastern Ontario, and seven plots from northwestern Ontario for a total of 32 plots (Table 26). Six of the 32 plots were randomly selected as check plots, leaving 26 computational plots.

One, two, and three-variable models (equations L1, L2 and L3, respectively) were computed using backward stepwise regression and 'all possible subsets' regression simultaneously (Table 41). An F-test showed that the three-variable model (equation L3) statistically explained more variation than the two-variable model, at $P < 0.05$.

Each independent variable was tested to see if a quadratic transformation improved the R^2. Pore pattern (P_PAT) was found to be significantly improved by a quadratic term. However, this transformation did not significantly improve the precision of equation L3.

Table 41. Multiple regression equations for the pooled lacustrine landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
L1	SI = 14.80 - 0.0550 (BC%CLAY)	0.008	26	0.637	0.622	1.38
L2	SI = 17.12 - 0.4851 (MR) + 0.0593 (A%CLAY)	0.198 0.013	26	0.663	0.633	1.36
L3	SI = 18.08 - 0.5404 (MR) + 0.0317 (BC%CLAY) - 5.1285 (BCROOTSIZ)	0.218 0.011 2.193	26	0.735	0.699	1.23
L4	SI = 18.99 - 0.4773 (MR) + 0.0180 (BC%CLAY) - 7.5608 (BCROOTSIZ)	0.265 0.014 2.193	32	0.394	0.374	1.66
L5	SI = 17.09 - 0.3000 (MR) + 0.0548 (A%CLAY)	0.227 0.017	32	0.420	0.380	1.79
L6 (final equation)	SI = 15.68 - 0.0436 (BC%CLAY)	0.010	32	0.523	0.472	1.66

Interaction terms were created using all independent variables. Backward stepwise regression and 'all possible subsets' regression were used simultaneously to determine which interactions should be included in the model. The interactions did not significantly increase R^2, therefore further analyses were restricted to equation L3.

An attempt was made to increase the accuracy of the final regression equation by combining the six check plots with the 26 computation plots. The 32 plots were then used with equation L3 to compute equation L4. Addition of the six check plots into equation L3 resulted in a dramatic decrease in R^2, from 0.70 to 0.37. Therefore, equations L6 and L5 were computed using the independent variables from equations L1 and L2, respectively. Unfortunately, the addition of the check plots into these models also resulted in large decreases in R^2. Equation L4 was chosen as the final model, since equation L4 has greater precision than other equations containing the full data set.

Valid soil-site regression equations must have a minimum R^2 value of 0.55 (Carmean 1975). Therefore, no site index prediction table was developed for equation L4.

Moraine

The combined moraine data set consists of 41 plots from north central Ontario, 19 plots from northeastern Ontario, and six plots from northwestern Ontario for a total of 66 plots (Table 26). Thirteen of the 66 plots were randomly selected as check plots, leaving 53 computational plots.

A two-variable model (equation M1) was computed using backward stepwise regression and 'all possible subsets' regression simultaneously (Table 42). There were no valid three or four-variable models.

Table 42. Multiple regression equations for the pooled moraine landform.

Eqn #	SI Equation	S_b	N	R^2	R^2 (adj)	SEE (m)
M1	SI = 19.21 - 0.3531 (APH) - 0.0924 (BCFSTONE)	0.163 0.027	53	0.248	0.217	2.01
M2 (final equation)	SI = 18.85 - 0.2780 (APH) - 0.0664 (BCFSTONE)	0.125 0.021	66	0.194	0.168	1.97

Each independent variable was tested to see if a quadratic transformation improved the R^2 of equation M1. No independent variables were found where a quadratic transformation significantly improved the precision of the model.

Interaction terms were created using all independent variables. Backward stepwise regression and 'all possible subsets' regression were used simultaneously to determine which interactions should be included in the model. This computation showed that no interactions significantly improved the precision of equation M1.

An attempt was made to increase the accuracy of the final regression equation by combining the 13 check plots with the 53 computation plots. Addition of the 13 check plots into equation M2 resulted in a small decrease in R^2. Valid soil-site regression equations must have a minimum R^2 value of 0.55

(Carmean 1975). Therefore, no site index prediction table was developed for equation M2.

A comparison of the soil-site equations from northeastern Ontario, north central Ontario, combined northeastern and north central, and pooled northeastern, north central, and northwestern Ontario is shown in Table 43. The independent variables for each equation were also listed by landform and geographic area.

Table 43. Important soil variables for jack pine in north central and northeastern Ontario.

LANDFORM	northeastern Ontario	north central Ontario (Schmidt and Carmean 1988)	combined north-eastern & north central Ontario	combined north-eastern, north central, and north-western Ontario
Bedrock-Glaciofluvial	too few plots *N = 4*	too few plots *N = 14*	1) depth to average rooting; 2) depth to maximum rooting; 3) % gravel & cobbles in B horizon *eqn. BRGF3* *N = 18* R^2=0.84	no data
Bedrock-Moraine	1) slope %; 2) B thickness; 3) % stones (0 - 25 cm) *eqn. BRM4* *N = 15* R^2=0.78	1) depth to bedrock; 2) % coarse fragments in A horizon *N = 20* R^2=0.83	1) depth to bedrock; 2) slope %; 3) % gravel + cobbles in A horizon *eqn. BRM3* *N = 26* R^2=0.55	no data

Table 43. (continued)

LANDFORM	northeastern Ontario	north central Ontario (Schmidt and Carmean 1988)	combined north-eastern & north central Ontario	combined north-eastern, north central, and north-western Ontario
Glaciofluvial	1) depth to average rooting; 2) DMRL; 3) B%Silt *eqn. GF5* *N = 33* R^2=*0.51*	1) DMRL; 2) slope % *N = 31* R^2=*0.65*	(combining data drastically reduced equation precision - use original equations instead) *eqn. GF6* *N = 76* R^2=*0.37*	(combining data drastically reduced equation precision - use original equations instead) *eqn. GF2* *N = 79* R^2=*0.22*
Lacustrine	too few plots *N = 6*	1) thickness of A horizon; 2) pH of BC horizon *N = 18* R^2=*0.75*	1) thickness of the combined A, B, & BC horizons; 2) rooting abundance (%) of the B horizon; 3) root size in the BC horizon *eqn. L5* *N = 25* R^2=*0.57*	(combining data drastically reduced equation precision - use original equations instead) *eqn. L6* *N = 32* R^2=*0.47*
Moraine	1) depth to maximum rooting; 2) pore pattern; 3) % sand in BC horizon; 4) % silt in BC horizon *eqn. M3* *N = 18* R^2=*0.60*	1) depth to root restricting layer; 2) coarse fragment % of C horizon; 3) % clay in A horizon *N = 30* R^2=*0.65*	(combining data drastically reduced equation precision - use original equations instead) *eqn. M4* *N = 60* R^2=*0.24*	(combining data drastically reduced equation precision - use original equations instead) *eqn. M2* *N = 66* R^2=*0.17*

DISCUSSION

A. NORTHEASTERN ONTARIO

SOIL-SITE EQUATIONS

The first objective of this thesis was to provide soil-site equations for jack pine in northeastern Ontario. Soil-site equations were developed for bedrock-moraine, glaciofluvial, and moraine landform groups in northeastern Ontario.

The second thesis objective was to determine the soil features that are significantly related to the height growth of jack pine. These soil features are the independent variables in each soil-site equation. Additional important soil features are listed in Table 5.

Preliminary Computations

Regression analyses combining all 76 plots in northeastern Ontario yielded an unacceptably low R^2 value of 0.21. But, stratification of the data set into four landform groupings yielded R^2 values of 0.69, 0.68, and 0.46 for bedrock-moraine, glaciofluvial, and moraine landforms, respectively. Accordingly, all subsequent data analyses was stratified by landform. This finding was not surprising, as other site-quality research in northern Ontario (Schmidt and Carmean 1988, LaValley 1991, and Li 1991) also found that landform stratification greatly increased the precision of regression equations.

Bedrock-Moraine

Soil variables that were most closely related to site index for the bedrock-moraine soils were soil depth, coarse fragment content, and topography (Table 7). The final equation (BRM4) included the variables slope percent, B thickness, and percent stones in the top 25 cm of the soil profile.

Slope percent was inversely related to height growth. Schmidt and Carmean (1988) also found this same relationship for glaciofluvial soils in north central Ontario. Height growth might be poorer on steeper slopes due to rapid down slope flow of subsurface water. This greater moisture loss would decrease available moisture, thus reducing height growth.

Thickness of the B horizon (BTHICK) was more closely related to site index than depth to bedrock (BR). In contrast, Schmidt and Carmean (1988) found that depth to bedrock was the strongest variable in the bedrock landform. However, the two variables are closely related because northeastern Ontario A horizons were relatively shallow and had relatively little variation in depth. Accordingly, for northeastern Ontario the thickness of the B horizon appears to be a better measure of effective rooting depth than was depth to bedrock. Thickness of the B soil horizon had a positive influence on height growth, as did depth to bedrock in north central Ontario. Shetron (1972) also found thickness of the B soil horizon to be positively correlated to the site index of jack pine, but on landforms other than bedrock. This relationship is logical and makes biological sense, since depth to bedrock defines the effective soil depth, which is associated with tree growth in many forest regions (Coile 1952, Carmean 1975, Pritchett and Fisher 1987). Having greater soil volumes available for root development allows for more moisture and nutrients to be available for height and volume growth.

There is an inverse relationship between percent stones in the top 25 cm of the soil profile and height growth. Schmidt and Carmean (1988) also found an inverse relationship between site index and the A soil horizon coarse fragment content for bedrock-moraine soils in north central Ontario. Coarse fragments have an inverse relationship to height growth, since they displace soil, reducing the effective volume of soil available for root development (Ralston 1964, Carmean 1994).

Glaciofluvial

Soil variables most closely related to site index on glaciofluvial soils were soil depth and texture (Table 9). A and B soil horizon variables had consistently higher correlations than did the BC and C soil horizon variables, suggesting that BC and C horizon variables have relatively little influence on the site-quality of jack pine.

The final equation (GF5) included depth to average rooting, depth to moisture restricting layer (DMRL), and an interaction consisting of DMRL and percent silt in the B layer. Depth to average rooting was positively correlated to site index, a result that Hamilton and Krause (1985) also found. This result was expected, since deeper rooting would indicate that the roots are utilizing more soil volume which in turn may lead to increased tree growth.

Depth to moisture restricting layer (DMRL) was positively correlated to site index. DMRL includes depth to coarse sandy subsoil, mottles, gley, water table, bedrock, carbonates, or basal till. Schmidt and Carmean (1988) also found that depth to moisture restricting layer was correlated to site index. In contrast, these researchers also found percent slope to be correlated to site index, while this study not. This relationship is biologically reasonable because deeper moisture restricting layers result in a greater volume of soil available for tree growth. Similar results were obtained in north central Ontario where depth to root restricting layer was the most important soil feature with glaciofluvial soils.

The interaction of DMRL and percent silt in the B horizon was also positively correlated to site index. More silt in the B horizon will hold more moisture and provide additional nutrients, thereby increasing site-quality, and hence, site index. Both Pawluk and Arneman (1961) and Wilde *et al.* (1964) also found the presence of silt increased site index.

Lacustrine

Only six lacustrine plots were established in northeastern Ontario (Table 4), thus too few plots were available for exploratory regression analyses. Jack pine stands on clay soils are very rare in northeastern Ontario because these soils almost always have black spruce or trembling aspen stands. Very abrupt stand boundaries occur where clay soils are adjacent to beach sands, and for these areas, black spruce or aspen occurs on the clay and jack pine occurs on the sand.

We attempted to find scattered jack pine stands in the boundaries where there might be a transition zone, but usually there was no transition zone. Jack pine apparently competes poorly with black spruce or aspen on clay soils, but six pure jack pine plots on clay soils were located and established. A severe fire may have removed all competing tree species at these stands, allowing jack pine to re-seed the burned area and become established before spruce and aspen could regenerate.

Moraine

Soil variables most closely related to site index on moraine soils were depth to maximum rooting, texture, pore pattern and profile coarse fragments (Table 11). Variables in the A and B soil horizons had much higher correlations to site index than did variables in the BC and C soil horizons.

The final moraine equation (M3) included depth to maximum rooting, together with three interactions consisting of depth to maximum rooting with pore pattern, percent sand in the BC horizon, and percent silt in the BC horizon. Surprisingly, none of the many profile coarse fragment variables were in the final equation. Coarse fragments may differentiate moraine soils from other soil groups, and displace a significant volume of soil. One might expect to find a strong inverse relationship between coarse fragments and site index, as observed in north central Ontario (Schmidt and Carmean 1988). However, coarse fragment variables had a lower correlation to site index than variables such as depth to maximum rooting and pore pattern. Including coarse fragment variables in the regression model resulted in regression equations with unacceptably low R^2 values, thus coarse fragment variables were deleted from the model in favour of other variables.

Depth to maximum rooting (MAXROOT) was the most influential variable, for it is included with all three interactions. MAXROOT has a positive correlation with site index, a similar finding to Hamilton and Krause (1985). All three interactions of MAXROOT with pore pattern, BC percent sand, and BC percent silt have inverse relationships. Therefore, the three interactions cause a decrease in site index as depth to maximum rooting increases (Table 12).

Use of these four variables to estimate site index will be difficult, because of the need to dig a soil pit 120 cm deep to find the depth to maximum rooting. It would be much easier to estimate site index in the field if the A horizon were to contain all the significant soil variables. This would allow a quick, shallow excavation instead of digging a deep soil pit. Possibly, future soil-site work could collect additional data, while explicitly looking for soil variables in the A horizon that are strongly correlated with site index. Alternatively, understory vegetation indicator plants that are strongly correlated with site index should be sought. These indicator plants could also be used as dummy variables in a moraine soil-site equation.

CATEGORICAL DATA

Some of the data collected were categorical (i.e. qualitative), and could not be included with the regression analyses. Therefore, exploratory data analyses were used by utilizing one-way ANOVA's. Variables found to be statistically significant at $P < 0.05$ were further explored by using Student-Newman-Keul's (SNK) multiple range test, grouping classes within variables, and reiterating the multiple range test. This was done in an attempt to stratify site index (productivity) using variables such as: classes of topography; soil classifications; and, ecosystem classifications.

The categorical data analyses were made using all landforms combined, and by stratifying data according to landform. All landforms combined had more significant variables than separate landform groups (i.e. bedrock-moraine, glaciofluvial, and moraine). The soil-site equations for this study and others (Schmidt and Carmean 1988, LaValley 1991, Li 1991) found more precise equations by stratifying into landform groups. Therefore, this result of unstratified data delineating site-quality better, is surprising.

Two statistically different groups of humus form (Table 14) were delineated. The difference between the two humus form groups is that group 'A' (humifibrimor) has an H layer (nitrogen and nutrient rich) at least 1 cm thick, while group 'B' (fibrihumimor and fibrimor) does not have an H layer. Therefore, a quick field inspection of the humus layer could be used to assist in the determining of site-quality. It should be cautioned that humus form and humus thickness change over time with tree species, stand age and stand structure, and therefore the approach may present some potential errors in estimating site index.

Both Clay Belt and NWO FEC classification types (operational groups, soil types, and vegetation types) were statistically significant for all landform groups combined (Table 13). Clay Belt FEC soil types were stratified into two statistically significant groups. The first group consists of 73 plots (Table 16), and many soil types combined. The second group consists of only three plots and one soil type (Clay Belt FEC type S1). This indicates that Clay Belt FEC soil types can only separate the very poorest sites, and treat all other sites as having the same productivity. These poor results were also found by Edmonds (1985).

Northwestern Ontario FEC soil types identified in northeastern Ontario were stratified into two groups. The first group consists of many FEC soil types, both shallow and deep. Soil textures within this group varied from sand to clay, showing that soil texture could not be characterized by this group. The second group had a significantly lower average site index and consists of shallow soils, and soils whose moisture regime is four or greater (i.e. wetter sites). Therefore, the NWO FEC soil types can be used to define two broad productivity classes, high and low.

Note that the NWO FEC classification system was not intended to be used in northeastern Ontario. However, this preliminary analyses shows that there may be potential for extrapolation of the NWO FEC classification into northeastern Ontario for the purposes of site-quality estimation.

Clay Belt FEC vegetation types were stratified into two groups. The first group consists of vegetation types V3, V4, and V6, with a high average site index, but differing understory vegetation. Vegetative associations V3 and V4 are characterized by the presence of the following understory vegetation: *Vaccinium angustifolium*, *Linnea borealis*, and *Lonicera canadensis*. The V6 vegetative association is characterized by *Epigaea repens*, *Cladina stellaris*, *Ptillium crista-castrensis*, *Ledum groenlandicum*, and *Rosa acicularis*. The second group has a medium site index, and consists of vegetation types V1, V2, V5, V7, and V23. These vegetation types all have feathermoss and herb-poor understory vegetation, but vary greatly in soil moisture regime. V1 and V2 are characterized by understory vegetation that is commonly found on dry poor sites (e.g. *Epigaea repens* and *Cladina stellaris*). V5 is found on fresh to moist sites, and is characterized by a wide variety of understory vegetation. V7 is characterized by richer, moist sites and understory vegetation such as *Petatsites palmatus*.

Northwestern Ontario FEC vegetation types were subjectively stratified into three significantly different groups (Table 19). The highest site index group consists of vegetation types V7, V16, V17, V18, V28, and V34. This group includes conifer-mixedwood, pure conifer, and hardwood stands. The understory vegetation among these vegetation types varies greatly. The medium site index group consists of vegetation types V29, V31, and V32. This group includes only pure conifer stands whose understory vegetation is characterized by feathermoss or asters. The third and lowest site index group has a single vegetation type (V30: blueberry - lichen). This group consists of only pure jack pine stands. The conifer-mixedwood vegetation types had the highest site index values, while the pure conifer vegetation types had medium and low site index. Forest inventory cover types containing jack pine and hardwoods, can be classified as high productivity, while pure jack pine stands can be classified as medium productivity, or low productivity if the sites are dry blueberry-lichen sites.

Clay Belt FEC Operational Groups (OG's) were stratified into two significantly different groups (Table 20). The higher site index group includes OG2 to OG6, inclusive. The second group has a significantly lower site index, and consists of only one operational group (OG1: Very Shallow Over Bedrock). Operational groups are a poor stratifier of site index, as all OG's were lumped together, with the exception of OG1. This makes OG's operationally unuseable for forest management tools such as prime land management.

B. COMBINED NORTHEASTERN AND NORTH CENTRAL ONTARIO DATA

The third objective of this thesis was to compare soil-site relations in northeastern Ontario with those produced by: a) Schmidt and Carmean (1988) in north central Ontario; and, b) Jackman (1990) in northwestern Ontario. Objective 3a was completed by using north central Ontario soil-site equations to predict site index of northeastern Ontario data.

PREDICTING SITE INDEX IN NORTHEASTERN ONTARIO USING NORTH CENTRAL ONTARIO EQUATIONS

All four of Schmidt and Carmean's (1988) soil-site equations did not predict site index adequately for the plots located in northeastern Ontario, based on correlation analysis at $P < 0.05$ (Tables 22, 23, 24 and 25). The bedrock-moraine equation (Table 22) had a probability of 0.06, which is very close, but still higher than the acceptance probability level of 0.05.

There are several possible reasons for Schmidt and Carmean's (1988) equations not being able to predict site index in northeastern Ontario. The most obvious is pedogenic differences between regions. Different soil formations may result in soil variables that are significant in north central Ontario, but not significant in northeastern Ontario. Secondly, there are potential climatic differences between these two regions of Ontario. The genetics of jack pine in these different areas may be different. Furthermore, through adaptive variation there may be an interaction between environmental components of phenotypic variation and the genetics of jack pine (Monserud and Rehfeldt 1990).

COMBINED NORTHEASTERN AND NORTH CENTRAL DATA

The fourth objective of this thesis was to compute new soil-site equations applicable to all areas of northern Ontario, based on a pooled data set from all regions. A combined data set of northeastern and north central Ontario data was used to compute these new soil-site equations.

Combined Bedrock-Glaciofluvial

The combined bedrock-glaciofluvial data set consists of 14 plots from north central Ontario, and four plots from northeastern Ontario (Table 26). These 18 plots were enough to complete a statistically significant soil-site equation, but not sufficient to verify the equation using check plots. Soil variables most closely related to site index of jack pine on bedrock-glaciofluvial soils were rooting depth, coarse fragment content, and pore pattern (Table 29). The equation (BRGF3) fills an important gap across northern Ontario, since there is no other equation for bedrock-glaciofluvial soils (Table 43) in either northeastern or north central Ontario.

The final bedrock-glaciofluvial equation (BRGF3) included depth to average rooting (AVGROOT), depth to maximum rooting (MAXROOT) and percent cobbles and stones in the B horizon (BCFCOBST). AVGROOT was positively correlated to site index. This result was expected, as deeper roots utilize more soil volume, which may lead to higher height growth.

Depth to bedrock, was expected to be in the final equation, but was not. MAXROOT may be very similar to depth to bedrock, but it probably defines the actual rooting depth and volume, where depth to bedrock defines the potential rooting depth. Depth to maximum rooting on bedrock sites is usually several centimetres shallower than depth to bedrock, due to trapped water above the bedrock. This waterlogged layer of soil becomes mottled and probably does not contribute to the height growth of jack pine. Therefore, MAXROOT explains more variation than depth to bedrock. This finding is similar to Hamiltona and Krause (1985), who found rooting depth to be positively correlated to the site index of jack pine.

BCFCOBST was inversely related to site index, similar to coarse fragment content in the A soil horizon for Schmidt and Carmean's (1988) bedrock equation from north central Ontario. The B soil horizon was significant instead of the A soil horizon, because in northeastern Ontario, most of the A soil horizons were very thin. Therefore, most of the roots would be in the B horizon, which may influence height growth of jack pine.

Combined Bedrock-Moraine

The combined bedrock-moraine data set consists of 12 plots from north central Ontario, and 15 plots from northeastern Ontario (Table 26). Soil variables most closely related to site index of jack pine on bedrock-moraine soils were depth to bedrock, coarse fragment content, and slope steepness (Table 31).

The combined bedrock-moraine equation uses independent variables from both the northeastern and north central Ontario bedrock-moraine equations (Table 43). The final equation (BRM3) included depth to bedrock (BR), slope percent (SLOPE%), and percent gravel and cobbles in the A horizon (A%GRVCOB). Depth to bedrock has the highest simple correlation with site index, and was also found by Schmidt and Carmean (1988) in north central Ontario, and in the author's original data set for bedrock-moraine soils (Table 43). This relationship makes biological sense, since depth to bedrock defines the effective soil depth, which is associated with tree growth (Coile 1952, Carmean 1975, Pritchett and Fisher 1987).

The combined bedrock-moraine equation had an inverse relationship to slope, similar to Schmidt and Carmean's (1988) equation for glaciofluvial soils. This was expected, since height growth might be poorer on steeper slopes due to rapid down slope flow of subsurface water. This greater moisture loss would decrease available moisture, thus reducing height growth.

A%GRVCOB was also inversely related to site index, similar to Schmidt and Carmean's (1988) equation for bedrock-moraine soils. Coarse fragments have an inverse relationship to height growth, since they displace soil, reducing the effective volume of soil available for root development (Ralston 1964, Carmean 1994).

Combined Glaciofluvial

The combined glaciofluvial data set consists of 46 plots from north central Ontario and 34 plots from northeastern Ontario, for a combined total of 80 plots (Table 26). Soil variables most closely related to site index of jack pine on glaciofluvial soils were rooting depth, texture, topography and slope steepness (Table 33). The northeastern and north central Ontario glaciofluvial equations have R^2 values of 0.51 and 0.65, respectively. Combining data from the two regions reduced the R^2 value to 0.37 (Table 43), well below the minimum acceptable R^2 limit of 0.55 (Carmean 1975), thus making the combined north central and northeastern Ontario glaciofluvial equation unacceptable.

Combined Lacustrine

The combined lacustrine data set consists of 19 plots from north central Ontario and six plots from northeastern Ontario, for a combined total of 25 plots (Table 26). Soil variables most closely related to site index of jack pine on lacustrine soils were soil horizon depth, root size, and pore pattern (Table 34). Schmidt and Carmean's (1988) north central Ontario glaciofluvial equation had an R^2 value of 0.75, but when data were combined with northeastern Ontario data, the R^2 dropped to 0.57 (Equation L5, Table 43). This decrease in precision is probably due to pedogenic soil differences between the two areas. Lacustrine soils sampled in northeastern Ontario had a much larger fraction of coarse fragments, than lacustrine soils sampled in north central Ontario.

The final combined lacustrine equation (L5) included depth to the C horizon (ABETHICK), rooting abundance in the B horizon (BRTAB), and root size in the BC horizon (BCROOTSIZ). All three of these independent variables were inversely related to site index, but a positive correlation was expected. Thicker A and B horizons, which have more nutrients and aeration than the C horizon, result in a greater depth to the C horizon. Therefore, one would expect depth to the C horizon to be positively correlated with site index. A speculation for this inverse relationship is that the C horizon has more available moisture; for deeper C horizons, the available moisture is perhaps lower, and therefore height growth is reduced.

Rooting abundance in the B horizon also had a surprising inverse relationship. Possible explanations for this result include: 1) roots in the more fertile A horizon contribute more to height growth than do roots in the B horizon;

and, 2) a high rooting abundance in the B horizon may mean that roots could not penetrate the BC and C horizons, reducing effective rooting depth.

Root size in the BC horizon was inversely related to site index. Small roots were associated with higher site index, while large roots were associated with lower site index. Small roots have many more feeder roots that absorb soil moisture than do large roots. Large roots merely transport water, and have few feeder roots attached to them. Therefore, the small roots absorb greater quantities of water, which may increase height growth.

Schmidt and Carmean's (1988) lacustrine equation for north central Ontario has higher precision. Therefore, the author suggests using this equation when estimating site index in north central Ontario.

The final regression equation for the combined study areas is acceptable. However, the user should be cautioned that only six out of the 25 plots were from northeastern Ontario, thus this small sample size may be strongly influenced by the north central Ontario plots. The combined lacustrine equation has a lower level of precision than the Schmidt and Carmean (1988) lacustrine equation; R^2 values of 0.57 and 0.75, respectively.

Lacustrine soils in north central Ontario consist of gray acidic clay and red calcareous clays. Both types of clay are generally free of coarse fragments. In contrast, northeastern Ontario lacustrine sites are usually gray acidic clay, mixed with varying amounts of coarse fragments. More detailed investigations in the future may wish to examine the lithologically different lacustrine soils in greater detail.

Combined Moraine

The combined moraine data set consists of 41 plots from north central Ontario and 19 plots from northeastern Ontario, for a combined total of 60 plots (Table 26). Soil variables most closely related to site index on moraine soils were soil horizon thickness, coarse fragment content, and clay content (Table 36). The northeastern and north central Ontario moraine equations have R^2 values of 0.60 and 0.65, respectively. But when data were combined, the R^2 value dropped to 0.24 (Tables 36 and 43), which is well below the minimum acceptance level of 0.55 (Carmean 1975). Therefore, equation M4 cannot be used for the combined study areas. Instead, the original moraine equations for north central Ontario (Schmidt and Carmean 1988), and the author's moraine equation for northeastern Ontario should be used.

Moraine soils in north central Ontario consistently had a coarse sand subsoil layer, which was closely related to site index. In contrast, very few moraine soils in northeastern Ontario had a coarse sand subsoil layer; northeastern moraines also had much higher coarse fragment contents than moraine soils in north central Ontario. Moraine soils in north central Ontario often have a coarse sand BC or C soil horizon, and have 10 to 50% coarse fragments. In contrast, northeastern Ontario moraine soils generally have fine sand or silty sand BC and C soil horizons, with much higher percentages of coarse fragments. Therefore, combined moraine equation precision may be low due to the above-mentioned pedogenic soil differences between regions.

C. COMBINED NORTHEASTERN, NORTH CENTRAL AND NORTHWESTERN ONTARIO DATA

Jackman's (1990) data had insufficient quantitative soils information, and thus were incompatible with the northeastern and the north central Ontario data. Therefore, the only plots available in northwestern Ontario were the supplementary plots sampled by Niznowski (1994) and the author. Three glaciofluvial, seven lacustrine, and six moraine plots were sampled (Table 26). These minimum data from northwestern Ontario were combined with the northeastern and north central Ontario data to explore possible trends.

The third objective of this thesis was to compare soil-site relations in northeastern Ontario with those produced by: a) Schmidt and Carmean (1988) in north central Ontario; and, b) Jackman (1990) in northwestern Ontario. Objective 3b was completed by using northeastern and north central Ontario soil-site equations to predict site index of northwestern Ontario data.

PREDICTING SITE INDEX IN NORTHWESTERN ONTARIO USING NORTHEASTERN, NORTH CENTRAL ONTARIO AND COMBINED EQUATIONS

Glaciofluvial

The pooled data consisted of three northwestern Ontario plots, 34 northeastern and 46 north central Ontario plots, for a combined total of 83 plots (Table 26). The north central Ontario equation (Schmidt and Carmean 1988) for glaciofluvial soils estimated site index poorly for the three northwestern Ontario plots (Table 37). These results should only be considered preliminary, since they are only based on three plots; at least 20 plots should be established to have a valid comparison.

Lacustrine

The pooled data consisted of seven northwestern Ontario plots, six northeastern and 19 north central Ontario plots, for a combined total of 32 plots (Table 26). The north central Ontario equation (Schmidt and Carmean 1988), and the combined northeastern / north central lacustrine equation (equation L5, Table 34) were evaluated on their ability to predict site index of northwestern Ontario plots. Both equations did not predict site index adequately (Table 38), and consistently over-estimated site index.

Moraine

The pooled data consisted of six northwestern Ontario plots, 19 northeastern and 41 north central Ontario plots, for a combined total of 66 plots (Table 26). The north central Ontario equation (Schmidt and Carmean 1988) and the northeastern moraine equation were evaluated on their ability to predict site index on the six northwestern Ontario plots. Both equations did not predict site index adequately. The northeastern moraine equation predicted site index more accurately than the north central equation, but site index was consistently over-estimated by both equations (Table 42).

Schmidt and Carmean's (1988) and the author's soil-site equations failed to predict site index on all three landforms (i.e. glaciofluvial, lacustrine, and moraine) in northwestern Ontario. since soil-site equations from other areas of Ontario are not adequate, new soil-site equations should be developed for northwestern Ontario, based on data from that area. Note that the bedrock landform was not tested, due to lack of data from northwestern Ontario.

SOIL-SITE EQUATIONS FOR NORTHEASTERN, NORTH CENTRAL, AND NORTHWESTERN ONTARIO COMBINED

The fourth objective of this thesis was to compute new soil-site equations applicable to all areas of northern Ontario, based on a pooled data set from all regions. A pooled data set of northeastern, north central, and northwestern Ontario data was used to compute these new pooled soil-site equations.

Glaciofluvial

Pooling the northwestern Ontario plots with northeastern and north central Ontario plots does not produce an acceptable glaciofluvial equation. The northwestern Ontario glaciofluvial data does not fit well with the data from northeastern and north central Ontario. This may be due to differences in glaciofluvial soils, climate, or genetics of jack pine between these regions.

Lacustrine

The final lacustrine equation (L5) was deemed unacceptable, since the R^2 value was below the 0.55 minimum acceptable limit (Carmean 1975). The northwestern Ontario lacustrine data does not fit well with the data from northeastern and north central Ontario.

This poor precision is probably due to differences in lacustrine soils between regions. Northeastern Ontario lacustrine soils are grey acidic and calcareous clays, often with mixed coarse fragments in the soil profile. North central Ontario soils have two distinct lacustrine soil groups: 1) red calcareous clays; and 2) grey acidic clays. Both of these clays have very few or no coarse fragments in the soil profile. Northwestern Ontario lacustrine soils seem to have a higher clay content, and have grey clays with a mixture of acidic and calcareous soils. These clay soils are often drier, because they are commonly found on upland sites. Therefore, these differences between lacustrine soil contribute to the poor fit of data between regions. Other potential contributing factors to poor precision of the pooled equations are climate and genetics.

Moraine

No acceptable moraine soil-site equation was possible for pooled northwestern data. Combining northeastern data with north central moraine data also produced unacceptable equations. The northwestern Ontario moraine data does not fit well with the data from northeastern and north central Ontario. This is probably due to the difference in moraine soils between plots in northeastern Ontario and plots in north central Ontario. The author's moraine plots have higher coarse fragment contents than plots in north central Ontario, which have less coarse fragments and BC horizons with coarse sandy soil. Northwestern

Ontario moraine plots have fine sandy sub-soils with low to medium coarse fragment contents. Other potential contributing factors to poor precision of the pooled equations are climate and genetics.

PRACTICAL APPLICATIONS

Determining Site Index in the Field

It is much easier and more practical to use the site index prediction tables in the field, rather than the soil-site equations. Use of tables eliminates the need for a calculator in the field.

One must first determine if the site chosen is applicable to the site index prediction tables as follows:

1. If suitable jack pine trees (i.e. dominant or codominant crown class, uninjured and disease-free) are available on or near the site in question, directly measure site index using Niznowski's (1994) site index curves if in northeastern Ontario, or use Carmean and Lenthall's (1989) site index curves if in north central Ontario;

2. The landform must be bedrock-glaciofluvial, bedrock-moraine, glaciofluvial, lacustrine, or moraine (landform descriptions on page 49);

3. The land area in question must have relatively homogeneous soil horizons and textures. Homogeneity can be quickly assessed with a soil auger;

4. Avoid pits and mounds caused by wind-thrown trees. Live trees, decayed stumps, animal burrows, rock outcrops, and small local depressions should also be avoided. An ideal site would have even and unbroken microtopography where no obvious tree or soil disruptions occur (Carmean 1994);

5. Clearcut or partially-cut areas are applicable to these site index prediction tables if only the root mat and surface litter have been disturbed. Cut areas whose A and B soil horizons have been disturbed, such as rutted areas, road

right-of-ways, and landings are not applicable to the site index prediction tables; and

6. Site index prediction tables are applicable on scarified sites (e.g. anchor chains) whose A and B soil horizons have not been significantly disturbed. However, if site preparation practices (e.g. straight-blading) have removed or significantly disturbed the A and B soil horizons, proper soil variable measurements for the site index prediction tables cannot be taken. This makes moderately or heavily-disturbed sites not applicable to the author's site index prediction tables.

Once the site in question has met all the applicability criterion, use the site index prediction tables as follows:

1. Determine landform (landform descriptions on page 49);

2. One to three 1 m X 1 m soil pit(s) should be excavated, with the pit positioned so it will be well lighted. The pit face should face south, so direct sunlight will better illuminate soil horizons being described (Carmean 1994). The depth of the pit is variable, as there is no need to excavate deeper than the depth to maximum rooting. A soil auger can be used to obtain some, but not all, soil variable information required for the site index prediction tables. Therefore, soil pit(s) must be used to determine soil variables such as depth to maximum rooting and percent coarse fragments.;

3. Measure soil variables appropriate to the site's landform and site index prediction table. Measurement should fall within the range outlined by the table. Site index prediction is not valid if measurements are beyond the tables range. Either do not use the tables, or be prepared for extrapolation errors;

4. The moraine and lacustrine equations require soil variables from the BC soil horizon. If no BC soil horizon exists, measure percent sand, percent silt, or root size as appropriate, of <u>both</u> the B and C soil horizons then average the two measurements; and

5. Match soil variable measurements to the appropriate site index prediction table by landform, and obtain site index.

The following table can assist users in determining which equations to use for northeastern and north central Ontario, by landform (Table 44).

Table 44. Applicable soil-site equations by area and landform for northeastern (NE) and north central (NC) Ontario.

Area	Bedrock-Glaciofluvial	Bedrock-Moraine	Glaciofluvial	Lacustrine	Moraine
NE	eqn. BRGF3 for NE/NC *(author)*	eqn. BRM4 for NE *(author)*	eqn. GF5 for NE *(author)*	eqn. L5 for NE/NC *(author)*	eqn. M3 for NE *(author)*
NE/NC combined	eqn. BRGF3 for NE/NC *(author)*	valid eqn. for combined areas, but precision much lower than area-specific equations	no valid equation	eqn. L5 for NE/NC *(author)*	no valid equation
NC	eqn. BRGF3 for NE/NC *(author)*	shallow to bedrock moraine *(Schmidt and Carmean 1988)*	Outwashed glacial sands *(Schmidt and Carmean 1988)*	Glacial lacustrine *(Schmidt and Carmean 1988)*	Deep moraine *(Schmidt and Carmean 1988)*

Jack Pine Productivity Mapping and Modelling

It is not practical to sample large numbers of soils to determine jack pine productivity over a large area (e.g. a Forest Management Agreement area). Yet, it is desirable to create a spatial map which displays productivity. A common approach to predictive mapping is to model the desired attribute that cannot be field-sampled in every location. Predictive mapping of jack pine productivity is possible if there are sufficient mapped soil attributes available to drive the soil-site equations, tables, or categorical productivity stratifications.

Several map products can be used to determine landform over large areas. The surficial geology map of Ontario (Sado and Carswell 1987) at a scale of 1:1,200,000 is a potential source for determining landform of large areas, on a regional planning level. Ontario Land Inventory (OLI) land classification maps at a scale of 1:250,000 were photo-interpreted in the 1960's. OLI maps were also ground-checked, and contain information on soil texture, soil moisture regime, soil depth class, and calcareousness. Northern Ontario Engineering Geology Terrain Study (NOEGTS) maps (Gartner *et al.* 1981) at a scale of 1:100,000 may also be used to determine landform over large areas. The NOEGTS maps provide landform polygons as small as 150 ha, and show significant landform features such as end moraines and esker ridges. Additional map information includes soil material, topography and drainage. Forest Land Productivity Survey (FlaPS) soil maps for northeastern Ontario determine landform percentages in 10% classes, within 200 ha or greater map polygons. The FLaPS map series has a scale of 1:50,000, and provides additional information on soil depth classes, texture classes, soil moisture, topography, stoniness and lime content.

The previously mentioned map products can be used as a first-approximation of landform and soil variables. However, forest management practices usually occur at scales of 1:15,000 or 1:20,000, with map polygon (stands) sizes of five to 100 ha. Therefore, if further refinement of landform mapping is desired, one could photo-interpret landform at an operational scale of 1:15,000 or 1:20,000.

Note that not all areas may be able to be predictively mapped, but even if only 50% of the area desired to be mapped is covered, this saves an incredible amount of field sampling. Their will also be various reliabilities attached to each productivity group. For example, the previously mentioned productivity (site index) class 16 may be modelled, field-checked, and found to have a reliability of 75%. The remaining error may be productivity class 14 20% of the time, and the last 5% of predicted sites may be a wide variety of productivity classes. On a GIS system, this data can be layered to account for the reliability as follows:
16 - 0.75, 14 - 0.20.

Topographic variables such as slope, aspect, upslope length, and surface shape of forest sites can now be easily and accurately predicted at operational map scales, utilizing contour data and a Digital Elevation Model (DEM). Slope percent is used in the northeastern bedrock-moraine equation, and in Schmidt and Carmean's (1988) glaciofluvial equation for north central Ontario. Therefore, the DEM derived slope percentages could be used as inputs to mapping site-quality of jack pine. Furthermore, this study found that site index is significantly related to surface shape on glaciofluvial landforms. Site index class 20 can be assigned to concave sites, class 18 to convex, and class 16 to flat surface shapes. This is a good framework for high, medium and low site index classes for jack pine.

Other categorical variables, especially Forest Ecosystem Classification types, can also be used to assign site index classes for jack pine productivity. Of course, FEC mapped types or FEC predictive mapping capabilities must exist to achieve this goal.

Productivity classes are useful for predictive mapping of jack pine productivity. It is simpler and more realistic for the user to have classes of productivity, rather than estimates of site index to 0.1 m. LeBlanc and Towill (1989) suggested using 2 m productivity classes for Schmidt and Carmean's (1988) tables. Productivity classes of 2 m should be used for two reasons: 1) the accuracy of most soil-site equations for jack pine are ±1.0 m, or stated otherwise, a range of 2 m; and, 2) site index curves are presented in families of 2 m curves (Carmean and Lenthall 1989, Niznowski 1994). These 2 m site index productivity classes are defined as:

Site Index Class	Site Index Range
24	23.0 +
22	21.0 - 22.9
20	19.0 - 20.9
18	17.0 - 18.9
16	15.0 - 16.9
14	13.0 - 14.9
12	11.0 - 12.9
10	9.0 - 10.9

These productivity classes differ from those outlined in LeBlanc and Towill (1989) in several ways. First, the site index class is the actual site index, while the previous work suggested a scale of one to six, with productivity class one being the best site. Secondly, the mid-point of the 2 m site index classes are different. The outline above uses even-numbered midpoints of the productivity class, similar to site index curves, but LeBlanc and Towill (1989) used odd-numbered mid-points. The author suggests that this new scheme is more practical.

Table 45. Generalized site index prediction table for the bedrock-moraine landform using equation BRM4.

	B Thickness (cm)											
	0 - 20			20 - 40			40 - 60			60 - 80		
	% Stone (0-25 cm)											
slope %	0 - 10	10 - 20	20 - 30	0 - 10	10 - 20	20 - 30	0 - 10	10 - 20	20 - 30	0 - 10	10 - 20	20 - 30
0 - 10	14		16	18								
10 - 20	12		14	16	18		18					
20 - 30			10	12	16	18	16			20		
30 - 40					12	16	14	18		16		
40 - 50						12		14	18	14		

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; B thickness = thickness of the B horizon; % Stone (0-25cm) = percent stones in the top of the soil pit (0 to 25 cm); Slope % = percent slope.

Table 46. Generalized site index prediction table for the glaciofluvial landform using equation GF5.

	Depth to Average Rooting (cm)											
	0 - 10			10 - 20			20 - 30			30 - 40		
	B % Silt											
DMRL (cm)	0 -15	15-30	30-45	0 -15	15-30	30-45	0 -15	15-30	30-45	0 -15	15-30	30-45
0 - 25		14		14		16	16				16	
25 - 50				16				18		18		
50 - 75		16	18		18				20		20	
75 - 100	16	18	20			20	18	20	22			22
100 -125			22	18	20	22				20	22	

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; depth to Average Rooting = average depth of rooting. B % Silt = percent silt in the B horizon; DMRL = depth to moisture restricting layer (i.e. coarse sandy subsoil, mottles, gley, water table, bedrock, carbonates or basal till).

Table 47. Generalized site index prediction table for the moraine landform using equation M3.

Maxroot (cm)	Pore Pattern 0		1		2		3	
BC %SAND	70	50	70	50	70	50	70	50
BC % Silt	20-40	40-60	20-40	40-60	20-40	40-60	20-40	40-60
30 - 50	20	20	18	20	18	18	18	18
50 - 70	20	20	18	18	18	18	16	16
70 - 90	20	20	18	18	16	18	16	16
90 - 110	18	20	18	18	16	16	14	14
110 -130	18	20	16	18	16	16	▨	14

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; BC% Sand = percent sand in the BC horizon; BC% Silt = percent silt in the BC horizon; maxroot = depth to maximum rooting.

BC %sand = 90% (BC %silt = 10% by default)

Maxroot (cm)	Pore Pattern 0	1	2	3
30 - 50	20	18	18	18
50 - 70	20	18	18	16
70 - 90	18	18	16	16
90 - 110	18	16	16	14
110 -130	18	16	14	▨

where SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; maxroot = depth to maximum rooting.

Table 48. Generalized site index prediction table for the combined bedrock-glaciofluvial landform using equation BRGF3.

Maxroot (cm)	AVGROOT (cm)								
	0 - 10			10 - 20			20 - 30		
	B cf% Cobbles + Stones								
	0 - 10	10 - 20	20 - 30	0 - 10	10 - 20	20 - 30	0 - 10	10 - 20	20 - 30
15	14	16	18	12	14	16	10	12	14
30	16	18		14	16	18	12	14	16.4
45	18			16	18		14	16	18
60				20			18	20	
75							20		

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; maxroot = depth to maximum rooting; avgroot = depth to average rooting; B cf % Cobbles + Stones = percent cobbles and stones in the B horizon.

Table 49. Generalized site index prediction table for the combined bedrock-moraine landform using equation BRM3.

	% SLOPE														
	0 - 10			10 - 20			20 - 30			30 - 40			40 - 50		
	A% gravel+cobbles														
BR (cm)	0 - 20	20 - 40	40 - 60	0 - 20	20 - 40	40 - 60	0 - 20	20 - 40	40 - 60	0 - 20	20 - 40	40 - 60	0 - 20	20 - 40	40 - 60
0 - 15	14	12	10	14	12	▨	14	12.	▨	12	10	▨	12	10	▨
15 - 30	16	14	12			10			▨	14	12	▨			▨
30 - 45				16	14	12	16		10			▨	14	12	▨
45 - 60	18	16	14					14	12	16		10			▨
60 - 75				18	16	14					14	12	16		10
75 - 90	20						18	16	14					14	12

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; slope % = percent slope; A% gravel+cobbles = percent gravel plus percent cobbles in the A horizon; BR = depth to bedrock (cm).

Table 50. Generalized site index prediction table for the combined lacustrine landform using equation L5.

	B % rooting abundance								
	0 - 7.5			7.5 - 15			15 - 22.5		
	BC Root Size (cm)								
Depth to C horizon (cm)	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
0 - 50	18		16	18	16	14	16.6	14.9	13.2
50 - 100		16	14	16	14	▨	15.1	13.4	▨
100 - 150	16	14	▨	14	▨	▨	13.5	▨	▨
150 - 200	14	▨	▨	▨	▨	▨	▨	▨	▨

where: SI = site index (SI_{BH50}) is total height of dominant and codominant trees at 50 years breast height age; B % rooting abundance = percentage of roots in the B horizon; BC root size = size of roots (cm) in the BC horizon; depth to C horizon = depth of soil above C horizon.

AREA OF APPLICATION

Northeastern Ontario

Plots for this investigation were located across a broad range of soil, topography and site-quality in northeastern Ontario. The soil-site equations developed are applicable to natural stands that are fully-stocked, disease-free, and greater than 50 years breast-height age. These equations apply to bedrock-moraine, glaciofluvial, and moraine soils; there were not enough plots on bedrock-glaciofluvial, lacustrine, alluvial, and colluvial soils, so equations here do not apply to these soil groups.

Plots were not randomly located, but were subjectively selected in an attempt to assess the full range of site-quality, soils, topography, and geography of northeastern Ontario. Statistically, the results of this study apply only to the conditions sampled in the selected 76 site plots. However, it may be assumed that the results of this study may apply more generally to bedrock-moraine, glaciofluvial, and moraine soils of northeastern Ontario. This assumption was supported by randomly selected check plots, used to test the accuracy of prediction of regression equations, based on the computation plots.

Combined Northeastern and North Central Ontario

The combining of northeastern and north central Ontario data resulted in acceptable jack pine soil-site equations for the bedrock-glaciofluvial, bedrock-moraine, and lacustrine landforms. These combined equations have a much wider area of application than Schmidt and Carmean's (1988) equations for north central Ontario, or the author's equations for northeastern Ontario.

However, combining data from northeastern and north central Ontario for glaciofluvial and moraine landforms resulted in unacceptable equations.

Equations for combined bedrock-glaciofluvial and combined bedrock-morainal soils are very good, despite the large geographic area represented by the two data sets. This is probably because the same soil variables are closely related to site-quality in both areas. Bedrock soils have only one metre or less of soil, and usually only two soil horizons (i.e. A and B), thus there are fewer soil variables, increasing the likelihood of having the same soil variables correlated with site-quality in both areas.

Unfortunately, the combining of data drastically decreased the precision of the deep glaciofluvial and moraine equations, thus these two landforms have unacceptable equations when combined. This low precision supports the observation that glaciofluvial and moraine soils vary greatly, and that soil conditions are probably different between northeastern and north central Ontario. Therefore, Schmidt and Carmean's (1988) glaciofluvial and moraine equations should be used in north central Ontario, and in northeastern Ontario, the author's glaciofluvial and moraine equations should be used instead of the combined equations.

Pooled Northwestern Ontario

The pooling of northwestern Ontario data with northeastern and north central Ontario data also resulted in unacceptable equations for glaciofluvial, lacustrine, and moraine landforms. The lacustrine equation is close to being acceptable; possibly, establishment of additional lacustrine plots in northwestern Ontario could result in sufficient data for developing an acceptable soil-site equation. The glaciofluvial and moraine landforms had poor precision values, and it is obvious that acceptable combined equations are presently impossible. These results again indicate that glaciofluvial and moraine soils differ greatly for different regions of northern Ontario. More data are needed for glaciofluvial and moraine soils in northwestern Ontario, to provide sufficient data for separate soil-site analyses.

No soil-site equations were developed for northwestern Ontario, because only a few plots were available for this region. Using equations developed in other regions for predicting site index on the few northwestern Ontario plots gave poor results, thus indicating that equations developed in other regions were not applicable to northwestern Ontario. Possible reasons why equations developed in other regions are not applicable to northwestern Ontario are:

1. the geographic range across northern Ontario is too great;
2. there are climatic differences between regions which affect site-quality differently on identical soils;
3. there are differences in site-quality between the regions that cannot be explained by soils;
4. soil variables related to site-quality differ between northeastern, north central, and northwestern Ontario; and
5. possible genetic or autecological differences for jack pine occur in different geographic areas of northern Ontario.

RECOMMENDATIONS FOR FUTURE RESEARCH

1) Establish at least 20 additional bedrock-glaciofluvial, 20 bedrock-moraine, and 20 moraine soil-site plots in northeastern Ontario. This would increase the sample size for each of these landforms, thus regression equations could be re-computed and tested against check plots.

2) Establish at least 100 plots in northwestern Ontario for the development of valid soil-site equations for this area. This additional data and resulting soil-site equations could then be pooled with data from other regions, thus providing a comprehensive comparison to equations for north central and northeastern Ontario.

3) Develop an improved methodology for assessing the coarse fragment content of moraine soils. Some improved estimation methodology may further strengthen and refine the correlation between coarse fragment content and site index. An unbiased, reliable and accurate classification system would assist future soil-site studies by better relating site index variation to coarse fragment content on moraine landforms.

4) Separate moraine soils into two groups: i) moraine soils with 10% or greater coarse fragments; and ii) sketetal-structured moraine soils. It is the author's opinion that there will be different significant soil variables for each of these two soil populations, increasing the equation precision of each type of moraine.

5) Stratify lacustrine soils into two groups: 1) lacustrine clays; and 2) lacustrine-moraine soils. These two groups probably represent distinct groupings, just as the bedrock-glaciofluvial and bedrock-moraine soils are two different groupings.

6) Measure percent rooting abundance in the L, F and H organic layers. These measurements could also be stratified by a root size class, or classify the roots as primary, secondary and tertiary roots. There are probably some strong correlations between site index and organic rooting.

7) Future FEC and growth and yield sample plots, and othjer field sampling should provide for additional quantitative soil variables. Soil variables found to be closely related to site-quality by Schmidt and Carmean (1988), LaValley (1991), Li (1991), and the author, should be included in these FEC soil cards. These important soil variables include depth to root restricting layers, effective rooting depth, and coarse fragment content.

8) Jack pine permanent sample plots must be established and periodically measured in order to clarify the link between jack pine site index and jack pine volume growth over time. This thesis quantifies the link between soils and site index, and further study is needed to quantify this additional linkage.

9) Researchers need better statistical approaches (other than multiple regression with dummy variables and multiple range tests) to integrate quantitative and categorical (i.e. qualitative) data.

10) Confirm the suitability of the soil-site equations presented in this thesis with other field-based soils data.

11) Explore linking soils work such as this thesis to spatially-based information from soil maps and surficial deposit maps.

12) Link both Schmidt and Carmean's (1988) soil-site equations and the combined northeastern and north central Ontario soil-site equations to projects such as the Rinker Lake Research Area (Sims and Mackey 1994).

CONCLUSIONS

The objectives of this thesis were to:

1) provide soil-site equations for jack pine in northeastern Ontario;
2) determine the soil features that are significantly related to the height growth of jack pine;
3) compare soil-site relations in northeastern Ontario with those produced by: a) Schmidt and Carmean (1988) in north central Ontario; and, b) Jackman (1990) in northwestern Ontario; and
4) determine if the comparison to other regions leads to the conclusion that the soil-site relations are essentially the same between regions. If so, new soil-site equations applicable to all areas of northern Ontario will be computed based on a pooled data set from all regions.

All four of these objectives were met, as detailed below. Additional insights on categorical soil and topographic data were also discovered.

Objective 1

Jack pine soil-site equations were developed for northeastern Ontario, based on a total of 76 plots. These equations related features of soil and topography to site index, using multiple regression techniques. Site index (SI_{BH50}) at breast height age 50 years was used as the dependent variable, and 119 soil and topographic values were considered as possible independent variables. An initial regression equation was computed combining all 76 plots, but this equation was found to have an unacceptably low R^2 value. Data were then stratified into bedrock-moraine, glaciofluvial, and moraine landform groups and R^2 values of 0.78, 0.51, and 0.59 were obtained, respectively, for these three landforms. No equation was possible for the lacustrine landform, since only six plots were available, thus too few plots existed for preliminary regression analyses.

Objective 2

Soil features that were significantly related to the site index of jack pine in northeastern Ontario are as follows:

Equation BRM4	i) slope percent; ii) B horizon thickness; and iii) percent stones in top 25 cm of horizon
Equation GF5	i) depth to average rooting; ii) depth to moisture restricting layer (DMRL); and iii) percent silt in the B horizon
Equation M3	i) depth to maximum rooting; ii) pore pattern; iii) percent sand in the BC horizon; and iv) percent silt in the BC horizon

Categorical soil, vegetation and topography classifications from northeastern Ontario were tested for their ability to stratify site index into statistically different groups. The predictive capability of the variables were greater when the data were unstratified, than if the data were stratified into landform groups. This improves the area of application and the ease of utilizing these variables as stratifiers of site index. Ecosystem classification variables stratified plots into groups having average site index values significantly different from other groups.

Objective 3

Schmidt and Carmean's (1988) site index equations for north central Ontario were tested to evaluate their accuracy in estimating site index in northeastern Ontario. Results indicated that these equations did not accurately predict site index for the plots located in northeastern Ontario. However, the bedrock-moraine equation almost met the $P < 0.05$ croteria, as this equation's probability level was 0.06. All other landforms had very high probability levels, and therefore predicted site index very poorly.

Objective 4

The 76 sample plots from northeastern Ontario were combined with Schmidt and Carmean's (1988) 131 plots. Again, initial regression equations combining all soils were found to have unacceptably low R^2 values. Regressions had R^2 values of 0.84, 0.55, 0.37, 0.57, and 0.24 when plots were stratified into bedrock-glaciofluvial, bedrock-moraine, glaciofluvial, lacustrine, and moraine landforms, respectively. These analyses showed that valid soil-site equations could be developed for northeastern and north central Ontario combined, except for glaciofluvial and moraine landforms.

The northeastern, north central Ontario (Schmidt and Carmean 1988) and combined site index prediction equations were tested to evaluate their accuracy in predicting site index in northwestern Ontario. All of these equations predicted site index poorly for the northwestern plots, as all sites over-estimated site index. This suggests that site-quality for jack pine in northwestern Ontario is lower than northeastern and north central Ontario. Possible reasons for lower site quality in northwestern Ontario are the climatic influence of less rainfall, a shorter growing season, and genetic differences in jack pine between these three areas.

Pooling northwestern Ontario data with northeastern and north central Ontario data resulted in regression equations for the glaciofluvial, lacustrine, and moraine landforms that had unacceptably low precision. These results suggest that jack pine site-quality in northwestern Ontario is related to different soil and topographic variables than in northeastern or north central Ontario. Soil-site equations exclusively for northwestern Ontario are needed for accurately predicting site index of jack pine in northwestern Ontario. Possible reasons why equations combining data from other regions could not accurately predict site index in northwestern Ontario are:

1) the geographic range across northern Ontario is too great;
2) there are climatic differences between regions which affect site-quality differently on identical soils;
3) there are differences in site-quality between the regions that cannot be explained by soils;
4) soil variables related to site-quality differ between northeastern, north central, and northwestern Ontario; and
5) possible genetic or autecological differences for jack pine occur in different geographic areas of northern Ontario.

Results from this soil-site study in northeastern Ontario, and comparisons with results from north central Ontario (Schmidt and Carmean 1988), showed that the precision of soil-site equations are dramatically increased by stratifying the data into landform types. This result also was found by other site-quality studies in north central Ontario (Schmidt and Carmean 1988, LaValley 1991, and Li 1991). The soil features consistently related to site-quality in north central Ontario (Carmean 1994), as well as other regions (Coile 1952), are soil features that influence the quality and quantity of growing space for tree roots (Coile 1952). Several topographic variables also were related to site index of jack pine in northeastern Ontario.

Results from this soil-site study apply only to northeastern Ontario, and to the landform and topographic conditions within this area. However, independent testing has shown that north central Ontario (Schmidt and Carmean 1988) data can be pooled with northeastern Ontario data for the bedrock-glaciofluvial, bedrock-moraine, and lacustrine landforms.

It is important to note that the soil-site equations are only correlations and not cause and effect relationships. Soil variables found to be highly correlated to site index of jack pine, such as effective depth, coarse fragment content, and texture, may be considered as indicators of the true biological soil moisture and nutrient causative features that affect forest site-quality. Other soil, topographic, or climatic variables also may influence and interact with these highly correlated soil variables.

This soil-site study provides an indirect quantitative method of estimating site index on areas where jack pine stands or trees are lacking for direct site index measurements. These results complement the jack pine site index curves developed by Lenthall (1986) and Niznowski (1994) for direct measurement of jack pine site index.

The site index equations and tables developed by this study also can be used to develop soil or vegetation systems designed for classifying forest land productivity. Forest management programs such as prime land management and site classification can utilize these results for designing forest land classification units based on easily identifiable soil and topographic features.

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APPENDICES

APPENDIX I

FIELD TALLY SHEET

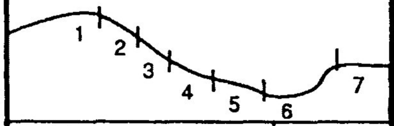
date (D/M/YR) | |	name(s) LEBLANC	site index bh tot	# sample trees	mode of dep BR GF M L	Plot #

ME MG MH	GD GE GK GO	LB LD LP	AP	CS CT CW	ED	OT	RL RN RP RR /R

sample #	horizon	depth	texture	color	mottles				structure			consist.	boundary	c. frag. (%)				roots	
					color	ab %	si (cm)	co	grade	class	kind			total	gravel	cobble	stones	ab %	si (cm)

TOPOGRAPHY	
slope length (m)	
upslope length (m)	
slope (%)	
aspect (azimuth)	
site surface shape convex str concave	

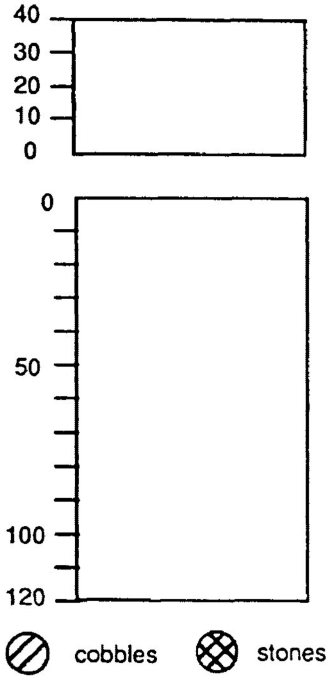
SITE POSITION



moisture regime	
drainage class	
pore pattern	
family particle size	
forest humus form	
soil classification	
excavation method (cm) shovel auger	
STRATIFICATION	
soil stratified (y/n)	
P.S.D (cm)	
lenses	
bands	

DEPTH TO . . .	(cm)
bedrock	
water table	
seepage	
carbonates	
faint mottles	
distinct mottles	
prominent mottles	
grey gley	
dense rooting	
avg. rooting	
maximum rooting	
Microtopography (1-7)	
FEC Soil Type	:
FEC Veg Type	:
Claybelt FEC O. G.	
surface stones (%)	
surface bedrock (%)	
cobbles-top	
cobbles-bottom	
cobbles-total	
stones-top	
stones-bottom	
stones-total	
depth to silt lenses	
depth to basal till	

schematic soil profile



COMMENTS:

date (D/M/YR)	Name(s) NIZNOWSKI & LEBLANC	NOEGTS soil category	Actual soil category	plot #

topo map #	elevation (m)	latitude	longitude	FRI map #	stand #	composition

Soil Sample Numbers (1) (2) (3) (4) (5)	site index (m) bha tha	# sample trees	photos roll # picture #

LOCATION MAP:

N

NOEGTS map #

N

face

pit

tree no.	total height of tree (m)	height of last cookie (m)	age (years)
1			
2			
3			
4			

COMMENTS:

LAB ANALYSIS RESULTS

Lab #	Final (y/n)	Horizon	Depth (cm)	Texture	cGr	Gr	Vcs %	cs %	ms %	vfs %	sand %	silt %	clay %	pH	CaCO3	Org Mat