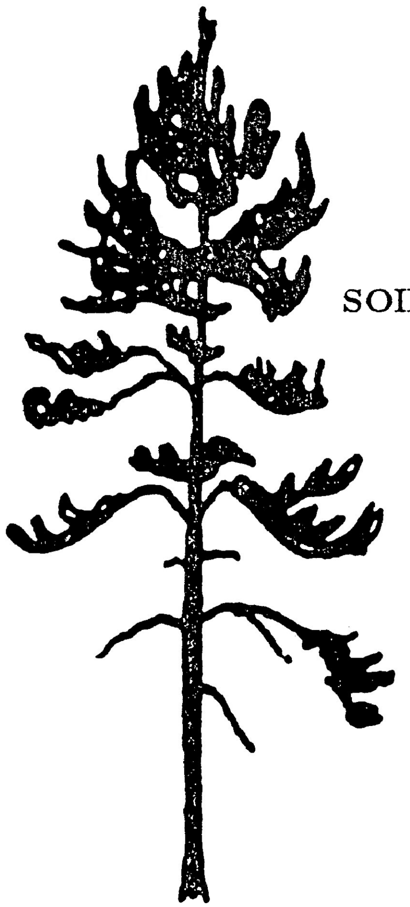

SOIL-SITE RELATIONS FOR JACK PINE

IN

THE THUNDER BAY AREA

by

Margaret G. Schmidt (C)
February 1986

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Margaret G. Schmidt

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ABSTRACT

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Keywords: bedrock, glaciofluvial, jack pine *(Pinus banksiana* Lamb.), lacustrine, moraine, site index, site quality, soil, soil-site, topography.

Site index of natural jack pine *(Pinus banksiana* Lamb.) in the Thunder Bay area was related to features of soil and topography using multiple regression analyses. Site index (SI, height of jack pine trees at 50 years from breast height) was used as the dependent variable and 129 soil and topographic variables were considered for the analyses. Due to problems associated with numerous independent variables, multicollinearity, and highly variable soil groups, the four preliminary regression equations computed from 95 plots could not be accepted as valid equations. The final analyses limited the number of independent variables considered for analyses and landform types were more precisely defined. The "best" final regression equations explain 83, 65, 65, and 75 percent of the variation in SI for bedrock, morainal, glaciofluvial, and lacustrine landforms, respectively. The variables included in the bedrock equation are depth to bedrock (DBR), and coarse fragment content of the A horizon (CFRAGA). The variables included in the moraine equation are depth to a restricting layer (DRL), percent clay in the A horizon (CLA), and coarse fragment content of the C horizon (CFRAGC). The variables included in the glaciofluvial equation are depth to a moist restricting layer (DMRL), and percent slope (SLOPE). The variables included in the lacustrine equation are thickness of the A horizon (THA), and pH of the BC horizon (PHBC). The final regression equations for bedrock, moraine, and glaciofluvial sites predict SI reasonably well for 15 check plots.

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INTRODUCTION

Forest history shows that initially foresters are primarily harvesters of trees (Rowe, 1962). The foresters' role remains that of a tree harvester as long as natural forests are plentiful. As these natural forests become depleted, foresters are faced with the challenge of regenerating and managing new forests to sustain wood industries that were originally dependent upon natural forests.

Many factors influence the intensity of management that can be profitably applied to forest land. Such factors include: markets, labour supply, accessibility, and site quality (McLintock and Bickford, 1957). When these factors are favourable, more intensive forest management is economically feasible. Within the limitations set by markets, labour, and accessibility, the potential productivity of the site influences the level of management that can be economically practiced.

In most forested areas there is a wide range in the productive capacity of the land. Some land is so poor that a forester has little hope of gaining any return from investments in time and money (Carmean, 1975). Other land is much more productive and thus more profitable for management. Since the site quality of forest land varies and better land produces greater yields of wood, productive forest lands should be considered first for more intensive management (Carmean, 1982).

The same forest land can produce a different quantity of yield depending upon the tree species that is selected for management. Thus site quality is species specific. Many factors should be considered when choosing a species for a particular site. One important factor is the productive potential of the species for a particular site (Carmean, 1975).

The preceding discussion reveals that the first step in selecting the most productive and valued species for a particular area is the estimation of the productive capacity of the land for the various alternative species. Comparisons can then be made of the estimated potential yield and value of various species so the most productive and valued tree can be selected for each area of land (Carmean, 1975).

A variety of methods have been developed to estimate forest site quality (Carmean, 1975). Three major systems considered in the United States use: (1) volume as an index of site; (2) "forest site types" ; and (3) height growth as an index of site. Site index based on height growth has become the most widely accepted method of site quality evaluation.

Site index is used directly to estimate site quality in older forest stands and as a standard for developing indirect methods of site quality evaluation. Direct methods of estimating site index include: site index curves, site index comparisons between species, and growth intercepts. Indirect methods of estimating site index include: plant indicators, physiographic site classification, synecological coordinates, soil surveys, and soil-site evaluation (Carmean, 1975; 1982).

Of all the methods for indirectly estimating site quality, soil-site methods have received the most emphasis in the United States (Carmean, 1975). In general, soil-site methods involve using features of soil, topography, and climate for estimating site quality. The most common approach is to determine the relationships between site index of a given tree species and specific features of soil, topography, and climate by means of multiple regression analysis. Many studies concerning the relationship between site quality and site features have been made, in North America and Europe (Carmean, 1975; Hägglund, 1981).

Northwestern Ontario is almost through the stage where foresters are primarily harvesters of trees. The steady depletion of accessible natural forest has forced the Province of Ontario to face the challenge of more intensively managing the second growth forest. There are a number of species available for management in northwestern Ontario, including: jack pine *(Pinus banksiana* Lamb.), black spruce *(Picea mariana* (Mill.) B.S.P.), white spruce *(Picea glauca* (Moench) Voss), red pine *(Pinus resinosa* Ait.), balsam fir *(Abies balsamea* (L.) Mill.), tamarack *(Larix laricina (Du Roi) K. Koch)* trembling aspen *(Populus tremuloides* Michx.), and white birch *(Betula papyrifera* Marsh.). With more intensive management, exotics, such as European larch *(Larix decidua* Mill.), Japanese larch *(Larix leptolepis* (Sieb. and Zucc.) Gard.), Scots pine *(Pinus sylvestris* L.), lodgepole pine *(Pinus contorta* Dougl.), Norway spruce *(Picea abies* (L.) Karst.), and hybrid poplars *(Populus spp.)*, could be considered. The forest land of northern Ontario varies considerably as to its productive capacity for different species. Information about the productive capacity of the land for these alternative tree species would be a great asset to forest managers in northwestern Ontario.

There is little forest site quality information available for the boreal forest of northwestern Ontario. A site quality evaluation method commonly used involves the site curves of Plonski (1981). Plonski developed site curves and normal yield tables for black spruce, jack pine, aspen, white birch, tolerant hardwoods, white pine, and red pine. Plonski's site curves are based on older construction methods and minimum data, and no estimation of precision is given in Plonski's tables. More accurate site curves can be developed using newer construction methods. Currently a study is being carried out involving polymorphic site index curves for jack pine in the Thunder Bay area (Lenthall, 1985). These curves are based on stem analysis and non-linear regression models.

Jack pine is one of the most economically important and widespread forest trees in northwestern Ontario. Jack pine grows on a wide variety of sites including: rock outcrops; stony tills; glaciofluvial sands, and occasionally clay soils (Fowells, 1965). Lenthall (1985) found significant differences in the capacity of the land to grow jack pine, with site index (height of trees at 50 years from breast height age) ranging from 8.5 to 22.5 metres.

Plonski's or Lenthall's jack pine site curves can be used to estimate site index for land supporting even-aged, well-stocked, undisturbed stands. Much of the forest land of northwestern Ontario supports stands that do not contain jack pine, are uneven-aged, very young, partially or fully cut, or poorly stocked. Thus, estimates of site quality for jack pine cannot be obtained with the site index method. Forest managers need site index predictions on these lands as well as on lands having stands and trees suitable for directly estimating site index.

The soil-site method has been widely used in other areas to predict site index based on soil and topographic features. Accordingly, the goal of this study is to determine relationships between the site index of jack pine and features of soil and topography, using multiple regression analysis. Results of the analyses can be used for estimating site quality of forest lands where stands and trees are not suitable for directly estimating site index of jack pine.

LITERATURE REVIEW

HISTORY OF FOREST SITE QUALITY EVALUATION

The history of forest site quality evaluation in North America dates back to the beginning of the twentieth century. The need for a standard system of site quality evaluation for forest management was recognized in the period of approximately 1910 to 1925 (Mader, 1963b). A controversy arose over the methods to be adopted. At the time, the standard system in Germany was based on volume at 100 years (Roth, 1916). This system based on volume was accepted in principle in the United States, but did not appear to be satisfactory because few yield tables were available for the major forest types of the United States.

Three main bodies of opinion developed as to the most suitable standard of site quality evaluation (Mader, 1963b). The three standards suggested were: volume growth, site-types, and height growth. The Society of American Foresters recommended height as the most simple, and most easily measured indicator of site quality (Sparhawk *et al.*, 1923; Munn *et al.*, 1926). Thus height growth became widely accepted as the standard indicator of site quality.

The measure of site quality based on height growth is referred to as site index. Site index is defined by the Society of American Foresters as "a particular measure of site class, based on the height of the dominant trees in a stand at an arbitrarily chosen age" (Ford-Robertson, 1971). Fifty years is most often used as the index age in eastern North America and 100 years is used for the longer-lived species in western North America. Though various criticisms have been raised concerning the use of site index (Gaines, 1949; Vincent 1961; Mader, 1963b; Sammi, 1965), it is still generally accepted as the best indicator of site quality (Carmean, 1975).

Volume is recognized as the ultimate measure of site quality (Carmean, 1975). Thus site index is often related to growth and yield in terms of some measurement of wood (Doolittle, 1963). This is usually accomplished through the construction of yield tables where yields are given for various ages at various levels of site index (Carmean, 1975). Site index estimates for a particular tree species are often related to growth and yield tables for different stand areas and levels of site index. In this way, site index is used as an intermediate step toward the ultimate goal of predicting the capability of forest land to produce wood volume.

Forest site quality evaluation research and development has been widely conducted in North America. Coile (1952) reviewed the literature before 1952, and Carmean (1975) provided a comprehensive review of site quality evaluation work in the United States. Ralston (1964) reviewed the literature from the period of 1954 to 1964. Graney (1977) reviewed site quality relationships of the oak-hickory forest type in the United States. Hägglund (1981) reviewed literature on site quality published after 1973. Carmean (1982) reviewed site quality relationships for conifers in the Upper Great Lakes area of the United States and Canada.

In addition to aforementioned works, reviews and evaluations of various methods of forest site quality estimation are given by Coile (1948; 1952), Rennie (1963), Ralston (1964), Jones (1969), Carmean (1975; 1982), Shrivastava and Ulrich (1976), Pritchett (1979), and Spurr and Barnes(1980).

FOREST SITE QUALITY EVALUATION METHODS

Direct Estimation of Site Index

Site index is estimated directly from free-growing, uninjured dominant and codominant trees growing in fully stocked, even-aged stands (Carmean, 1975). Measurements of these trees are used with a family of height-age curves to estimate total height of trees at a specified index age. Thus, when suitable trees and accurate site index curves are available, directly measuring site index is a convenient way for estimating site quality.

Site index estimates for a particular tree species are often related to growth and yield tables for different stand areas and levels of site index. In this way, site index is used as an intermediate step toward the goal of predicting the capability of forest land to produce wood (Carmean, 1975).

Many factors aside from the quality of a site can influence site index. These non-site factors include: stand density, genetic variation, competing vegetation, diseases, and insects (Carmean, 1975; Ralston, 1964; Pritchett, 1979). Though tree height is usually independent of stand density, dominant trees of certain species growing in overstocked or understocked stands may have reduced height growth. Lynch (1958) and Alexander *et al.* (1967) developed separate site index curves for various stand densities of Ponderosa pine *(Pinus ponderosa* Laws) and lodgepole pine, respectively.

The amount of genetic variation in height growth is largely unknown for most commercial timber species and genetic variation cannot be measured in the field. Thus, within species variability in height growth due to genetics is often treated as a component of the residual error in site evaluation studies (Carmean, 1975).

Competing vegetation during the establishment of a stand may inhibit growth of trees. Errors in site appraisal due to effects of competing vegetation can be minimized to some degree by basing site index on years from breast height age rather than on total age (Ralston, 1964). Disease and insects can cause reductions in height growth and if undetected can result in biased site quality measurements.

Most older site index curves were constructed with the harmonizing procedure. Total height and total age measured for dominant and codominant trees in a large number of study plots were used to construct a single average regional height-age curve often referred to as a guiding curve. Curves for a range of poor and good sites then were proportionally fitted to this average curve (Carmean, 1975).

Site index curves portraying a more realistic pattern of tree height growth have been developed based on actual measurements of tree height growth. Measurements from permanent growth and yield plots, stem analyses, and internode data have been used together with nonlinear regression models for developing these more accurate site index curves. These curves, called polymorphic site index curves, portray the diverse height growth patterns often associated with differences in soil, topography and climate.

The species site index comparison method involves estimating the site index of one species based on the site index of another species (Carmean, 1975). This method is useful in stands where only one species is present, and where estimations of site index for other alternative species are needed. Paired site index estimations from two or more species are obtained from study plots; site index is determined preferably by stem analysis. Linear regression is then used to relate site index of one species with that of another.

The growth intercept method uses a period of early height growth as an index of site quality rather than the long-term height growth portrayed in site index curves (Carmean, 1975; 1982). The total length of the first three to five internodes produced after trees reach breast height is often used as the index of site quality. This method is used for conifers having easily recognized internodes marking annual height growth.

Indirect Estimation of Site Index

The presence, abundance, constancy of occurrence, and size of certain plant species have been used as indicators of forest site quality (Carmean, 1975). The plant indicator method involves identifying various plant communities and then determining the average site index associated with these plant communities.

Physiographic features have been used to subdivide forest regions into areas with similar climate, moisture, and nutrient status (Carmean, 1975). This method is based on a "holistic" concept of site in which the complex of land and forest features within particular regions are integrated. Hills "total site" classification for Ontario is such a system (Hills, 1952; 1960).

A system of forest site classification called the synecological coordinate method was developed by Bakuzis *et al.* (1962) in Minnesota. Environmental factors considered important for tree growth (moisture, nutrients, heat, and light) were rated for each tree species on a scale from one to five. Ecographs were then constructed relating tree and stand features to paired coordinates for the assigned ratings of environmental factors. Ecographs can be used to portray relations between site index and general stand and environmental conditions (Carmean, 1975).

Soil surveys have been used as a basis for estimating site quality in some forest regions. In the United States and in Canada, the priority lands for soil surveys have been agricultural lands with forest lands receiving little attention. More recently however soil surveys have been conducted on selected forest lands. In the United States average site index values have been determined for different soil types and are included in many soil survey reports. One major criticism is that many soil units for forested land are too broad, site index varies widely within these soil units, and thus these soil units have limited usefulness for site quality estimation (Carmean, 1975).

SOIL-SITE EVALUATION

Direct measurement of site index is only possible where suitable stands and trees are available for height and age measurements. Where stands are very young, poorly stocked, uneven-aged, partially or fully cut, or do not contain the desired tree species, alternative methods may be used to evaluate site quality. Soil, topographic, and climatic features can be used as a basis for indirectly estimating forest site quality. This method is commonly referred to as the soil-site method of site quality evaluation.

In general, the soil-site method of site quality evauation involves estimating site index based on various site features. The most common approach involves correlating site index estimated from many site plots with associated features of soil, topography, and climate using multiple regression analysis.

History

The relationship between various site characteristics and the long-term growth of trees has been a topic of study in Europe for many years (Czapowskyj and Struchtemeyer, 1958). In the late 1920's, foresters and soil scientists in North America became interested in the site factors that affected tree growth (Nash, 1963). Prior to that time, work involving soil and its relation to tree growth had been conducted mainly by soil physicists and soil chemists.

The first soil-site study in North America was reported by Haig (1929). This study concerned the relation between the site index of young red pine plantations in Connecticut and the "colloidal" content of various soil horizons. Haig concluded that the site index of red pine increased with an increase in the percentage of silt-plus-clay in the A horizon.

Another early soil-site study was made in Connecticut by Hicock *et al.* (1931). This study involved red pine plantations from 12 to 30 years of age, occurring on a wide range of soil types. Many more site attributes were measured in this study than in Haig's study. However, the only factors found to be notably related to site index were silt-plus-clay content and total nitrogen of the A horizon.

Turner (1938), another early soil-site worker, studied second-growth shortleaf pine *(Pinus echinata* Mill.) and loblolly pine *(Pinus taeda* L.) in Arkansas. He concluded that site index of these species was most closely associated with soil texture, depth to the B horizon, and slope steepness.

Coile (1948, 1952) has made a substantial contribution to the field of soil-site evaluation (Doolittle, 1963). Coile and his students conducted most of their soil-site work in the southern pine region of the United States from the middle 1930's to the 1960's. His main philosophy on the productive capacity of soils was that "site quality is largely determined by soil properties, or other features of site which influence the quality and quantity of growing space for tree roots" (Coile, 1952). Coile placed much emphasis on the importance of physical soil properties in determining site quality. He considered that available moisture is the most important factor determining site quality and that aeration and rooting space greatly influence water availability (Doolittle, 1963).

Coile (1948) recognized that site index was also affected by chemical soil properties. However, he felt that nutrient deficiencies were usually not as limiting as physical properties and that nutrient deficiencies would usually be reflected in various physical properties (Doolittle, 1963). He also realized that physical soil factors and topography are more easily recognized in the field than are chemical soil factors. Thus many early soil-site studies did not consider chemical soil properties, but focussed mainly on physical soil properties.

Lutz and Chandler (1946) as well as others did not agree with the idea that physical soil factors were all-important. Several studies have indicated the importance of certain nutrient elements as factors influencing site index. For example, Voigt *et al.* (1957) found that northern Minnesota soils with high levels of calcium, potassium, and nitrogen are more productive than soils with low levels of these nutrients. Many of the more recent soil-site studies have considered the effect of soil chemical properties on site quality.

Past work concerning soils and site have been reviewed by Coile (1948, 1952), Doolittle (1957), Della-bianca and Olson (1961), Rennie (1962), Ralston (1964), Van Dyne *et al.* (1968), Shrivastava and Ulrich (1976), and Carmean (1975, 1982). Burger (1972) reviewed the development and present status of forest site classification in Canada. Burger's review does not address the matter of site quality evaluation directly, but deals with the application of classification in site evaluation.

Wright and Van Dyne (1971) presented a critical reexamination of the multiple regression techniques used in site evaluation. Included in the review by Van Dyne *et al.* (1968) is a comprehensive tabular summary of the data from many studies showing relationships of site factors to vegetation productivity. Carmean (1975) presents a tabular summary of about 170 soil-site studies from the United States.

Site Factors Associated With Productivity

Many site factors influence the existing productivity of forest land. Biotic (biological) factors such as stand density, genetics, competing vegetation, diseases, and insects as well as disturbances from fire, wind, and man influence the existing productivity of a site. However, site quality evaluation is concerned with the potential productivity as opposed to existing productivity. Thus, we consider the potential yield of a species (or genotype) under a stated level of management, i.e. fully stocked, even-aged, undisturbed stands. The factors that influence the potential productivity of forest land are the abiotic factors. Abiotic factors that influence forest land productivity include: climate, topography, physical soil properties, and chemical soil properties. Most variables measured in soil-site studies fall within these categories. A discussion of the abiotic factors follows.

Climate

Climatic variation generally occurs gradually over rather great distances (Pritchett, 1979). Thus, except in areas of extremely irregular topography, climate rarely varies within small geographic areas (Gaines, 1949). In soil-site studies for large geographic areas, where substantial climatic variation is suspected, such variables as temperature, growing season sunshine and precipitation can be measured. One common method of describing climate is through geographical location. Variables such as latitude, longitude and altitude have proven effective in some soil-site studies (Hägglund, 1981). For expressing the effects of local microclimatic variation, topographic variables such as aspect, slope, and distance to ridge have also been used (Gaines, 1949; Hägglund, 1981).

Topography

Topography can exert a substantial effect on tree growth through local modification of edaphic and climatic variables such as moisture, light, and temperature (Pritchett, 1979). The position on the slope and the extent and degree of slope can influence both subsurface and surface movements of water (Coile, 1952). Lower slopes generally have a greater potential supply of moisture than upper slopes and ridges. In very flat locations, minor topographic variations may reflect effective soil depth over poorly aerated lower horizons (Spurr and Barnes, 1980).

The association between site quality and topography can be evaluated using various topographic features such as aspect, percent slope, and topographic position (Pritchett, 1979; Carmean, 1975; 1982). In general, aspect, topographic position, and slope steepness and shape are more important in areas having steeper slopes and pronounced relief.

Aspect is usually recorded as an azimuth from magnetic north. Forest growth is frequently best at a specific optimum aspect. Gaiser (1951) expressed the relation between site index and aspect by a sine wave transformation. This transformation implies that poorest sites are on southwest slopes and best sites are on northeast slopes, and site index increases or decreases in an even manner between these extremes. A cosine transformation has been used to express uneven relations between site index and aspect in studies by Carmean (1964; 1965), Beers *et al.* (1966), Lloyd and Lemmon (1968), and Hartung and Lloyd (1969). Stage (1976) proposed a method to calculate the combined effect of slope and aspect on tree growth. An interaction between aspect and slope steepness was used for expressing site quality relations for upland oaks in southeastern Ohio (Carmean, 1965).

Soil Physical Properties

Various soil physical properties are often related to tree growth. Such properties include: parent material, soil texture, percentage coarse fragments, soil structure, soil depth, soil moisture, water table depth, drainage, soil aeration, and soil colour (Carmean, 1975; Pritchett, 1979; Spurr and Barnes, 1980).

Parent material, a major contributor to the process of soil development, can have an indirect effect on tree growth (Pritchett, 1979) by influencing forest productivity through its effect on soil physical, chemical, and microbiological properties. The degree of this influence is modified by climate which influences the leaching of nutrients, accumulation of organic matter, and acidity of the soil. Parent material affects the mineral composition of soils which subsequently influences tree growth. Soils with a wide variety of minerals have been found to be more productive than those of less varied composition (Lutz and Chandler, 1946). Soils with a high percentage of heavy minerals or a low percentage of quartz are more productive than those with the proportions reversed (Gaines, 1949).

Where soils differ greatly in parent material origin, the analysis of site quality may be simplified by stratification of data into parent material classes (Ralston, 1964; Pritchett, 1979). However, the effect of soil parent materials is usually expressed indirectly through derivative properties such as soil texture and drainage.

Soil texture has been shown to be related to site quality (Gaines, 1949; Coile, 1952; Ralston, 1964; Pritchett, 1979) by influencing soil moisture, root development, nutrient availability, and soil aeration. The relationship between texture and tree growth is usually curvilinear if observed over the entire range of textural classes (Ralston, 1964). Tree growth generally increases as a function of moisture supply as silt and clay content increases to the point where air space becomes limiting. Then additional increases in clay content result in declining growth rate due to aeration difficulties (Pritchett, 1979). Poor aeration and poor drainage are often indicated by soil mottles or gley colours. Increased nutrient availability is generally associated with finer-textured soils (Pritchett, 1979).

Coarse material in the soil can affect tree growth due to its influence on rooting space, aeration, nutrient supply, and moisture relations (Ralston, 1964). A great amount of coarse fragments can cause a large reduction in effective soil volume available for tree roots; the resulting decrease in moisture, air, and nutrient supplies can adversely affect tree growth. Ralston (1964) suggests that moderate amounts of coarse fragments favour better aeration and deeper penetration of light rains, thus reducing evaporation losses and benefiting tree growth.

Content of coarse fragments (greater than 2 millimetre fraction) is usually measured in terms of percent gravel, cobbles, and stones, or combinations of these. Gravel content is often determined by laboratory analysis in terms of a percentage by weight of the soil and gravel fractions. Percent cobbles and stones are usually visually estimated as a percentage by volume of the various soil horizons or for the entire profile. Mader (1976) sieved a 45.4 kilogram soil sample through a mesh screen as a means for estimating percent coarse fragment content by weight.

Soil structure influences moisture relations, aeration, pore space, and permeability (Pritchett, 1979). However, soil structure is difficult to quantify, and further, soil structure may be altered by harvesting, thus soil structure has rarely been quantitatively related to site quality (Gaines, 1949).

Soil depth is directly related to soil volume and the volume of soil available to tree roots influences tree growth (Coile, 1952; Pritchett, 1979). Various measures of soil depth have been shown to be related to tree growth (Coile, 1935; Gaines, 1949; Pawluk and Arneman, 1961; Ralston, 1964; Stratton and Struchtemeyer, 1968; Spurr and Barnes, 1980). Increments of growing space for tree roots are generally more critical on shallow soils than on deeper ones

(Ralston, 1964), thus tree growth response to increasing root space usually is curvilinear.

Soil depth can be measured either for the entire soil body or for specific horizons. When the soil depth variable defines the "effective depth" of the profile for tree roots, soil depth functions are more easily interpreted. "Effective depth" is often measured as the depth to a restricting layer such as bedrock, water table, clay pan, or a horizon of reduced permeability to water and air (Ralston, 1964). Depth to water table is often measured directly or is inferred from measurements of depth to mottling, gley, or a hardpan layer.

Soil moisture has been viewed as the most important single factor in determining forest growth (Gaines, 1949). In general, site quality increases with an increase in available water supply, and then decreases when excessive water results in poor drainage and poor soil aeration.

The available water-holding capacity of a soil is determined largely by structure and texture (Pritchett, 1979). Thus, soil texture has been frequently used in soil-site studies as an estimator of water-holding capacity (Ralston, 1964). The use of soil texture to estimate water availability is complicated by the influence of texture on other soil properties such as soil aeration and nutrient availability (Pritchett, 1979).

Soil water supply has been characterized by various laboratory measurements of available water. Quite frequently pressure cell equipment has been used to estimate water retention at permanent wilting percent and field capacity (Ralston 1964; Pritchett, 1979).

Soil drainage as a factor in moisture relations has been shown to be related to site quality (Gaines, 1949). In general, poor drainage limits soil aeration and thus reduces site quality. In contrast, excessive drainage associated with shallow coarse-textured soils reduces tree growth because of temporary drought conditions. Soil drainage is usually recorded in terms of subjectively defined drainage classes, such as rapidly, well, and poorly drained.

Drainage class is most often inferred from profile morphology and landscape position (Pritchett, 1979).

The importance of various soil properties indicative of aeration has been cited frequently in studies of site productivity (Ralston, 1964). Lack of oxygen in soil prevents root penetration and exploitation of nutrients (Pritchett, 1979). Soil moisture regime is closely related to soil aeration since movement and supply of air is limited when soil voids are occupied by water (Ralston, 1964). Pore volume influences soil aeration, with large pore volume generally associated with good sites and small pore volume with poor sites (Lutz and Chandler, 1946).

Soil colour has been used as an indicator of other soil properties that influence tree growth. Soil colour in subsurface horizons is largely influenced by oxidation of some of the soil's mineral components (Auten, 1945). Oxidation is dependent on air, and air movement and supply is dependent on drainage. Thus, soil colour has been used as an indirect measure of soil drainage. For example, reddish colours indicate well drained and well aerated soils while, in contrast, mottling or gley colours indicate poorer drainage. Soil colour of the surface horizons can be an indicator of organic matter content with the darker colours indicating a greater organic matter content. Soil colour is usually recorded in terms of hue, value, and chroma using standard Munsell notation (Munsell Color Company, 1971).

Soil Chemical Properties

Though soil physical features have been given the most emphasis in soil-site work, it is generally recognized that soil chemical properties also affect site quality (Doolittle, 1963; Ralston, 1964). Several studies have indicated the importance of features such as nutrients, organic matter, and acidity to tree growth. However, in many cases site potential has shown better correlation with soil physical properties than with chemical properties (Einspahr and McComb, 1951; Gaiser, 1951; Coile, 1952; Gaiser and Arend, 1953; Beaufait, 1956; Trimble and

Weitzman, 1956; Doolittle, 1957; McClurkin, 1963).

Forest trees require the same elements for their growth as do other higher plants (Pritchett, 1979). Generally, hardwoods require more nutrients than conifers and pines require the least nutrients (Gaines, 1949). Nutrient deficiencies are uncommon in undisturbed forests largely due to the following factors: trees root deeply, trees are conservative nutrient cyclers, mycorrhizal roots extract minimally available nutrients from soils, and large amounts of nutrients are not removed by conventional harvesting methods or by volatilization associated with burning.

In general, site productivity studies do not emphasize fertility factors. However, nutrient relations still may be indirectly expressed by other variables such as depth, texture and organic content. (Ralston, 1964; Pritchett, 1979). Several investigators, however, have found that certain soil nutrients can be limiting for tree growth (Ralston, 1964). The elements found to exert the most influence on tree growth are nitrogen, phosphorus, potassium, calcium, and magnesium (Pritchett, 1979; Carmean, 1975).

Available nutrients can be approximated from chemical analyses of soil (Spurr and Barnes, 1980). These chemical analyses are often time-consuming and expensive, and further, variable forest soils often require large numbers of samples for dependable soil nutrient values (Mader, 1963a; Tarjan, 1984). These techniques employ nutrient extracting solutions developed for agriculture with unknown significance in relation to tree requirements (Ralston, 1964). Thus, it is quite difficult to diagnose the fertility of forest soils (Pritchett, 1979). Because of these soil analyses difficulties many investigators use foliar analysis of tree material for estimating nutrient levels (Spurr and Barnes, 1980).

Soil organic matter is often measured through laboratory analyses, but is sometimes visually estimated in the field (Ralston, 1964). Soil organic matter content has been correlated with site quality in several studies (Ralston, 1964). In coarse and medium-textured soils, an increase in organic matter content is often associated with an increase in the amount of available water (Coile, 1952). In general, increased soil organic matter results in increased moisture and nutrient supply and retention and in improved soil structure. Thus, greater amounts of organic matter are usually associated with better tree growth. However, the opposite trend may occur for poorly drained soils where increased organic matter may be associated with decreased organic decomposition and greater acidity.

Soil acidity has little direct effect on tree growth since most trees have a wide pH tolerance (Lutz and Chandler, 1946). However, soil pH is often associated with the availability of nutrients. At very low or very high pH values, toxic effects may occur for certain mineral elements (Gaines, 1949) and thus may indirectly affect tree growth.

Soil pH is either determined from the surface soil only or from each soil horizon. Yawney and Trimble (1968) stated that soil pH is not stable and that it can be greatly influenced, by changes in stand composition, especially in surface horizons. For example, converting a spruce stand to an aspen stand would raise the pH at the soil surface. Thus they felt that it would not be desirable to use soil pH as an estimator of site quality.

SOIL-SITE STUDIES FOR JACK PINE

Scattered soil-site studies for jack pine have been made in the Lake States and in Canada. These studies concern the relationship between the growth of jack pine in both natural stands and in plantations to factors of soil and the environment. These soil-site studies vary greatly including: (1) the size, type, and location of the study area; (2) the amount, and type of data collected; (3) the method of data analysis used; and (4) the results found.

Soil-site Studies for Jack Pine in Natural Stands

Northern Minnesota

Pawluk and Arneman (1961) studied forest soil characteristics and their relationship to jack pine growth in natural stands in northern Minnesota. Data were collected from eighteen 0.04 hectare plots in pure, even-aged stands. Site index values for three dominant and two codominant trees were obtained using Gevorkiantz's (1956) site index curves. Soil profiles were described to a depth of 0.61 metres and samples were collected for laboratory analysis. The soil attributes measured were: soil texture, moisture content, bulk density, cation exchange capacity, various nutrients, and soil pH.

The relationships between site index and soil properties were tested using linear and curvilinear regression analysis. The physical soil properties found to be significantly related to jack pine growth were: (1) content of very fine sand, silt and clay in the upper portion of the soil profile; and (2) available moisture holding capacity. The only closely related chemical property was found to be cation exchange capacity. This study revealed that the growth of jack pine in the study region was closely related to the characteristics of the soil which influenced fertility and available moisture holding capacity.

Frissel and Hansen (1965) compared site index and synecological coordinate values for natural jack pine stands in northern Minnesota. Data were collected from 58 stands in one area and 25 stands in another area. Multiple regression analyses revealed that moisture and nutrient regimes combined were significantly related to site index (R^2 = 0.36). Jack pine site index relationships were plotted within edaphic fields.

Pluth and Arneman (1963) conducted a study similar to that of Frissel and Hansen. One of the study objectives was to relate site index to synecological coordinates. Soil profiles were described, species lists made, and site index values determined for each of 38 plots in northern Minnesota. Data analysis revealed no relationship between the synecological coordinates and site index.

Northern Lower Michigan

Shetron (1969) studied individual soil taxonomic units in northern lower Michigan. Data were collected on 84 0.04 hectare plots in natural jack pine stands growing on outwash sands. Statistically significant differences in site index occurred between several soil taxa. The soil properties contributing to variation in growth were found to be: (1) depth to sandy materials having a high percent of particles finer than 0.25 millimetres; and (2) kilograms per hectare of phosphorus, potassium, and calcium in the A and B horizons.

Shetron (1972a) conducted a similar study to the previous one using data from 49 jack pine plots growing on eight soil taxa located in northern Lower Michigan. Better site index values on two soil types were correlated with shallower depths to finer textured lenses ($R^2 = 0.46$). For two soil taxa increased depth to mottling from 50 to 130 centimetres was found to be closely related to decreased jack pine growth ($R^2 = 0.80$). Jack pine was found to have significant differences in growth in five of the eight soil taxa.

Wisconsin

In northwestern Wisconsin, Shetron (1972b) investigated the relationship of native jack pine growth on three sandy soil series to selected soil and stand properties. Soil, topographic, and stand data were collected on 54 continuous forest inventory plots. No significant differences were found in jack pine site index between the three soil series. A significant difference was found when the soils were regrouped into coarse and fine soil units. The study results indicated that best jack pine sites are those with thick B horizons, a high percent of fine sands close to the surface, and low topographic positions. Separate prediction equations were developed for all plots and for each of the three soil series. The equation for the Omega series with an R^2 value of 0.85 is as follows:

$$Y = 52.3 - 0.388(X1) - 0.20(X2) \qquad \text{(L1)}$$

where Y = site index in feet

X1 = depth to maximum percent sands

X2 = thickness of B21 horizon.

Southern Michigan

Hannah and Zahner (1970) studied the influence of non-pedogenetic texture bands on the growth of 12 natural stands of jack pine and 18 red pine plantations. Soil pits were dug in each stand to expose discontinuous lenses, which rarely extended laterally for more than a few metres. Root proliferation was most pronounced where the bands occurred. Tree roots almost always penetrated and expanded within the thick till-like bands. Site index values were found to be significantly higher on soil with the till-like bands than on either sandy soils with deep texture bands or without bands. Hannah and Zahner concluded that forest production is nearly doubled on sites with maximum occurrence of bands. Apparently the texture bands play an important role in supplying water and nutrients to jack pine forests.

Northern Ontario

A study of the effects of site on natural jack pine growth in northern Ontario was conducted by Chrosciewicz (1963). The specific objective of this study was: "to determine the effects of soil moisture regime, soil texture, soil petrography, and regional macroclimate on height growth and diameter growth of dominant jack pine trees as represented by site indices at age 50 years."

Data were collected from pure, fully-stocked, undisturbed jack pine stands on uniformly-sorted, acid-podzolized sandy soils of aeolian, fluvial and glaciofluvial origin. The 43 to 97 year old stands were located in Hills (1960) Site Regions 4E, 4S, and 3W. Stem analyses were made for three to six dominant jack pine trees per plot. Soil pits were dug to a depth of 1.2 metres and probes were made to a depth of 2.1 metres. The following site attributes were recorded: texture, compactness, colour, petrography, depth to horizons, topographic position, ground water depth, and pH.

Chrosciewicz (1963) found that "site indices vary in relation to changes in the individual site factors and their combinations within each of the regions and between regions". The highest site indices were associated with: (1) soils having a soil moisture regime of 3 (moderately moist); (2) very fine sand having silty or loamy upper horizons; (3) silicious soil materials containing 30 to 40 percent basic intrusive and effusive rock particles; and (4) mid-humid, warm-boreal climates. The relationships between jack pine growth and the various site factors were not quantified.

Shea (1973) studied the growth and development of jack pine in relation to edaphic factors in northeastern Ontario. On each of 14 sample plots, stem analyses were made on two dominant and two codominant trees. Root form, distribution, and quantity were studied on each plot by excavating one dominant and one codominant tree. Soil samples were collected from all horizons of each soil profile associated with the excavated trees. Various soil physical and chemical properties were determined.

Due to the relatively small number of sample plots, no statistical analyses were made. The sites were grouped on the basis of similarities of site and growth characteristics into seven site types. A discussion of the above and below ground growth characteristics of the trees from each of the seven site types was presented. Hypotheses were formulated on the factors controlling jack pine growth and development. Shea produced a prediction model which showed that fluctuations in tree growth were correlated with soil moisture deficit.

Saskatchewan

Jameson (1963) studied the relationship of jack pine height growth and site types in the mixedwood forest section of Saskatchewan. Six site types were formed by grouping soil pore pattern and soil moisture regime values. Soil pore pattern was based on soil texture and structure. Soil moisture regime was based on soil profile development, the position on the slope, and the position of the ground water table as indicated by depth to and intensity of mottling. Two site types were fresh sites, three were sandy and gravelly, and one type consisted of dry sands.

Data were collected from 28 0.1 hectare plots in 70 year old, even-aged, undisturbed, pure jack pine stands. A detailed soil profile description was made to a depth of 1.2 metres. Plots were assigned to site types based on soil moisture regime and pore pattern. Soil samples were collected and analyzed for pH, texture, organic matter content, and cation exchange capacity. Total height and age measurements were taken on 10 dominant jack pine trees per plot. On each plot stem analyses were conducted on two of the ten dominant jack pine trees.

Jameson concluded that the three interrelated factors: soil texture, soil moisture regime, and soil nutrient regime, had the greatest influence on height. No statistical analyses were conducted as part of this study.

Soil-site Studies for Jack Pine Plantations

Northern Minnesota

Allison (1931) studied the growth of jack pine in northern Minnesota in a plantation growing on Hinckley loamy fine sand. The study was based on measurements of total height and volume growth using two representative 0.1 hectare sample plots in a 10 year old plantation. The growth of jack pine on the Hinckley loamy fine sand was compared to the growth of jack pine in another plantation where the soil was termed: "better sands and sandy loams".

Hinckley loamy fine sand is a gray loamy fine sand, with a coarse substratum. It is non-calcareous and is of glacial origin. The productivity on this soil type was considered to be low. Therefore, Allison was surprised to find that the growth of jack pine was more rapid in the very droughty Hinckley sand than it was on the "better sands and sandy loams". The trees in Allison's study area had been planted in the open, in furrows, whereas the trees on the "better sands and sandy loams" had not been planted in furrows. Allison felt that the furrows in his study area probably reduced the competition of other vegetation with the planted trees. This might explain the more rapid tree growth on the Hinckley loamy fine sand.

Wisconsin

The relationship of jack pine growth and soil factors in plantations has been studied in Wisconsin. Wilde *et al.* (1951) studied the yield and quality of jack pine planted for pulpwood on five different types of sandy soils. The five soil types were considered to vary in site quality; that is, in the ability to grow forest crops.

Soil and tree data were collected from 47 0.1 hectare plots. The age, average diameter, and current increment for the last 10 years were measured from 10 to 15 dominant trees per plot; site index was determined using the site index curves of Gevorkiantz (1947). Soil profiles were described and soil samples collected for laboratory analyses of fertility factors.

An analysis of the data revealed that the variation between yields of different plots on the same soil type did not exceed 10 percent. A comparison of growth data and soil analyses revealed that the aeolian sands and moss peat sites were less-productive due to: (1) a deficiency of absorbing colloids; (2) a lack of nutrients; and (3) impeded drainage. This study revealed general relationships between various sandy soils and jack pine growth in Wisconsin, however, these relationships were not quantified.

Wilde *et al.* (1964, 1965) made further studies of the growth of jack pine plantations in relation to the fertility of sandy soils in Wisconsin. They found that jack pine growth is strongly correlated with physical and chemical soil factors. Data were collected from 34 0.04 hectare plots in 16 to 30 year old plantations throughout Wisconsin. The diameters of all plot trees and the height of seven dominant or codominant trees were measured. The surveyed plantations were subdivided into three classes according to the following average annual height growth measurements: 23 to 33 centimetres (low); 34 to 43 centimetres (medium); and 43 to 58 centimetres (high). For each plot a soil profile was described and soil samples collected for laboratory analysis.

Simple correlations revealed that annual height growth was strongly correlated with: (1) cation exchange capacity; (2) soil texture; (3) organic matter content; and (4) total nitrogen, available phosphorus, and available potassium. Neither the contents of exchangeable calcium and magnesium, nor soil reaction were found to be statistically significant.

Multiple regression analyses were made using height growth as the dependent variable. The following are the most significant regression equations produced by these analyses:

$$Y = 10.2 + 3.68 \qquad R^2 = 0.468 \tag{L2}$$

$$Y = 9.9 + 2.77 + 0.033P_2O_5 \qquad R^2 = 0.547 \tag{L3}$$

$$Y = 8.07 + 2.43H + 0.031P_2O_5 + 0.22F \qquad R^2 = 0.588 \tag{L4}$$

Where:

Y = average annual height growth of dominants (inches)

H = organic matter content in percent

P_2O_5 = available phosphorus in lb./acre of P_2O_5

F = percent silt plus clay

Wilde (1970) further studied the results of the 1965 study and attempted to simplify and generalize the statistically significant relationships. He produced a single regression equation with two coefficients, one for pine and one for spruce. No R^2 value was given for this equation.

$$Y = 8.1 + 0.2F + 2.3H + 0.03P_2O_5 + 0.01K_2O \quad \text{(L5)}$$

Where:

K_2O = available potassium in lb./acre of K_20

The site index (I) of the trees were given by the formulae: I = 3.4Y for pine; I = 1.8Y for spruce.

Rawinski and Bowles (1980) studied soil properties related to jack pine height growth in northern Wisconsin. A 0.25 hectare block in the Nicolet National Forest was hand planted with containerized seedlings. The block contained four replications in a randomized complete block design with 16 plots in each replication and 16 seedlings planted in each plot at two metre spacings.

Two years after planting, soil samples were extracted from 17 randomly selected jack pine plots. The following soil properties were measured: organic matter content, texture, and pH. Average plot height growth was determined for each of the plots. The soil data were then regressed with the height growth data.

Greater amounts of soil organic matter were related to increased growth of jack pine and jack pine grew better on the coarser soil textures. Height growth was significantly poorer on high than on low microsites, however, soil properties were also significantly different, thus no specific conclusion could be made.

JACK PINE

Distribution

Jack pine is one of the most widely distributed conifers in North America (Fowells, 1965; Riemenschneider, 1982). It grows further north than any other pine and is the most widely distributed pine in Canada (Moore, 1984). Jack pine is native to northern New England, the Lake States, and much of Canada. The distribution of jack pine in Canada extends from Nova Scotia, across New Brunswick, Quebec, Ontario, and the Prairie Provinces to northern British Columbia and the Mackenzie Valley in the Northwest Territories (Moore, 1984).

Jack pine is an upland species that occurs in extensive, pure, even-aged stands, and in mixtures with other species; particularly spruce and poplar (Moore, 1984). It is one of the most intolerant trees within its range (Fowells, 1965). Jack pine is a pioneer species, maintained mainly by wildfire as a major component of the boreal forest (Foster and Morrison, 1976). It is confined to the boreal and northern forest regions except for a small area on the south end of lake Michigan (Fowells, 1965).

In general, jack pine grows in areas with very cold winters, warm-to-cool summers, rather low rainfall, level to rolling topography, and light sandy soils (Fowells, 1965). Jack pine is capable of growing on very dry, gravelly, or sandy soils where other species scarcely can survive. It grows most commonly on level to rolling glacial outwash plains, till plains, and bedrock outcrops; it rarely grows on clay soils, because of competition from other species.

Growth Characteristics

In the Upper Peninsula of Michigan, shoot elongation of jack pine began on May 10, leafing began a week later, winter buds formed in mid-July, and height growth stopped on September 5 (Kaufman, 1945). Usually root growth began within a week of the onset of shoot growth. The root system of jack pine growing on dry, sandy soils consisted mainly of laterals confined largely to the upper 45 centimetres of soil (Cheyney, 1932). Frequently, jack pine develops a tap root as a seedling and maintains it to maturity (Fowells, 1965).

In general, height growth of jack pine is not affected by stand density (Fowells, 1965). Most natural jack pine stands are understocked, but dense sapling stands with 10 000 to 40 000 or more trees do occur. Height growth in these very dense stands may be slightly depressed (Guilkey and Westing, 1956). In a spacing trial in Michigan, no significant difference in average height attributable to different spacings were found (Ralston, 1953; Rudolf, 1958). In Vermont, height growth was lower in the closer spacing of 0.61 metres square and variable at the other spacings of 1.21 metres square, 1.83 metres square and 2.44 metres square (Adams, 1928). Jack pine has a wide geographic range and thus has likely developed considerable genetic diversity (Fowells, 1965). Tests of jack pine have shown some genetic variation in a number of traits including height growth (Schoenicke, 1976; Riemenschneider, 1982). Williams and Beers (1959) found that seed source affects height growth of planted jack pine in southwestern Indiana. Significant seed-source related differences in height development were found in studies involving thirty Lake States sources of jack pine (Arend *et al.*, 1961).

As demonstrated by provenance tests at numerous locations, jack pine is highly variable in climatic adaptation (Yeatman, 1984). Growth of jack pine provenances is related to environmental gradients in length and temperature of the growing season and in latitude (photoperiod) associated with seed origin. The species shows clinal variation over these environmental gradients (Yeatman, 1974; Rudolph and Yeatman, 1982).

Growth and Yield

Other than tamarack, jack pine (in its native range) is the fastest growing conifer during the first 20 years (Fowells, 1965). In early years, jack pine frequently outgrows two of its common competitors, red pine and aspen (Hacker *et al.*, 1983; Shetron, 1975). However, red pine has more sustained later growth and builds up a large basal area. Alban (1978) reports a study where red pine had a greater mean annual increment on both a volume and a weight basis than did jack pine. Jack pine reached its maximum growth in 50 to 60 years, averaging 16.8 metres tall and 18 to 20 centimetres in diameter (Hacker *et al.*, 1983). On better sites, rotation age can be extended up to about 80 years without substantial reduction in growth rates.

Jack pine stands usually break down after 80 to 100 years on the best sites, and after 60 years on the poorest sites (Fowells, 1965). In northwestern Minnesota, occasional 185 year old vigorous jack pine trees have been found (Rudolph, 1958). The oldest tree known, found east of Lake Nipigon, Ontario, was 230 years old.

The information base concerning the growth and yield characteristics of plantation grown jack pine is relatively small (Beckwith *et al.*, 1983). Little data is available comparing jack pine plantation yields to yields from Ontario's natural forests (Moore, 1984). The usual approach of estimating plantation yields is to use Plonski's (1981) normal yield tables (Beckwith *et al.*, 1983). These tables were intended for application in normally stocked natural stands. The appropriate site class is determined using average height and age measurements. The tabular yield figure is adjusted by an estimate of stocking, usually in terms of basal area. Another approach involves the use of variable-density growth and yield tables (Evert, 1976).

The main drawback in using Plonski's yield tables with young jack pine plantations is that Plonski had few observations below 20 years of age (Beckwith *et al.*, 1983). Stem analyses techniques can be used to construct site-specific height/age curves for natural jack pine stands. These curves can be used with jack pine plantations until more data are available from older jack pine plantations.

Northern jack pine plantations may grow substantially better than natural stands (Beckwith *et al.*, 1983). Potentially, jack pine plantations can produce 10 to 15 percent more gross total volume than natural stands on the same site. The greater productivity of plantations is mainly attributed to rapid early growth.

Importance of Jack Pine

Jack pine was once considered a weed tree in the Lake States area, but it now is a leading species in the production of pulp and saw timber in the region (Riemenschneider, 1982). Jack pine is a major source of raw material for the pulp and paper industry of northern Ontario; ranking second only to spruce in annual volume cut (Morrison *et al.*, 1976). Jack pine ranks third in area behind spruce and poplar among the Crown production forests in the North Central Region of Ontario (Davison, 1983). In this region, jack pine represents 31 percent of the annual volume harvested and 40 percent of the annual area regenerated. Thirty percent of the jack pine is used for sawlogs and 70 percent for pulpwood (Davison, 1983).

"Jack pine has exceptional advantages for wood production and forest renewal within the boreal forests of Canada" (Yeatman, 1984). Extensive even-aged stands of jack pine are amenable to mechanized silviculture. In terms of rapidity of juvenile growth, relative freedom from disease or major insect pests, and ease of regeneration, jack pine has the highest potential for intensive forest management of all the northern Ontario coniferous pulpwood species (Morrison *et al.*, 1976).

METHODS

DATA COLLECTION

Study Area

The study area is located in northwestern Ontario, Canada, and lies north of Lake Superior and west of Lake Nipigon (Figure 1). The area extends from approximately 48° 07′ to 50° 22′ latitude and 88° 38′ to 90° 45′ longitude. This area lies completely within the Ontario Ministry of Natural Resources (OMNR) North Central Region , covering the entire Thunder Bay District and approximately one quarter of Nipigon District. The study area was arbitrarily determined on the basis of accessibility and feasible travel distance from Thunder Bay.

The climate of the study area has wide annual extremes of temperature, moderately low humidity, high levels of solar radiation, and moderate winds (OMNR, 1982a). Lake Superior and Lake Nipigon exert a slight cooling effect in summer, and a slight warming effect in winter on the adjacent land. Chapman and Thomas (1968) have divided northern Ontario into nine climatic regions. Most of the study area lies within the Height of Land Region described by Chapman and Thomas, but parts of the study area lie in the Superior and Rainy River-Thunder Bay Regions.

The geology, topography, and soils of the area have been described by the OMNR (1982a, 1982b). The bedrock in the area is Precambrian in age with much being overlain by surficial glacial deposits. Most of the bedrock is Early Precambrian , overlain by flatlying sedimentary rocks of Middle Precambrain age and intruded by igneous rocks of Late Precambrian age.

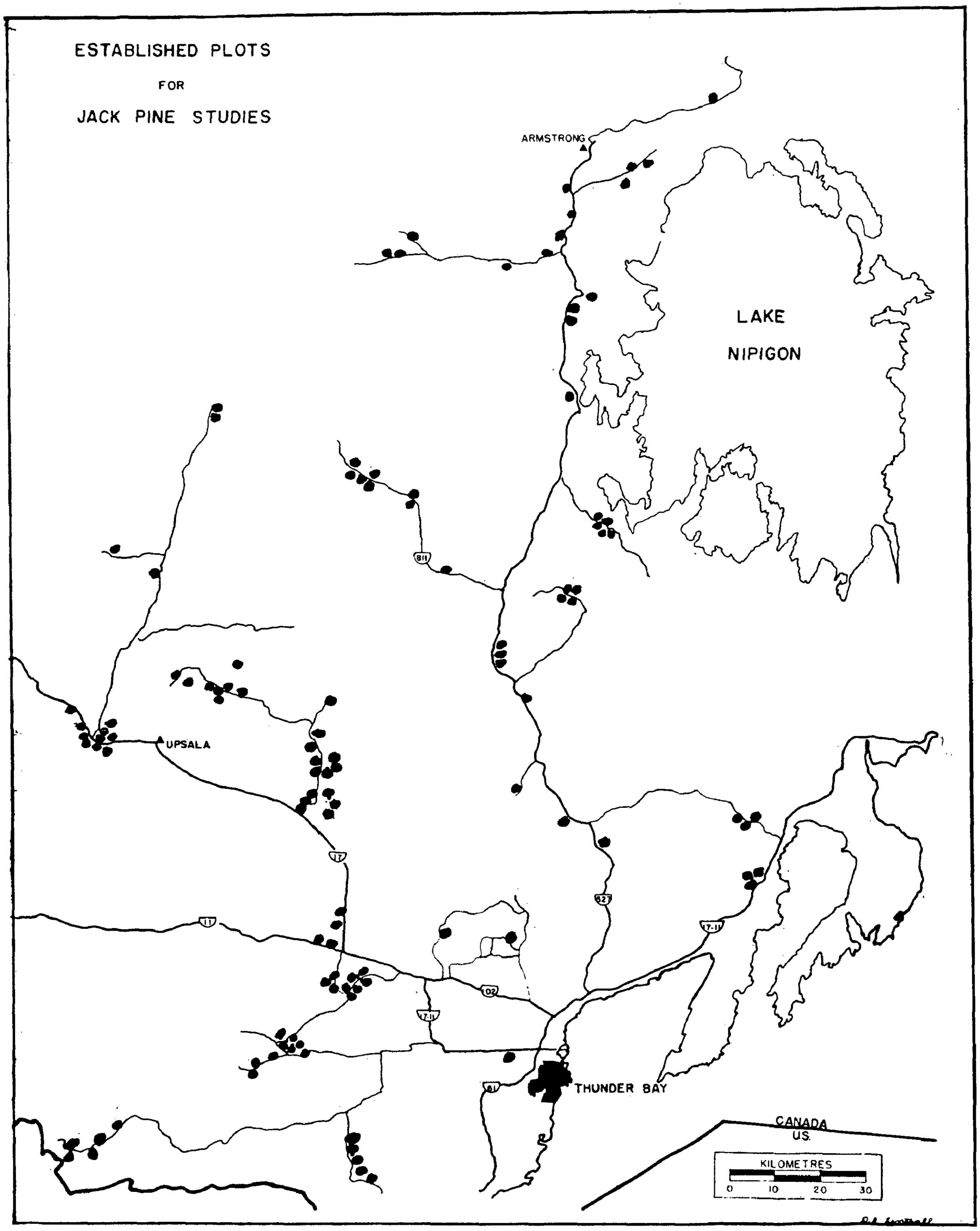

Figure 1. Location of jack pine soil-site study plots in the Thunder Bay area.

The most common soil parent material in the area is glacial debris of granite and granite-gneiss origin, occurring either as granite-derived till or in situ as bedrock (Crown *et al.*, 1978). Other parent material types are rocks of sedimentary and volcanic origins and their related tills.

The study area lies within the physiographic region of the Precambrian Shield (OMNR, 1982a). The original landscape of the Shield has been greatly modified by glaciation. Ice masses covered the area and produced the existing landscape during the last continental glaciation (Crown *et al.*, 1978). The weathered material that had accumulated prior to glaciation was removed and redeposited mainly as unsorted till over most of the area. The composition of the till depends on the nature of the bedrock over which the ice advanced.

As the glacial ice melted and retreated, post-glacial lakes were fed by glacial meltwaters. Relatively level lacustrine plains were formed by the deposition of fine-textured sediments in the lake basins. Both gray and red lacustrine clay plains were formed depending upon the type of shale from which the sediments were derived. Silt sediments and deltaic sands were deposited with these clays.

Coarse-textured sands and gravels were deposited on the edges of the shallow lakes and in stream beds fed from glacial meltwater. Sand and gravel kame deposits formed at the edge of the melting glacial ice. Similar deposits are also found in abandoned beaches and flood plains. Scattered peat bogs formed throughout the area in lowlying, depressional, and level areas.

Soil survey maps are not available for most of the study area. However, a general inventory of the soil resources of the Thunder Bay map sheet (52A) has been produced (Crown *et al.*, 1978). Thus, general soil survey maps, at a scale of 1:50 000 are available for the southeast corner of the study area. Ontario Geological Survey maps, at a scale of 1:100 000 are available for the entire study area (Gartner *et al.*, 1981). The legend for these maps is composed of four main components: parent material, topography, landform, and drainage. A report accompanies each map, containing a description of each terrain unit.

Most of the study area lies within the boreal forest region in which the principal tree species are jack pine, black spruce, white spruce, balsam fir, trembling aspen, and white birch (OMNR, 1982a; 1982b); the southern part of the study area lies within the Great Lakes St. Lawrence Region. The study area lies within part of five sub-regions: the Central Plateau, Upper English River, Superior, Nipigon, and Ontario Regions (Rowe, 1972).

Hills (1976) divided Ontario into 14 site regions based on thermal and humidity belts. Most of the study area is located within Lake Nipigon Site Region (4 Hdv) and part of Pigeon River Site Region (5 Hdv). The humidity class (Hdv or dry to very moist humid) is the same for both regions. The thermal class is higher for Pigeon River Site Region (5=hottest) than for Lake Nipigon Site Region (4=warm).

Plot Location

One hundred, nineteen study plots were located throughout the study area (Figure 1). Most of the study plots were located by Dr. W. H. Carmean of Lakehead University in the summers of 1981, 1982, and 1983. Some additional plots were located by Lenthall (1985). Due to the difficulties of getting equipment to the study plots, all plots were located within 300 metres of access roads. The plots were not randomly selected, but instead were located on major landforms and soils that represented the full range of jack pine site quality in the study area.

Plots were located in fully stocked, evenaged, pure jack pine stands, and in mixed stands containing dominant and codominant jack pine trees. The main stand selection criteria was the presence of dominant jack pine trees that appeared to have been free-growing and uninjured throughout their lives. In some cases, such as with shallow bedrock sites, understocked stands were accepted. All stands were at least 50 years in age. If the ages of plot trees varied by more than 10 years, the plots were abandoned as being uneven-aged. The dominant trees in the stand were examined for evidence of major injury, deformity, or past suppression. If such disturbance was visible the stand was not selected for study.

The study area is quite varied in soil and topographic characteristics. A simple landform classification was devised. Study plots were broadly classified on the basis of soil depth, as shallow soils (bedrock at less than one metre depth) or deep soils (bedrock at more than one metre depth). The deep soils were further subdivided into morainal, glaciofluvial, and lacustrine sites. The morainal sites consist of unstratified till with varying amounts of coarse fragments. The glaciofluvial sites were considered to be of glaciofluvial, fluvial or aeolian origin. They are predominantly stratified sands with little to no coarse fragment content. Lacustrine sites consist of stratified deposits of clay and silt.

An effort was made to obtain as many plots as feasible in each of the four landform types: bedrock, morainal, glaciofluvial, and lacustrine. Within each of these broad groups, plots were located on a range of topographic positions. Within stands, plots were located in areas that appeared to have relatively homogeneous soil and microtopographic conditions, thus minimizing variation of site quality within each plot.

Site Index Estimation

The plots used in this study were 119 of the total of 142 plots used by Lenthall (1985). Lenthall felled and sectioned three to five dominant or codominant jack pine trees on each study plot. The selected trees were sectioned at the base, 0.75, 1.3, and 2.0 metres, and at each one metre interval up to 13.0 metres, and at 0.50 metres thereafter.

Careful annual ring counts under illumination and magnification were made at each section point. Height-age curves were then plotted for each tree. The average age at each sectioning height was calculated, and then average height growth curves were plotted for each study plot. The average height of the site trees 50 years after they reached breast height were read from these curves; these are the values used as site index for this study. Breast height age was used rather than total age to reduce erratic early height growth that occurs below breast height. This erratic early height growth is usually unrelated to site quality (Carmean, 1978; Monserud, 1984).

Soil Data

Three one metre square soil pits were excavated on each study plot to a depth of one metre, or to bedrock. Care was taken not to disturb the litter layer and surface horizons along the edges of the pits. Each soil pit was located within two metres of a sectioned tree. If more than three site trees were sampled, one soil-pit was placed near the most centrally located site tree and the other two soil pits were placed near two other randomly chosen site trees.

A soil profile description was made for each pit according to standard Canadian methods (Bates *et al*, 1982; Canada Soil Survey Committee, 1978; Day, 1983). All observations were recorded on a tally sheet specially designed by the author for this study (Appendix I).

Representative depths of all mineral horizons (generally A, B, BC, and C) and organic layers (L, F, and H) were measured to the nearest centimetre. Boundary distinctness and form were evaluated and recorded. The following attributes were recorded for each horizon: texture class, soil colour, mottle description, soil structure, soil consistence, coarse fragment content, and root abundance.

Soil texture class for each horizon was estimated according to the guidelines and keys in the "Field Manual for Describing Soils" (Bates *et al.*, 1982). Soil colour was evaluated in terms of hue, value, and chroma by comparing moist soil samples with colour chips from a Munsell colour book (Munsell Color Company, 1971). Mottle colour, abundance, size, and contrast were recorded where appropriate. Primary soil structure was classified in terms of grade, class, and kind. Soil consistence was estimated for soil in a moist state.

The percentage of coarse fragments in each horizon was visually estimated where present. Area percentage charts (Bates *et al.*, 1982) were used to aid in the estimation of the content of gravel (2.0 to 7.5 centimetres), cobbles (7.5 to 25 centimetres), and stones (greater than 25 centimetres) in terms of percentages of the total horizon volume. The abundance of roots in each horizon was expressed as the number of visible fine roots (1 to 2 millimetres in diameter) in a 10 centimetre square area of the pit face.

Various depth measurements were taken including depths to bedrock, visible water table, water seepage, carbonates, mottles, grey gley colour, bottom of maximum rooting, and bottom of effective rooting. Depth to carbonates was estimated by determining at what depth dilute hydrochloric acid effervesced. Soil moisture regime and soil drainage class were determined using charts given by Bates *et al.* (1982).

Starting at the bottom of each soil pit, a composite soil sample was obtained from each of the four major horizons. Coarse fragments up to 7.5 centimetres in diameter were included in the samples. Sample size was approximately 0.5 litres (or 1.0 kilograms) for soils without coarse fragments and approximately 1.0 litres (or 2 kilograms) for soils containing coarse fragments. The soil samples from the major horizons of each of the three pits were mixed to obtain a composite sample for each horizon.

Site Description

The latitude and longitude of each study plot were determined from topographic maps. The topography in the general vicinity of the plot was described in terms of total slope length, upslope length, percent slope, aspect, site surface shape, and site position. Each plot was assigned to one of the following broad soil categories: bedrock, morainal, glaciofluvial, and lacustrine. Data were recorded on a tally sheet (Appendix I).

Total slope length and upslope length were measured to the nearest metre with a cloth measuring tape. Percent slope was measured with a Haga altimeter. Aspect was determined with the use of a compass and was recorded as an azimuth from magnetic north. Site surface shape was recorded as convex, straight, or concave. Site position was classified as either crest, upper slope, middle slope, lower slope, toe, depression, or level.

Averaging Plot Data

The various measurements made for each of the three pits were averaged to otbtain measurements for an "average" soil pit per sample plot. These measurements were recorded on a separate "average" plot tally sheet (Appendix II) and are the values that were used for further data analyses. A standard horizon designation method was used to facilitate the comparison of profile descriptions. For each plot, the four major soil horizons of the average soil profile were designated as A, B, BC, and C horizons.

LABORATORY ANALYSES

Air dried soil was passed through a two millimetre sieve. Sticks, bark, and foreign material were removed from the samples. The percent gravel was determined for samples containing coarse fragments (McKeague, 1978). The gravel remaining in the sieve was weighed and then discarded. The fine earth fraction was weighed and then mixed thoroughly in the sieve tray. Percent gravel was calculated according to the following formula:

$$percent\ gravel = \frac{weight\ of\ gravel \times 100}{weight\ of\ gravel\ plus\ fine\ earth} \qquad (L6)$$

A total of 420 soil samples were transported to the Ontario Institute of Pedology soil test laboratory in Guelph, Ontario. The following analyses were conducted: particle size analysis, soil reaction determination, and organic matter content determination. Nutrient analyses were not conducted due to time and money constraints.

Percentages of sand, silt, and clay were estimated by the pipette method (McKeague, 1978). The sand fraction was further subdivided into very coarse (1.0 to 2.0 millimetres), coarse (0.5 to 1.0 millimetres), medium (0.25 to 0.5 millimetres), fine (0.1 to 0.25 millimetres), and very fine (0.05 to 0.1 millimetres) sand fractions by passing it through a nest of sieves (McKeague, 1978).

Soil pH in 0.01 M $CaCl_2$ was measured for each sample. Percent organic matter for the top three horizons of each plot was estimated by the modified Walkley-Black method (McKeague, 1978). The methods as outlined by McKeague were followed with minor adjustments.

STATISTICAL ANALYSES

SPSSX (SPSS Inc., 1983) was used for data management and analysis on a Digital VAX 11/780 computer. The plotting capabilities of the statistical computing system Minitab (Ryan *et al.*, 1982) were also used on this computer. An interactive data analysis system named S (Beckers and Chambers, 1984) was used for analyses on a Digital VAX 11/750 computer.

Study Plot Stratification

The individual plots were classified into four landform types: bedrock, morainal, glaciofluvial, and lacustrine (described on page 36). Data analyses were then carried out for each of these four landform types. Twenty percent of the plots from each of the four landform groups were randomly selected to be used as check plots. The remaining plots were used for modeling.

Data were collected from a total of 119 study plots: 21 bedrock; 36 morainal; 44 glaciofluvial; and 18 lacustrine (Table 1). Data from these 119 plots were used for the preliminary data analyses. Twenty-four check plots were randomly chosen from the four soil

Table 1. **Number of study plots used in preliminary analyses.**

Landform Type	Total Plots	Check Plots	Computation Plots
bedrock	21	4	17
morainal	36	7	29
glaciofluvial	44	9	35
lacustrine	18	4	14
total	119	24	95

categories, leaving 95 plots for computation.

Summary Statistics, Scatterplots, and Simple Correlations

The dependent variable used in this study is the site index (SI) of jack pine. SI is the height in metres of dominant and codominant trees at 50 years breast height age (Table 2).

Summary statistics including the mean, standard deviation, minimum, and maximum values for the dependent variable and for the independent variables were computed. Normal probability plots were subsequently plotted for each variable using Minitab. Scatterplots of SI with each independent variable were subsequently plotted. Each data point on these plots was identified by landform type. The scatterplots revealed general relationships of SI with each of the independent variables for the four soil groups. The Pearson product-moment correlation (r) for SI with each independent variable was computed.

Table 2. List of variables.

A. Dependent Variable

SI Site index based on breast height age. Measured as height in metres at 50 years from breast height age.

B. Independent Variables

1. Climate

LAT	Latitude. Expressed in minutes north of 48° 00′ N.
LONG	Longitude. Expressed in minutes west of 88° 00′ W.
ELEV	Elevation. Expressed in metres above sea level.

2. Topography

SLOPE	Percent slope
POS	Position on the slope. Coded as 1=crest; 2=upper; 3=midslope; 4=lower; 5=toe; 6=depression; and 7=level.
ASP	Aspect. Predominant aspect of the plot measured in degrees.
SLPL	Slope length. Measurement of the total length of the slope in metres.
UPSLPL	Upslope length. Measurement of the distance from plot centre to the crest position, in metres.
SFRSHP	Surface shape. Coded as: 1=convex; 2=straight; and 3=concave.

3. Soil Texture: Expressed as a percent of the soil by weight determined by laboratory analysis.

VCSA	Very coarse sand in A horizon (2.0-1.0 mm)
VCSB	Very coarse sand in B horizon.
VCSBC	Very coarse sand in BC horizon.
VCSC	Very coarse sand in C horizon.
CSA	Coarse sand in A horizon.
CSB	Coarse sand in B horizon.
CSBC	Coarse sand in BC horizon.
CSC	Coarse sand in C horizon.
MSA	Medium sand in A horizon (0.5 - 0.25 mm)
MSB	Medium sand in B horizon.
MSBC	Medium sand in BC horizon.
MSC	Medium sand in C horizon.
FSA	Fine sand in A horizon (0.25 - 0.10 mm)
FSB	Fine sand in B horizon.
FSBC	Fine sand in BC horizon.
FSC	Fine sand in C horizon.
VFSA	Very fine sand in A horizon (0.10 - 0.05 mm).
VFSB	Very fine sand in B horizon.
VFSBC	Very fine sand in BC horizon.
VFSC	Very fine sand in C horizon.
SIA	Silt in A horizon (0.05 - 0.002 mm).
SIB	Silt in B horizon.
SIBC	Silt in BC horizon.
SIC	Silt in C horizon.
CLA	Clay in A horizon (<.002 mm)
CLB	Clay in B horizon.
CLBC	Clay in BC horizon.
CLC	Clay in C horizon.
SICLA	Silt plus clay in a horizon.
SICLB	Silt plus clay in B horizon.

SICLBC Silt plus clay in BC horizon.
SICLC Silt plus clay in C horizon.
FS2A Fine plus vey fine sand in a horizon.
FS2B Fine plus very fine sand in B horizon.
FS2BC Fine plus vey fine sand in BC horizon.
FS2C Fine plus very fine sand in C horizon.
FS3A Fine plus very fine plus medium sand in A horizon.
FS3B Fine plus very fine plus medium sand in B horizon.
FS3BC Fine plus very fine plus medium sand in BC horizon.
FS3C Fine plus very fine plus medium sand in C horizon.
CS2A Very coarse plus coarse sand in A horizon.
CS2B Very coarse plus coarse sand in B horizon.
CS2BC Very coarse plus coarse sand in BC horizon.
CS2C Very coarse plus coarse sand in C horizon.
CS3A Very coarse, coarse plus medium sand in A horizon.
CS3B Very coarse, coarse plus medium sand in B horizon.
CS3BC Very coarse, coarse plus medium sand in BC horizon.
CS3C Very coarse, coarse plus medium sand in C horizon.
SCDIF Silt plus clay in A and B horizons minus silt plus clay in BC and C horizons.

4. Coarse Fragment Content
GRA Gravel in A horizon (0.2 - 7.5 cm). Expressed as a percent of gravel and fine earth fraction. Measured in the laboratory.
GRB Gravel in B horizon.
GRBC Gravel in BC horizon.
GRC Gravel in C horizon.
GR2A Gravel in A horizon. A visual percentage estimate made in the field.
GR2B Gravel in B horizon.
GR2BC Gravel in BC horizon.
GR2C Gravel in C horizon.
COA Cobbles in A horizon (7.5 - 25 cm). A visual percentage estimate made in the field.
COB Cobbles in B horizon.
COBC Cobbles in BC horizon.
COC Cobbles in C horizon.
STA Stones in A horizon (>25 cm). A visual percentage estimate made in the field.
STB Stones in B horizon.
STBC Stones in BC horizon.
STC Stones in C horizon.
CFRAGAGravel, cobbles plus stones in A horizon.
CFRAGBGravel, cobbles plus stones in B horizon.
CFRAGBCGravel, cobbles plus stones in BC horizon.
CFRAGCGravel, cobbels plus stones in C horizon.
COSTA Cobbles plus stones in A horizon.
COSTB Cobbles plus stones in B horizon.
COSTBCCobbles plus stones in BC horizon.
COSTC Cobbles plus stones in C horizon.

5. Soil Depth (measured in centimetres)
THA Thickness of A horizon.
THAB Thickness of A plus B horizons.
DPC Depth to C horizon.
DMRL Depth to a moist restricting layer(mottles, gley and/or a visible water table).
DRL Depth to restricting layer(mottles, gley, water table, bedrock, carbonates and/or basal till).

DBR Depth to bedrock.
DC Depth to carbonates. If no carbonates present, DC=100.
DMR Depth of maximum rooting. The lower limit of the majority of the roots in the cross section.
DER Depth of effective rooting. The lower limit of all rooting within the cross section.
DVR Depth of visible rooting. Depth at which the last visible root is observed.
DWT Depth to water table.
DSE Depth to seepage.
DDM Depth to distinct mottles.
DPM Depth to prominent mottles.
DG Depth to gley.
DBT Depth to basal till.

6. Soil Moisture

MR Moisture regime. Coded as: 0=dry or moderately dry; 2=fresh; 3= very fresh; 4=moderately moist; 5=moist; 6=very moist.
DR Drainage class. Coded as: 1=very rapidly; 2=rapidly; 3=well; 4=moderately well; 5=imperfectly; and 6=poorly.
WT Presence of water table.
M Presence of mottles.
G Presence of gley colours.

7. Soil Reaction (determined in the laboratory)

PHA pH of the A horizon.
PHB pH of the B horizon.
PHBC pH of the BC horizon.
PHC pH of the C horizon.

8. Organic Matter Content. Expressed as a percent by weight of the soil determined by laboratory analysis.

OMA Organic matter in A horizon.
OMB Organic matter in B horizon.
OMBC Organic matter in BC horizon.
OMC Organic matter in C horizon.

9. Soil Colour

Hue: coded as: 0=5YR; 1=7.5YR, 2=10YR; 3=1.25Y; and 4=2.5Y.
HUA Hue of A horizon.
HUB Hue of B horizon.
HUBC Hue of BC horizon.
HUC Hue of C horizon.
VA Value of A horizon.
VB Value of B horizon.
VBC Value of BC horizon.
VC Value of C horizon.
CA Chroma of A horizon.
CB Chroma of B horizon.
CBC Chroma of BC horizon.
CC Chroma of C horizon.

10. Litter Layer (measured in centimetres)

THLFH Thickness of L, F and H layers.

THFH Thickness of F and H layers.
THH Thickness of H layer.

12. Other
EXPBR Presence of exposed bedrock. Coded as: 1=exposed bedrock; and 2= no exposed bedrock.
PDC Particle size distribution in C horizon. The number of soil particle sizes in the C horizon.
RB Roots in B horizon. The average number of fine roots (1-2mm) in a 10 cm by 10 cm area in the B horizon.

Preliminary Data Analyses

The independent variables were screened for further analyses to eliminate inappropriate variables. The criteria used for selecting variables are as follows: (1) a value for the variable is available for each plot; and (2) the variable is not greatly affected by site disturbances.

The backwards elimination method of model selection was used. The variable with the largest probability-of-F value is removed, provided that this value is larger than the removal criterion. The default F value of 0.10 was used.

The independent variables used in the subsequent regression analyses were chosen from the variables that passed this preliminary screening. Various subsets of the variables were tested. The subset size was limited to one less than the sample size for each soil group. The regression equation with the highest coefficient of multiple determination (R^2) was considered to be the "best" equation.

An analysis of residuals was carried out for the "best" equation for each landform group. The following assumptions of regression were tested to ensure the regression equation fit the data set.

1. All error terms belong to a population and thus there are no abnormal values. Bonferonni's t-test (Weisberg, 1980) was used for detecting outliers.

2. The error terms are random elements and are homoscedastic. The scatterplots of residuals

verses predicted values were studied to detect patterns indicating nonlinearity or heteroscedasticity (Chatterjee and Price, 1977).

The regression equations for the four landforms were used to compute predicted values of SI for each of the chosen check plots. Residuals were then computed by subtracting predicted SI from measured SI. These residuals were studied to determine if the developed equations accurately predict SI of the check plots.

Final Data Analyses

Study Plot Stratification

The preliminary analyses revealed that a wide range of soil properties exists within each of the four broad landform categories: bedrock, morainal, glaciofluvial, and lacustrine. For example, five of the 44 glaciofluvial sites contain appreciable amounts of cobbles and stones, while the other 39 sites contain no cobbles or stones. To obtain four specifically defined landform groups, criteria were defined.

1. Bedrock:
    (a) The parent material is till; and
    (b) the depth to bedrock is less than one metre in each of the three excavated pits.
2. Morainal:
    (a) The parent material is till;
    (b) the profile contains more than ten percent coarse fragments;
    (c) soil depth is greater than 100 centimetres; and
    (d) no exposed bedrock is visible on the plot.
3. Glaciofluvial:
    (a) the parent material is of glaciofluvial or fluvial origin;
    (b) the profile contains less than 20 percent gravel;
    (c) the profile contains no cobbles or stones; and
    (d) the fine earth fraction contains more than 50 percent sand.

4. Lacustrine:

(a) the parent material is of glaciofluvial or lacustrine origin; and

(b) the fine earth fraction contains less than 50 percent sand.

If a particular plot did not meet these specified criteria it was not considered to be part of the defined population and was thus not used for further analysis.

The individual tally sheets for each of the three soil pits located in each study plot were studied. If the three soil profile descriptions were quite dissimilar, indicating heterogeneous soil conditions within the plot, the particular plot was not included in further analyses. A random selection was made of 20 percent of the plots within the three soil categories: bedrock, morainal, and glaciofluvial. These plots were reserved as check plots to test the developed regression equations.

Ninety-nine of the 119 original study plots meet the criteria specified for the more precisely defined soil groups. Theses 99 plots were used in the final analyses and the other 20 plots were discarded. A total of 15 check plots were randomly chosen from the three soil groups: bedrock, morainal, and glaciofluvial. Lacustrine soils were only represented by 18 plots, thus all were retained so as to have adequate data for regression analyses. Table 3 gives the original number of study plots, the number of plots rejected because they did not fit the more refined selection criteria, and the number of check plots and computation plots.

Secondary Variable Screening and Candidate Variable Selection

For each of the four landform categories, independent variables were selected for further analyses from the prescreened variables. The criteria used for the secondary screening were: (1) the variable could "reasonably" be expected to be related to site index; and (2) the variable either can be measured in the field or can be obtained through simple laboratory analyses.

Table 3. Number of study plots used in final analyses.

Landform Type	Total	Plots Rejected	Plots Retained	Check Plots	Computation Plots
bedrock	21	1	20	4	16
morainal	36	6	30	5	25
glaciofluvial	44	13	31	6	25
lacustrine	18	0	18	0	18
total	119	20	99	15	84

SI was plotted against each of the soil and site variables selected in the secondary screening and simple correlations of SI with the selected independent variables were computed. Candidate independent variables were then selected for regression analysis. The criteria used for variable selection are as follows: (1) the variable has a relatively high simple correlation with SI; and (2) the variable is not highly correlated with other selected independent variables. The number of candidate variables selected was restricted to 10 or less for each landform group. At least one variable from each of the following main categories was included: topography, soil texture, coarse fragment content, soil depth, and soil moisture.

Final Multiple Regression Analyses

Regression equations were developed for the four precisely defined landform groups. For each of these groups equations related SI to a subset of the candidate soil and topographic variables. Throughout the analyses, careful attention was paid to the subset of independent variables considered for inclusion in the equations. Due to the small size of the samples only equations with three or fewer independent variables included were considered. At all stages of the analyses, the following question was kept in mind: "Does this equation make biological sense?"

The S function "leaps" was used to implement a technique known as "all-subsets regression by Leaps and Bounds" (Becker and Chambers, 1984). The "leaps" function is not limited to operating with a single variable at each iteration. Instead it uses complex computational techniques to examine all possible subsets of candidate variables. For each subset, a statistic is computed to evaluate the goodness of fit for the model.

The "leaps" technique was used to identify subsets of the candidate independent variables to be used in the regression analyses. The criterion used to evaluate each subset was the coefficient of multiple determination (R^2). The "best" subset of variables is considered to be the subset with the highest R^2, in which all variables significantly contribute to the R^2. The significance level of each correlation coefficient must be less than 0.10. Separate "leaps" regressions were computed for each of the four soil categories. Each "leaps" output was examined and the most promising subset of variables was selected.

For each of the four landform categories, a multiple regression equation and associated statistics and plots were calculated using the regression procedure of SPSSX. The dependent variable, SI, was regressed on the most promising subset of variables as determined by the "leaps" regression. The output was examined to ensure that all variables in the subset significantly contribute to the regression equation.

The following transformations for testing curvilinear relationships of each of the independent variables were tested:

(a) logarithm = log10 (variable)

(b) reciprocal = 1/variable

(c) square root = $(\text{variable})^{1/2}$

(d) quadratic = $(\text{variable})^2$

Interaction terms between the significant subset variables were also tested. The interaction terms are products of variables used to explore possible uneven "response surfaces" (Carmean, 1975).

Model Testing

The final regression equations were used to compute predicted SI values for the previously selected check plots. Residuals were then computed by subtracting predicted SI from measured SI. If the predicted SI values were reasonably in agreement with measured SI, the regression equation was recomputed with the check plots included. Theoretically, the inclusion of the extra check plots should produce better estimates of the regression coefficients.

Trend Graphs and Prediction Tables

The final regression equation for each landform was used to develop tables and graphs for predicting SI based on the identified soil and topographic features. If the plots used for the regression analyses adequately represent a particular landform, these prediction tables and graphs can then be used for predicting SI for the landform.

RESULTS

VARIABLE DEFINITION AND COMPUTATION

A total of 97 original independent variables were defined (Table 2). The variables are organized under the headings listed in Table 4. Thirty-two new variables were computed that summarize or combine several other variables. Sixteen of the computed texture variables summarize sand content. For example, CS3A is computed as the addition of VCSA, CSA, and MSA. The four variables SICLA, SICLB, SICLBC, and SICLC are computed from the eight silt and clay variables. The variable SCDIF was computed to describe the degree of textural change between the surface and the subsurface horizons.

Eight coarse fragment variables were computed as the addition of certain original coarse fragment variables. For example, COSTA is the sum of COA and STA; and CFRAGA is the sum of GR2A, COA, and STA. The two depth variables DMRL and DRL represent depths to root restricting layers such as mottles, gley, a water table, bedrock, basal till, and carbonates.

Summary statistics of the SI values for the four landform groups are give in Table 5.

PRELIMINARY DATA ANALYSES

Preliminary Variable Screening

The 129 original and computed variables listed in Table 2 were then subsequently screened. For all four landform types a total of 24 variables were eliminated in the preliminary screening leaving 105 variables for analysis. The A horizon was too thin to be sampled on some plots, thus, all horizon attributes except PHA and OMA were assigned the

Table 4. **The number of independent variables: original variables; computed variables; variables that passed the preliminary screening and variables that passed the secondary screening.**

Independent Variable Category	Original Variables	Computed Variables	Total	Preliminary Screening				Secondary Screening			
				R	M	G	L	R	M	G	L
Climate	3	0	3	0	0	0	0	0	0	0	0
Topography	6	0	6	3	3	3	3	2	2	2	2
Soil Texture	28	21	49	12	49	49	49	7	15	15	5
Coarse Fragments	16	8	24	8	24	24	24	3	7	3	3
Soil Depth	14	2	15	6	14	13	14	1	7	6	8
Soil Moisture	5	0	5	5	5	5	5	1	1	1	1
Soil Reaction	4	0	4	0	3	3	3	0	3	3	2
Organic Matter	4	0	4	0	3	3	3	0	0	0	0
Soil Colour	12	0	12	0	0	0	0	0	0	0	1
Litter Layer	3	0	3	0	0	0	0	0	0	0	0
Other	2	1	3	1	1	1	1	1	0	0	0
Total	97	32	129	35	102	101	102	16	35	30	22

Where: R = bedrock
M = morainal
G = glaciofluvial
L = lacustrine

Table 5. **Summary statistics of site index values for each landform: number of plots, mean, standard deviation, minimum, maximum, and range.**

		Preliminary Analyses			Final Analyses			
	All Plots	Comp. Plots	Check Plots	Predicted Values	All Plots	Comp. Plots	Check Plots	Predicted Values
Bedrock								
n	21	17	4	4	20	4	4	4
Y	12.95	12.70	14.02	12.76	12.74	14.02	12.86	12.43
s	3.02	3.08	2.98	3.38	2.94	2.98	3.26	2.94
min.	8.55	8.55	10.06	8.57	8.55	10.06	8.18	8.55
max.	18.75	18.75	17.13	16.09	18.75	17.13	15.50	18.75
range	10.20	10.20	7.07	7.52	10.20	7.07	7.32	10.20
Morainal								
n	36	29	7	7	30	5	5	5
Y	17.59	17.70	17.13	16.38	17.71	17.45	17.26	17.84
s	2.11	2.22	1.56	1.49	2.05	1.82	1.77	2.13
min.	13.63	13.63	14.25	14.28	13.88	14.75	14.87	13.88
max.	22.38	22.38	19.25	18.62	22.38	19.13	19.06	22.38
range	8.75	8.75	5.00	4.34	8.50	4.38	4.19	8.50
Glaciofluvial								
n	44	35	9	9	31	6	6	6
Y	17.59	17.64	17.38	19.20	17.82	18.48	18.80	17.59
s	2.58	2.20	2.12	5.28	2.02	0.50	1.41	2.10
min.	11.63	11.63	13.13	12.57	11.88	16.75	17.98	11.88
max.	21.00	21.00	19.88	30.22	21.00	20.38	19.08	21.00
range	9.37	9.37	6.75	17.65	9.12	3.63	1.10	9.12
Lacustrine								
n	18	14	4	4	18	0	0	0
Y	18.32	18.17	18.85	17.68	18.32	-	-	18.32
s	2.01	2.16	1.46	0.62	2.01	-	-	2.01
min.	13.63	13.63	16.88	16.86	13.63	-	-	20.75
max.	20.75	20.75	20.13	18.24	20.75	-	-	20.75
range	7.12	7.12	3.25	1.38	7.12	-	-	7.12

Where: n = number of sample plots
Y = average site index(m)
s = standard deviation
min. = minimum site index (m)
max. = maximum site index (m)

values obtained for the B horizon. No estimates are available for PHA and OMA for some plots, consequently, these two variables were dropped. The 12 soil colour variables were not used in the analyses. The thickness of the forest litter layer and the number of roots in the soil are not stable variables, but may be affected by such disturbances as a change in stand composition, stand density, stand age, and perhaps fire. Thus, the three litter layer variables and the variable RB, were dropped.

Certain variables were dropped for some landform types, but were retained for other types. The numbers of variables by category retained for each landform type are given in Table 4. Due to the shallowness of the bedrock sites, a number of plots do not have B, BC, or C horizons. The only common horizon for all bedrock plots is the A horizon, thus only site attributes for the A horizon were considered for the regression analyses. This left a total of 35 variables for the shallow landform analyses.

Some variables are specific to certain landform types and were not used for other landform types. For example, basal till is only found on morainal sites and thus, DBT was retained for morainal sites and dropped for other landforms.

Preliminary Multiple Regression Analyses

A preliminary regression equation was derived for each of the four soil landforms (Table 6). The regression equations had R^2 values of 0.898, 0.905, 0.875, and 0.995 for bedrock (equation P1), morainal (equation P2), glaciofluvial (equation P3), and lacustrine (equation P4) sites, respectively. The number of variables retained in each regression equation were 4, 10, 12, and seven, respectively. The four equations do not breach the assumptions of regression (page 45).

Test of Check Plots

The developed regression equations P1, P2, P3, and P4 were used to compute values of SI for the 24 check plots (Table 7).

Equation P1 predicts SI within 2.3 metres for the four bedrock check plots, and equation P4 predicts SI within 2.2 metres for the four lacustrine check plots. Predicted and

Table 6. Preliminary regression equations and associated statistics for bedrock, morainal, glaciofluvial and lacustrine sites.

	Regression Equation	N	R^2	SEE
P1	Bedrock SI=4.8285+0.1127(FSA)+0.2354(CLA)−0.0804(COA)+0.1281(DBR)	17	0.898	1.133
P2	Morainal SI=26.5652−0.1030($SLOPE$)−0.0560($FS2A$)+0.0755($FS2C$)−0.7285(CLA) −0.0295(GRC)−0.1093(THB)+0.0709(DPC)−4.64029(M)+2.625(WT) −1.0022(PDC)	29	0.905	0.857
P3	Glaciofluvial SI=26.3087−0.2177($SLOPE$)−0.4758(CLA)+0.8382(CLB)−1.3010($CLBC$) +3.1937(CLC)+0.1388(SIB)−0.1855(SIC)−0.2096($CFRAGBC$) +0.0560(DPC)−0.1637(PHA)−0.2263($PHBC$)−0.0649(OMB)	35	0.875	0.968
P4	Lacustrine SI=39.3685−0.0409($FS3A$)+0.1246(CLA)−0.1328(CLB)−0.0370($CLBC$) −0.0318(CLC)+0.3527(THA)−0.3284($PHBC$)	14	0.995	0.223

Where: Variable definitions are in Table 2.
N = number of plots
R^2 = coefficient of multiple determination
SEE = standard error of the estimate

Table 7. Testing of preliminary site index equations using the 24 check plots.

Landform Type	Plot	SI Actual	SI Predicted	Residual
Bedrock Sites	18	13.75	11.56	+2.19
	20	17.13	16.10	+1.03
	35	15.13	14.84	+0.29
	157	10.06	8.57	+1.49
Morainal Sites	16	17.13	16.18	+0.95
	21	18.38	14.28	+4.09
	56	19.25	16.20	+3.05
	64	17.13	18.62	-1.49
	91	17.13	16.89	+0.23
	98	14.25	17.58	-3.33
	116	16.63	14.91	+1.71
Glaciofluvial Sites	4	19.50	23.66	-4.15
	9	19.88	21.21	-1.33
	39	18.75	30.22	-11.47
	40	16.00	15.79	+0.20
	42	13.13	16.78	-3.65
	55	15.88	15.49	+0.39
	83	18.13	19.43	-1.30
	87	18.00	12.57	+5.43
	96	17.13	17.67	-0.53
Lacustrine Sites	31	16.88	16.86	+0.01
	121	18.63	18.07	+0.56
	145	20.13	18.24	+1.89
	146	19.75	17.56	+2.19

Where: SI = site index (m)

actual SI differ by more than three metres for three of the seven morainal check plots and predicted SI differs by more than 3.5 metres for four of the nine glaciofluvial check plots. The predicted value for one plot exceeds the actual SI value by 11.5 metres.

FINAL DATA ANALYSES

The landform groups: bedrock, morainal, glaciofluvial, and lacustrine were defined more precisely for the final data analyses. Summary statistics for the four landform types are given in Table 5.

Bedrock

Data were collected from 21 plots with bedrock at a depth of less than 100 centimetres. The parent material on all sites except for one is glacial till. The one exception is of glaciofluvial origin and thus was not used in the analysis as it did not meet the defined criteria for the bedrock sites. Four check plots were randomly chosen, leaving 16 plots for computation (Table 3).

More than 30 percent exposed bedrock is found on 14 of the plots, while the other six plots show no exposed bedrock. Average SI is lower on the 14 plots with much exposed bedrock (mean = 11.24 m, standard deviation = 1.85) than on the six plots with little or no exposed bedrock (mean = 16.25 m, standard deviation = 1.70).

Secondary Variable Screening and Candidate Variable Selection

A total of 16 of the 35 prescreened variables passed the secondary screening for these shallow to bedrock sites (Table 4). These 16 variables are marked by dashes (-) and the most significant simple correlations of SI with the various site attributes are listed (Table 8). The seven variables chosen for regression analysis are marked by asterisks (Table 8).

Final Multiple Regression Analysis

"All subsets regression by Leaps and Bounds" was used to determine the "best" subset of the seven candidate variables for regression. The variable DBR (depth to bedrock) alone produced an R^2 of 0.745. The addition of other variables did not increase the R^2 significantly.

Equation F1, regressing SI on DBR is given in Table 9.

Table 8. Variables used in final regression analyses.

Variables selected in the secondary screening (-); candidate variables selected for regression analyses (*); and Pearson correlation coefficients (r, 10 percent level of significance).

Feature	Variable	Bedrock	Morainal	Glaciofluvial	Lacustrine
1. Topography	SLOPE	- *	- *	-0.7010 *	- *
	POS	-	-	+0.6456	-
2. Texture	FS2A				
	FS2B		-	-0.5838	
	FS2C		+0.3255 *	-0.4550	
	FS3A				
	FS3B		-	-0.5849 *	
	FS3C		+0.3154	-	
	CS2A				
	CS2B		-	+0.3232	
	CS2C		-0.3182	-	
	CS3A	- *			
	CS3B			+0.3665	
	CS3C		-	+0.4341	
	SIA	-			
	CLA	-0.4377 *	-0.5276 *	-	+0.6796
	CLB		-	-	+0.6454 *
	CLBC		-	-	+0.6138
	CLC			-	+0.6270 *
	SICLA				
	SICLB			+0.5027 *	+0.3613 *
	SICLC			-	-
	SCDIF		-	+0.5362 *	
3. Coarse Fragments	GRA				
	GRB		-	-	-0.4576*
	GRBC		-	+0.3022 *	-
	GRC		-0.3929 *	-	
	COSTA				
	COSTB				
	COSTC				
	CFRAGA	- *			
	CFRAGB		-		
	CFRAGC		-0.3440 *		

Feature	Variable	Bedrock	Morainal	Glaciofluvial	Lacustrine
4. Soil Depth	THA		-	-	+0.5538 *
	THAB		+0.3215 *	+0.3115	-
	DPC		-	+0.4015 *	-0.3281
	DMRL		-	+0.3359 *	+0.3829 *
	DRL		- *		
	DBR	+0.8629 *			
	DC				
	DER		- *	+0.3542 *	
	DMR		-	+0.3136	-
5. Moisture	MR	+0.5021 *	- *	-0.3592 *	-0.3182 *
6. Soil Reaction	PHB		- *	-	
	PHBC		-	-0.3336 *	-0.7504 *
	PHC		-	-0.2861	-
7. Other	EXPBR	-0.7877 *			
	HUC				-0.6812 *

The number of computation plots (N), coefficient of multiple determination (R^2) and standard error of the estimate (SEE) are also given in Table 9.

The scatterplot of SI versus DBR indicates a possible curvilinear relationship. This possible curvilinear relationship was tested. The square, inverse and natural log of DBR do not significantly increase the R^2 value but the square root of DBR has a somewhat higher R^2 value than DBR. The resulting regression equation (Equation F2) for bedrock sites is given in Table 9.

The following two-way interactions were tested:

(1) $DBR \times (20 - CLA)$

(2) $DBR \times CFRAGA$

Table 9. Bedrock regression equations and associated statistics computed in final regression analyses.

	Regression Equation	N	R^2	SEE
F1	SI=9.4543+0.0899(DBR)	16	0.745	1.54
F2	SI=7.1731+1.0097$\sqrt{DBR}$	16	0.752	1.52
F3	SI=7.4778+0.9960$\sqrt{DBR}$	20	0.770	1.45
F4	SI=9.2217+0.1150(DBR)–0.0007[$DBR \times CFRAGA$]	16	0.830	1.28
F5	SI=9.4156+0.1125(DBR)–0.0006[$DBR \times CFRAGA$]	20	0.830	1.28

Where: SI = site index (m)
DBR = depth to bedrock (cm)
CFRAGA = coarse fragment content in A horizon (%)

(3) $EXPBR \times (100 - DBR)$

(4) $DBR \times MR$

The interaction term between DBR and CFRAGA significantly increased the R^2 value; the resulting regression equation (equation F4) is given in Table 9.

Model Testing

Regression equations F2 and F4 were used to compute predicted values of SI for the four check plots (Table 10). SI was predicted within 2.3 metres (maximum residual value) for all four check plots.

Table 10. Bedrock check plot results.

Plot	DBR	CFRAGA	SI actual	Equation (F2)		Equation (F4)	
				SI predicted	residual	SI predicted	residual
18	35	70	13.75	13.15	+0.60	11.47	+2.82
20	68	22	17.13	15.50	+1.63	15.96	+1.71
35	54	12	15.13	14.59	+0.54	14.96	+0.17
157	1	2	10.06	8.18	+1.88	9.34	+0.72

Where: DBR = depth to bedrock (cm)
CFRAGA = coarse fragments in A horizon (%)
SI = site index (m)

Regression equations F2 and F4 were then recomputed with the four check plots included. The new equations (equations F3 and F5) are given in Table 9. Equations F1, F2, F3, F4, and F5 do not breach the assumptions of regression (page 45).

Trend Graphs and Prediction Tables

Figures 2 and 3 show the relationships between SI, DBR, and CFRAGA. Figure 2 shows a curvilinear relationship between SI and DBR; figure 3 shows a linear relationship between SI and DBR over four CFRAGA classes.

Table 11 can be used for predicting SI for jack pine on shallow to bedrock sites.

Moraines

Data were collected from 36 morainal sites. Six of these sites were not used in the final analyses. One plot had excessive internal variation in stoniness, texture, and depths of horizons, thus it was rejected as being too heterogeneous. Five plots had some exposed bedrock visible at the surface and thus were excluded from the analyses because morainal sites

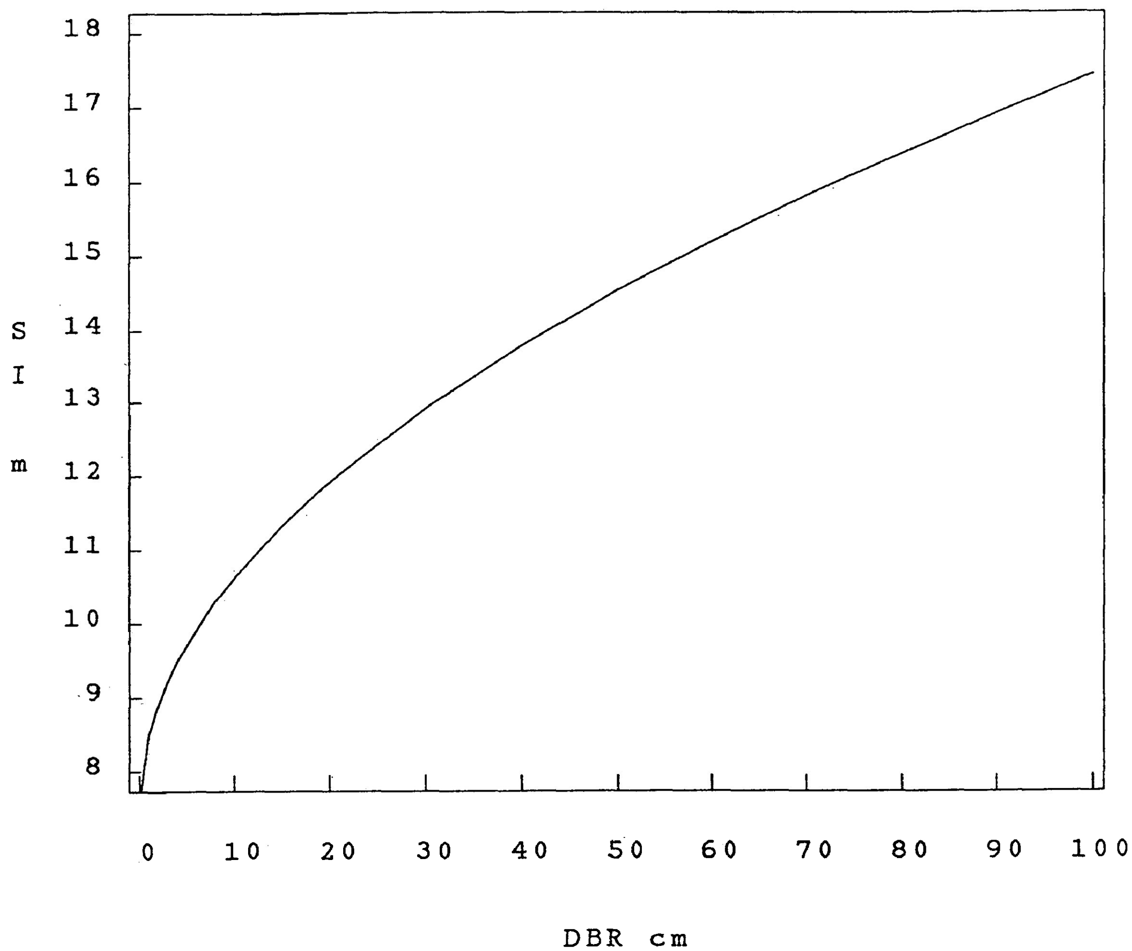

Figure 2. Site index (SI) versus depth to bedrock (DBR) computed using equation F3 (Table 9).

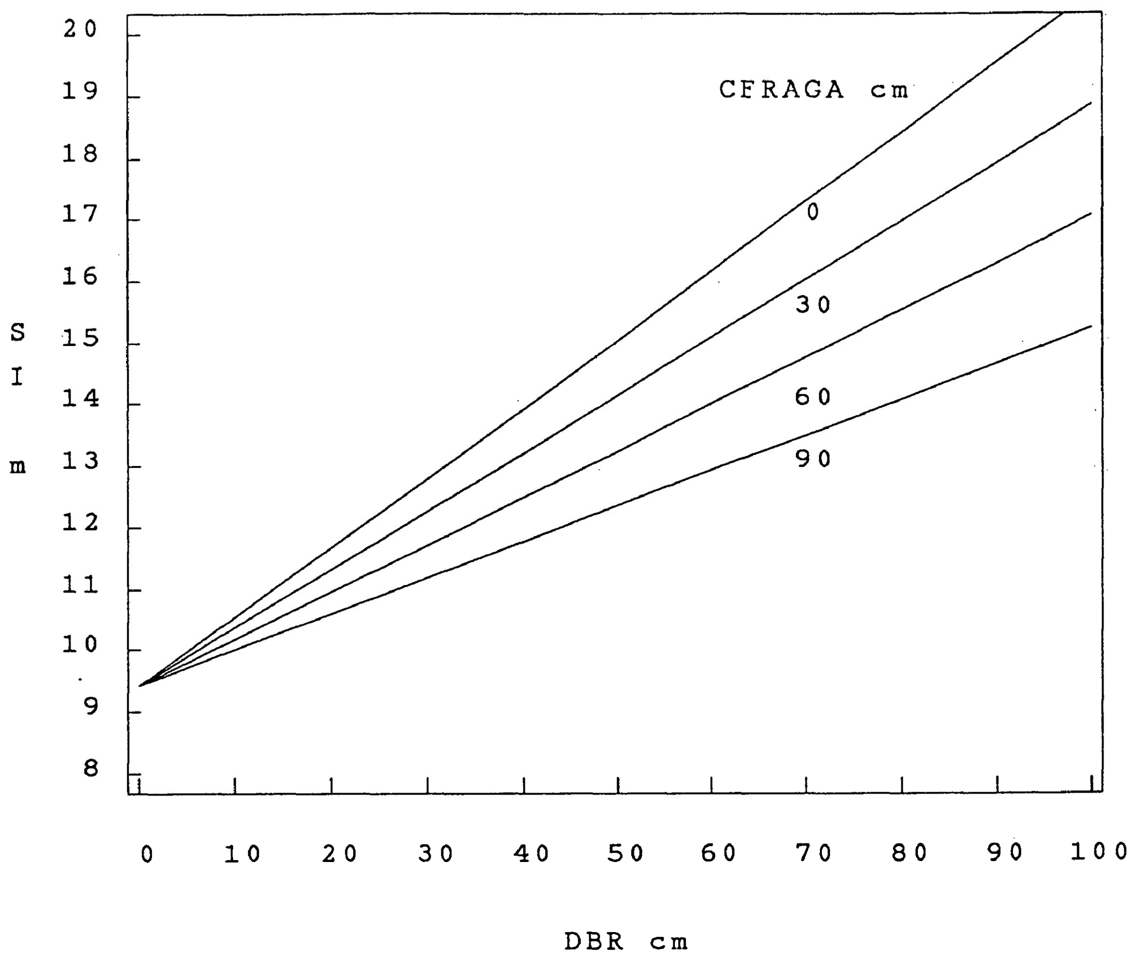

Figure 3. Site index (SI) versus depth to bedrock (DBR) by coarse fragment (CFRAGA) classes computed using equation F5 (Table 9).

Table 11. Site index prediction table for jack pine on bedrock sites.

Depth to Bedrock (cm) (DBR)	Equation F3 Site Index (m) (SI)	Equation F5 Coarse Fragments in A Horizon (%) (CFRAGA)			
		0-15	15-30	30-50	50-70
0-15	10.2	10.2	10.2	10.1	10.0
15-30	12.2	11.8	11.6	11.4	11.1
30-50	13.8	13.7	13.4	12.9	12.5
50-70	15.2	15.9	15.3	14.7	14.0
70-100	16.7	18.6	17.8	16.9	15.9

by definition should have depths to bedrock exceeding 100 centimetres. Five check plots were randomly chosen from the remaining 30 plots, leaving 25 plots for computation (Table 3).

Secondary Variable Screening and Candidate Variable Selection

Thirty-five of the 102 prescreened variables passed the secondary screening for morainal sites (Table 4). Aspect (ASP) and a cosine transformation of aspect were not correlated with SI in the preliminary analyses, thus, the variable ASP was not included in the analysis. Variables that summarize sand content variables and coarse fragment variables, such as CS3A and COSTA, were used rather than variables defining individual sand and coarse fragment sizes. Only variables for the B and C horizons were used; these variables were usually highly correlated with corresponding variables for the A and BC horizons.

The 35 variables passing the secondary screening are listed and the most significant correlations of SI with various site attributes are given in Table 8. The 10 variables chosen for regression analysis are marked by asterisks. Some of the variables that are significantly correlated with SI, such as FS2C and CS2C, were not selected because they were highly correlated with a selected variable.

Final Multiple Regression Analysis

"All subsets regression by Leaps and Bounds" was used to determine the "best" subset of the 10 candidate variables for regression. The "best" subset of variables indicated by the "leaps" regression consists of CLA, CFRAGC, and DRL.

SI regressed on the three variables: CLA, CFRAGC, and DRL, gave a regression equation (equation F6) with an R^2 of 0.600 (Table 12). None of the transformations expressing curvilinear relations significantly increased the R^2 value. An equation with a two-way interaction term between DRL and (100 - CFRAGC) had a higher R^2 of 0.615 (equation F7).

Model Testing

Regression equation F7 was used to compute predicted values of SI for the five check plots (Table 13). The regression equation predicts SI within less than one metre (maximum residual value) for all five check plots.

Table 12. Moraine regression equations and associated statistics computed in final regression analyses.

	Regression Equation	N	R^2	SEE
F6	$SI=19.9425+0.03671(DRL)-0.4194(CLA)-.04389(CFRAGC)$	25	0.600	1.44
F7	$SI=18.4284+0.0005239[DRL\times(100-CFRAGC)]-0.3727(CLA)$	25	0.615	1.38
F8	$SI=18.5362+0.0005113[DRL\times(100-CFRAGC)]-0.3783(CLA)$	30	0.652	1.26

Where: SI = site index (metres)
DRL = depth to restricting layer (cm)
CLA = percent clay in A horizon
CFRAGC = percent coarse fragments in C horizon

Table 13. **Moraine check plot results.**

Plot	DRL	CLA	CFRAGC	SI actual	SI predicted	Residual
11	21	6	35	16.88	16.91	-0.30
28	100	6	95	17.38	16.45	+0.93
38	63	3	47	19.13	19.06	+0.07
99	100	10	98	14.75	14.81	-0.06
117	63	6	15	19.13	19.00	+0.13

Where: DRL = depth to restricting layer(basal till, gley, mottles and/or water table, in cm)
CLA = clay in A horizon (%)
CFRAGC = coarse fragments in C horizon (%)
SI = site index (m)

Regression equation F7 was recomputed with the five check plots included. The resulting equation (equation F8) is given in Table 12. Equations F6, F7, and F8 do not breach the assumptions of regression (page 45).

Trend Graphs and Prediction Tables

Figure 4 shows the relationship between SI and the three independent variables CLA, CFRAGC, and DRL. Table 14 can be used for predicting SI of jack pine for moraines.

Glaciofluvial

Data were collected from 44 plots originally classified as glaciofluvial (Table 3). Thirteen of these plots were not used in the final analyses as they did not meet the specified criteria for the glaciofluvial site type. Two plots had less than 50 percent sand content in one or more horizons; excessive amounts of cobbles or stones were present in the soil on five sites; more than 20 percent gravel was present in the soil on three sites. Two sites were of aeolian origin, rather than glaciofluvial or fluvial origin, and one plot had drastically differing soil texture in the three soil pits and thus was considered too heterogeneous to be used for

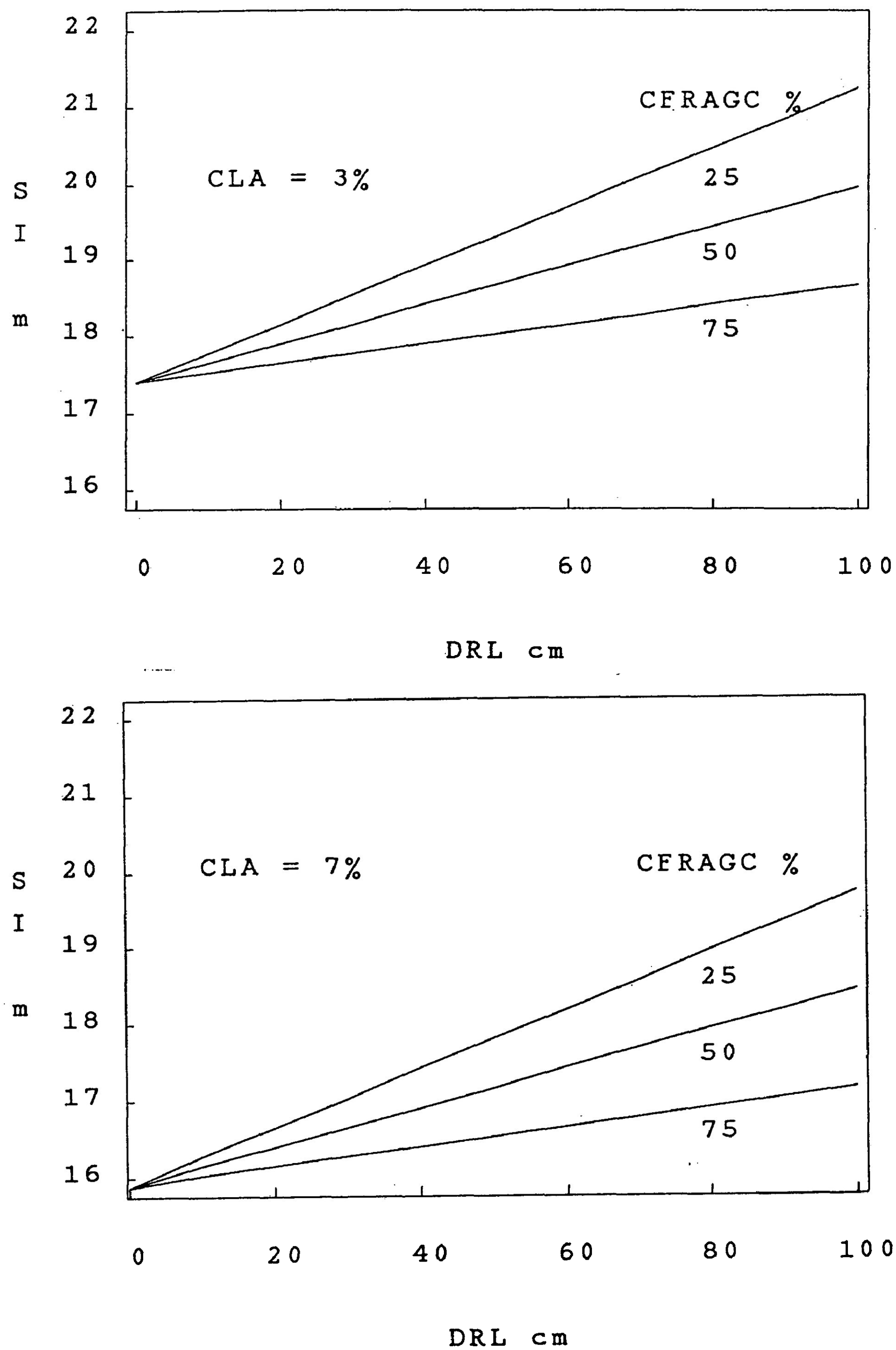

Figure 4. The relationship between site index (SI) and clay content of A horizon (CLA); coarse fragment content of C horizon (CFRAGC) and depth to a restricting layer (DRL) computed using equation F8 (Table 12).

Table 14. Site index prediction table for jack pine on moraines.

Clay in A Horizon (%) (CLA)	Depth to Restricting Layer (cm) (DRL) 0-30			30-70			70-100		
	CFRAGC			CFRAGC			CFRAGC		
	10-40	40-70	70-100	10-40	40-70	70-100	10-40	40-70	70-100
	-------SI-------			-------SI-------			-------SI-------		
2 - 4	18.0	17.7	17.5	19.3	18.6	17.8	20.7	19.4	18.1
5 - 7	16.8	16.6	16.4	18.2	17.4	16.6	19.5	18.2	16.9
8 - 10	15.7	15.5	15.2	17.0	16.3	15.5	18.4	17.1	15.8

Where: CFRAGC = coarse fragments in C horizon (%)
SI = site index (m)

analyses. Six check plots were randomly chosen from the remaining 31 plots, leaving 25 plots for computation (Table 3).

Twenty-four of the thirty-one plots used in the analyses are level, while seven of the plots have slopes of two to 12 percent. All of the five randomly chosen check plots are level. The mean SI (mean = 18.5 m, standard deviation = 1.31) for the 24 level plots is greater than the mean SI (mean = 15.5 m, standard deviation = 2.36) for the seven sloping plots.

Secondary Variable Screening and Candidate Variable Selection

Thirty of the 101 prescreened variables passed the secondary screening for glaciofluvial sites (Table 4). Most of these 30 variables are the same ones previously selected for the morainal sites. Exceptions were that no cobble or stone content variables were used because the 31 glaciofluvial sites by definition contain few cobbles or stones. Another exception is that by definition basal till is found only on morainal sites and thus the variable DBT was not used for glaciofluvial sites.

The most significant simple correlation coefficients of SI with various site attributes are given in Table 8. The 10 variables chosen for the final regression analyses are marked by asterisks.

Final Multiple Regression Analyses

The "best" subset of variables indicated by the "leaps" regression consists of SLOPE and DMRL. Equation F9 regressing SI on SLOPE and DMRL is given in Table 15. This equation has an R^2 of 0.657.

The log, inverse, square, and square root of SLPER and DMRL used to account for curvilinear relations, did not significantly increase the R^2 value. A two-way interaction term between DMRL and [20 - slope] increased the R^2 value(equation F10). Equations F9, F10, and

Table 15. Glaciofluvial regression equations and associated statistics computed in final regression analyses.

	Regression Equation	N	R^2	SEE
F9	$SI=16.72519-0.3848(SLOPE)+0.02566(DMRL)$	25	0.657	1.29
F10	$SI=17.24819+0.09817(DMRL)-0.6892(SLOPE)$ $-0.003993[(DMRL)\times(20-SLOPE)]$	25	0.712	1.21
F11	$SI=17.55834+0.10296(DMRL)-0.72679(SLOPE)$ $-0.004409[(DMRL\times(20-SLOPE)]$	31	0.653	1.26

Where: SI = site index (m)
SLOPE = percent slope
DMRL = depth to moist restricting layer (mottles, gley and/or water table, in cm)

F11 meet the assumptions of regression.

Model Testing

Equation F10 was used to compute predicted values of SI for the six check plots (Table 16). This equation predicts SI within 2.2 metres (maximum residual value) for all six check plots. Equation F11, recomputed with the six check plots included, is given in Table 15.

Trend Graphs and Prediction Tables

Equation F11 was used to construct Figure 5 which shows the relationship between SI and the two independent variables SLOPE and DMRL. Table 17 can be used to predict SI for jack pine on glaciofluvial sites.

Table 16. Glaciofluvial check plot results.

Plot	SLOPE	DMRL	SI actual	SI predicted	Residuals
8	0	100	18.63	19.08	-0.45
27	0	54	20.38	18.24	+2.14
37	0	67	20.00	18.48	+1.52
70	0	100	17.63	19.08	-1.45
88	0	40	16.75	17.98	-1.23
95	0	43	19.38	18.04	+1.34

Where: SLOPE = percent slope (%)
DMRL = depth to moist restricting layer (cm)
SI = site index (m)

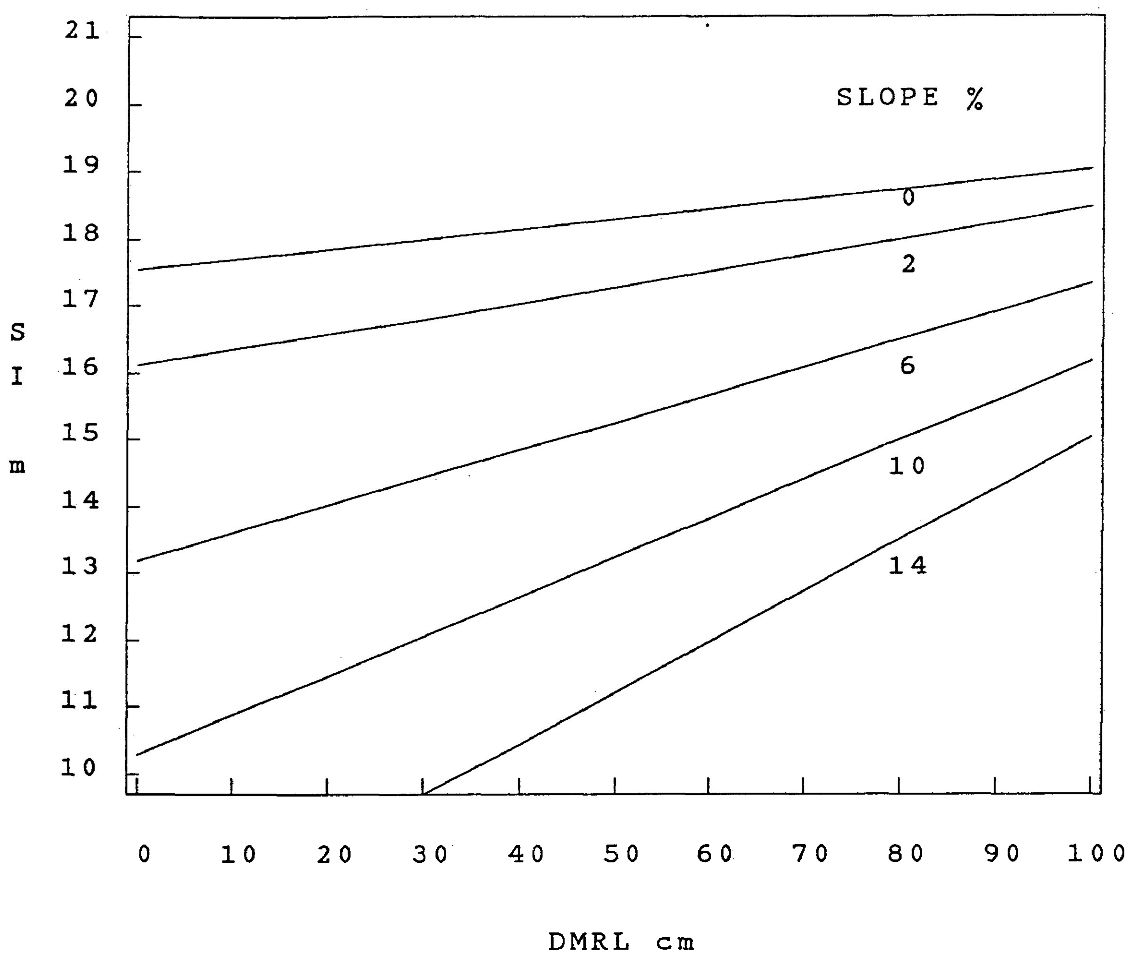

Figure 5. The relationship between site index (SI), percent slope (SLOPE) and the depth to a moist restricting layer (DMRL) computed using equation F11 (Table 15).

Table 17. Site index prediction table for jack pine on glaciofluvial sites.

Depth to a Moist Restricting Layer (cm) (DMRL)	Percent Slope (SLOPE) 0	0 - 7	7 - 14
	-----SI-----		
0 - 30	17.8	15.5	10.8
30-100	18.4	16.8	13.6
100	19.0	18.0	16.0

Where: SI = site index (m)

Lacustrine

Data were collected from 18 sites of lacustrine origin (Table 3). All plots were retained even though the lacustrine site type could be more narrowly defined. A more refined definition would exclude some of the plots and thus an insufficient number of plots would be available for regression analyses. Likewise, no check plots were used with the lacustrine soils as all 18 plots were required in the analyses.

The lacustrine parent material of 12 of the plots was derived from red shales, thus soils are reddish in colour and have a high clay content. The lacustrine parent material of the remaining six plots was derived from gray shales, thus soils are gray in colour and have less clay and more silt than the red clays. SI for the 12 red clay plots is consistently high (mean = 19.22 m, standard deviation = 1.10), whereas SI for the six gray silt plots is lower and more varied (mean = 16.25 m, standard deviation = 2.37). The red clays are located west and southwest of Thunder Bay in Mattawin and Devon Townships, and the gray silts are located north of Thunder Bay.

Secondary Variable Screening and Candidate Variable Selection

Twenty-two of the 102 prescreened variables passed the secondary screening for the lacustrine sites (Table 4). These 22 variables are the same variables selected for the morainal sites with some exceptions. Since the lacustrine soils contain very small amounts of sand particles, none of the sand variables were used; thus only silt and clay texture variables were selected. No cobble or stone variables were used because by definition the 18 lacustrine sites contain few cobbles or stones. Some lacustrine sites have carbonates in the C horizon, thus the variable DC was selected. The hue of the C horizon differentiates the red clays from the gray silts, thus the variable HUC was used.

Ten of the 22 screened variables had significant correlations with SI at the 90 percent significance level (Table 8); the 10 variables selected for regression analysis are marked by asterisks. The variables CLB and CLC were selected rather than CLA because a number of plots had thin A horizons, and thus texture values for the B horizons were assigned to the A horizons.

Final Multiple Regression Analysis

The "leaps" regression indicated three promising subsets of the 10 candidate variables for the final regression equation. The "best" subset of variables, with an R^2 of 0.729 was identified as PHBC and THA (equation F12, Table 18). Two other subsets of variables also produce regression equations with relatively high R^2 values of 0.654 (equation 13) and 0.653 (equation 14). These two subsets include HUC and PHBC; and CLC and PHBC respectively.

Equation F12 regressing SI on PHBC and THA is given in Table 18; equations F13 and F14 for the other two variables subsets are also given. The log, inverse, and square root of PHBC and THA did not increase the R^2 value. However, the squares of both PHBC and THA increased the R^2 value as shown for equations F15 and F16 (Table 18). All five equations

Table 18. Lacustrine regression equations and associated statistics computed in the final regression analyses.

	Regression Equation	N	R^2	SEE
F12	SI=31.0208+0.2496(THA)−2.486($PHBC$)	18	0.729	1.11
F13	SI=30.0849−0.4026(HUC)−2.003($PHBC$)	18	0.654	1.26
F14	SI=29.3479+0.02333(CLC)−2.182($PHBC$)	18	0.653	1.26
F15	SI=33.5707+0.01850(THA^2)−2.836($PHBC$)	18	0.748	1.07
F16	SI=25.3797+0.01798(THA^2)−0.2426($PHBC^2$)	18	0.751	1.07

Where: SI = site index (m)
THA = thickness of A horizon (cm)
PHBC = pH of BC horizon
HUC = hue of C horizon
CLC = clay in C horizon (%)

meet the assumptions of regression (page 45).

Trend Graphs and Prediction Tables

Equation F16 was used to construct Figure 6 that illustrates the relationship between SI, THA, and PHBC. Table 19 can be used for predicting SI of jack pine on lacustrine sites.

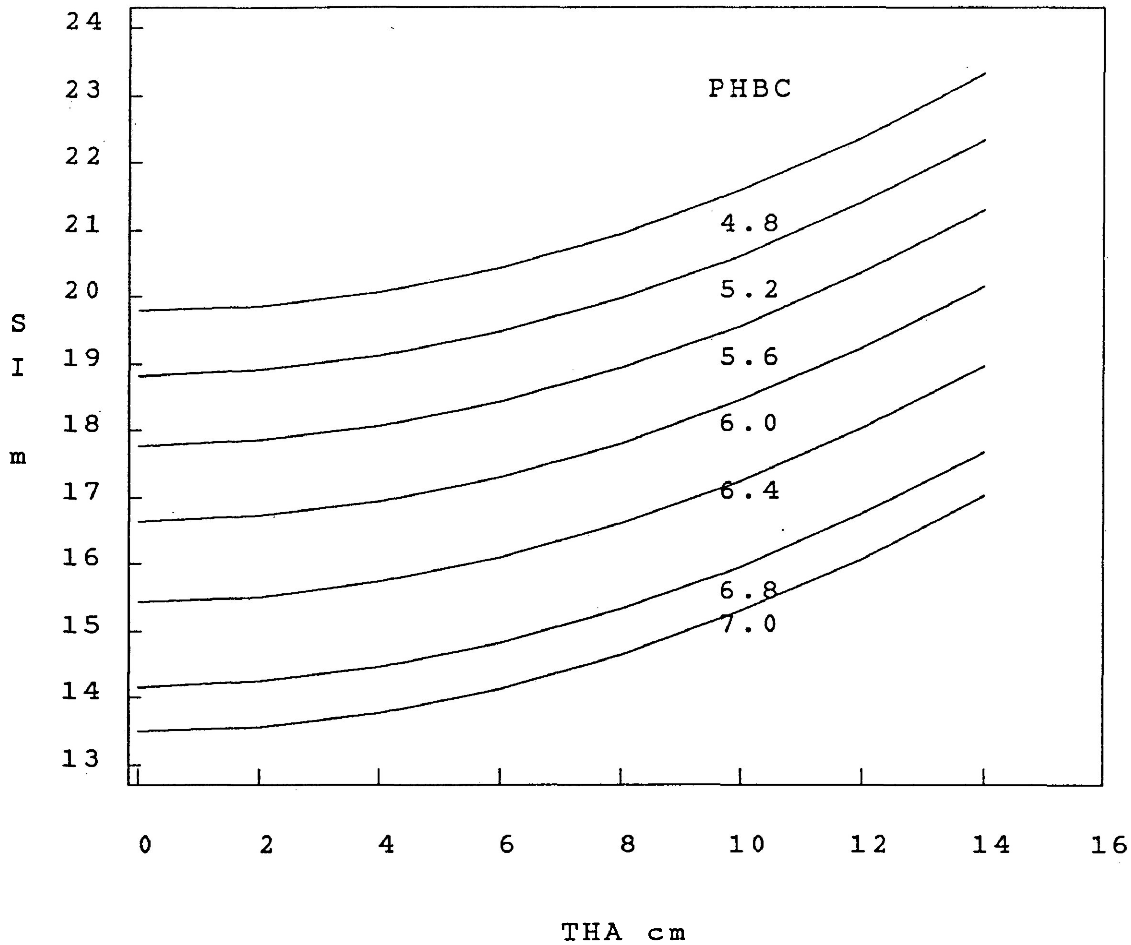

Figure 6. The relationship between site index (SI), thickness of the A horizon (THA) and pH of the BC horizon (PHBC) computed using equation F16 (Table 18).

Table 19. Site index prediction table for jack pine on lacustrine sites.

Thickness of A horizon (cm) (THA)	Reaction of BC Horizon (PHBC)			
	4.8 - 5.3	5.3 - 5.9	5.9 - 6.5	6.5 - 7.0
	-------Site Index (m)-------			
0 - 4	19.2	17.8	16.1	14.4
4 - 8	19.9	18.5	16.8	15.0
8 - 12	21.1	19.7	18.00	16.3
12 - 14	22.2	20.8	19.1	17.3

DISCUSSION

PRELIMINARY DATA ANALYSES

The four equations (equations P1, P2, P3 and P4) developed in the preliminary regression analyses are given in Table 6. These preliminary equations are included to illustrate some of the problems encountered for highly variable soil populations when attempting to regress SI with a large number of variables, and when some of these variables are highly correlated with others.

Problems Encountered

Numerous Independent Variables

Table 4 gives the numbers of variables considered for the preliminary regression analyses for each soil group. The numbers of variables (35, 102, 101, and 102) are very high in comparison to the numbers of computation plots (17, 29, 35, and 14) for bedrock, morainal, glaciofluvial, and lacustrine landforms, respectively. When a large number of variables are considered for regression analysis it is possible to explain random variation in a data set rather than systematic variation. This appears to be the case with the preliminary regression equations. The four preliminary equations include a large number of independent variables (4, 10, 12, and 7). The large number of variables included in these equations is probably a result of the numerous independent variables considered for the regression analyses.

The four preliminary equations have very high R^2 values; each equation explains more than 85 percent of the variation in SI. It would appear that, by random chance, these equations explain a large percent of the variation in SI. If this is true then the equations do not portray "real" relationships and are thus not useful.

A systematic method of limiting the number of variables to be used in the final regression analyses was needed to alleviate this problem. Therefore, secondary screening and candidate variable selection were carried out to select the 10 or fewer most promising variables for the final regression analyses.

Multicollinearity

The interpretation of the multiple regression technique depends on the assumption that the independent variables are orthogonal. Orthogonal variables are variables that are not interrelated (Chatterjee and Price, 1977). In most regression applications the independent variables may be interrelated and thus are not orthogonal, but the lack of orthogonality may not be serious enough to affect the analysis. However, in some cases the independent variables are so strongly interrelated that the regression results are ambiguous. The condition of highly interrelated independent variables is referred to as multicollinearity.

If multicollinearity exists in a data set , it is impossible to estimate the unique effects of individual variables in the regression equation. The estimated values of the coefficients are very sensitive to the addition or deletion of variables in the equation and to slight changes in the data. The regression coefficients have large sampling errors affecting forecasting and inference that is based on the regression model.

Indicators of multicollinearity include: (1) large changes in estimated regression coefficients when a variable is deleted or added; (2) large changes in the coefficients when a data point is dropped or altered; and (3) the algebraic signs of the coefficients do not conform to prior expectations (Chatterjee and Price, 1977).

These three indicators of multicollinearity were observed during the preliminary analyses. As variables were deleted or added or data points dropped or altered, large changes in the estimated regression coefficients were noted. Moreover, the algebraic signs of some of the coefficients in the preliminary equations do not conform to prior expectations. For example, in equation P4 (Table 6) for lacustrine sites, the signs of the coefficients for CLB, CLBC and CLC are negative, but were expected to be positive. These three variables are also highly correlated with each other.

Chatterjee and Price (1977) state that one must be "extremely cautious about any substantive conclusions based on a regression analysis in the presence of multicollinearity." Since it appears that multicollinearity is present in the preliminary regression analyses, the preliminary equations should be viewed with caution.

An attempt was made to alleviate the problem of multicollinearity in the final analyses by selecting a small number of variables that are not strongly correlated with each other.

Highly Variable Soil Groups

For the preliminary analyses the study plots were stratified into four broadly defined landforms: bedrock, morainal, glaciofluvial, and lacustrine (page 36). Substantial variation in soil conditions within each of these four landform groups is apparent. For example, the glaciofluvial landform contains plots with soils of fluvial, glaciofluvial, and aeolian origin. Some plots have an unusually low sand content; some have considerable cobble and stone content; and some plots contain a high amount of gravel. In order to adequately model soil-site relationships for such highly variable soil groups it would be necessary to have more plots that cover a precisely defined range of soil conditions. For the final analyses, the soil groups were more precisely defined in order to alleviate the problem of deriving equations for highly variable soil groups.

Regression Equations

Due to the problems associated with numerous independent variables, multicollinearity, and highly variable soil groups, the preliminary regression equations (equations P1, P2, P3, and P4) cannot be accepted as valid equations. These preliminary equations probably do not reveal "real" relationships, rather they "explain" random variation in the data sets. Since the equations do not appear to be valid, the particular variables included in the equations will not be discussed.

Test of Check Plots

The preliminary regression equations were used to compute values of SI for the 24 check plots (Table 7). Equation P1 for bedrock sites and Equation P4 for lacustrine sites are the only equations that predict SI reasonably well. Since the preliminary equations appear to be invalid, it is not surprising that the equations for morainal and glaciofluvial landforms do not predict SI well for the check plots.

FINAL DATA ANALYSES

Various steps were taken to alleviate the problems encountered in the preliminary regression analyses. The number of independent variables considered for regression analysis was limited through a secondary screening process and candidate variable selection. The problem of multicollinearity was alleviated by selecting a small number of variables that are not strongly correlated with each other. The highly variable soil groups were more precisely defined.

The problems associated with multicollinearity and highly variable soil groups are still present to a certain degree in the final analyses. The variables chosen for the regression analyses (Table 8), though not highly correlated with each other, are clearly interrelated. This lack of orthogonality may not be serious enough to affect the analyses. Though the four landforms were more precisely defined for the final analyses, substantial variation in soil and topographic conditions still exists within the four landforms. It would be desirable to have more sample plots for each landform in order to more adequately cover the range of soil and topographic conditions that occur on these landforms.

Inference Space

The sample plots were not randomly selected, but instead were selected with the goal of locating plots on major landforms and soils that represent the full range of jack pine site quality in the study area. As many plots as feasible were obtained for each of the four landforms: bedrock, moraines, glaciofluvial, and lacustrine (page 36).

A target population exists for each of the four landforms defined in this study. These target populations consist of all the sites in the study area that meet the criteria specified for the landforms. Totals of 16, 25, 25, and 18 computation plots were used in the final analyses for bedrock, morainal, glaciofluvial, and lacustrine sites, respectively. If we can assume that the sample plots adequately represent the target populations then we can apply the results of this study to the entire target populations. If this assumption does not hold then the results apply only to the sample plots used in the analyses.

Dependent and Independent Variables

Dependent Variable - Site Index

The average site index values for morainal (17.59 m), glaciofluvial (17.59 m) and lacustrine soils (18.32 m) are not statistically different from each other (Table 5). Site index was found to vary greatly within each of these three landforms; this large variation is closely associated with the features found to be significant in this soil-site study. Thus, these three landforms do not differentiate site quality. In contrast, the average site index value (12.95 m) for bedrock sites is less than the average for the other three soil groups.

Independent Variables

Climate rarely varies within small geographic areas (Gaines, 1949). The geographic area covered by this study is quite extensive, thus climatic variation may be substantial. Such variables as temperature, growing season sunshine, and precipitation have been used in other studies to describe climate. Such data are not available for each site in this study, thus climate has been described in terms of geographical location; latitude (LAT), longitude (LONG) and elevation (ELEV). The geographic location of the plots may be biased because of the criteria used in locating plots. Thus, the three climatic variables were not used in the analyses. If the study plots had been randomly located then the climatic variables could be considered.

Six variables were used to describe *topography* in this study. Topographic position (POS) is a qualitative variable and as such is not appropriate for use in regression analyses. Upslope length (UPSLPL), slope length (SLPL), and surface shape (SFRSHP) have very low simple correlations with SI. Most of the study plots are either level or gently sloping. Thus aspect and a cosine transformation of aspect are very poorly correlated with SI.

The only topographic variable that proved to be useful for predicting SI was percent slope (SLOPE). SLOPE was chosen as a candidate variable for regression analysis for all four soil groups. SLOPE is negatively correlated with SI for glaciofluvial sites. Twenty-four of the glaciofluvial plots are level and seven are gently sloping. In future studies it might be possible to stratify the glaciofluvial sites by topographic position. Based on the apparent differences in productivity I suggest that glaciofluvial sites be divided into sloping and level strata.

Soil texture was measured in this study in terms of percentages of sand, silt, and clay. The sand component was further divided into percentages of very coarse, coarse, medium, fine, and very fine sand. Thus, soil texture was expressed in terms of seven soil fractions, for four soil horizons resulting in a total of 28 texture variables.

A major statistical problem encountered in this study concerns the large number of variables describing soil texture, thus it was necessary to limit the number of texture variables to be used in the regression analyses. The number of texture variables were limited by computing summarized sand variables, and by using the B and C horizon variables for deep soils and the A horizon variables for shallow soils. Though this method of limiting the number of texture variables was quite effective, other ways of using soil texture variables in soil-site studies could be used.

Many texture variables are significantly correlated with SI (Table 8). However, no clear relationships between SI and soil texture variables are apparent across the four landforms. The amount of fine sand (FS2C) is positively correlated with SI for glaciofluvial sites; also percent clay in the A horizon (CLA) is positively correlated with SI for lacustrine sites. In contrast, percent clay in the A horizon is negatively correlated with SI for bedrock and morainal sites.

The final regression equation for morainal sites (equation F8, Table 12) includes only one texture variable. Also the preliminary equation for bedrock sites (equation P1, Table 6) contains a single texture variable. For both of these equations, CLA has a negative regression coefficient, indicating a negative relationship with SI. This negative relationship is surprising, since the expected trend is one of increased tree growth with increased clay content (Pritchett, 1979). This unexpected trend may be a result of multicollinearity in the data set.

Coarse material in the soil can influence rooting space, aeration, nutrient supply, and moisture relations and thus indirectly affect tree growth (Ralston, 1964). Coarse fragment content was expressed in terms of percent volume occuped by gravel, cobbles and stones, and by percent gravel by weight for four soil horizons. A total of 16 variables were used to describe coarse fragment content (Table 4). The same problem encountered with the soil texture variables occurs with the coarse fragment variables. The number of coarse fragment variables must be limited in some way. I chose to limit the number of variables by using computed summary variables and by only using the B and C horizon variables for deep soils, and the A horizon variables for shallow soils. Alternative methods of describing coarse fragment content and limiting the number of variables might have been used.

Four coarse fragment variables are significantly correlated with SI (Table 8). Three variables: GRB, GRC and CFRAGC, are negatively correlated with SI. This trend of decreased SI as coarse fragment content increases is the expected trend. However, the percent of gravel in the BC horizon (GRBC) is positively correlated with SI for glaciofluvial sites.

The final regression equations for bedrock sites (equation F5) and morainal sites (equation F8) contain interaction terms between a coarse fragment variable and a depth variable. The interaction term indicates that site index decreases with increasing coarse fragment content and that site index increases as soil depth increases. However, this interaction also indicates that SI increases with depth are more pronounced for soils having a lower coarse fragment content.

Various measures of *soil depth* have been associated with site quality in many soil-site studies (Coile, 1952). Nine soil depth variables were used in this study as expressions of the effective soil depth for rooting (Table 8). The soil depth measurements are fairly easy to obtain from field measurements. However, horizon boundaries and rooting depth boundaries are often indistinct and thus difficult to estimate. The variables DMRL, DRL, and DBR effectively express depth to root restrictions (gley, mottles, water table, basal till, and bedrock).

Seven of the soil depth variables are significantly correlated with site index (Table 8). All of the simple correlations for SI with a depth variable are positive. The trend of increasing SI with increasing soil depth is also reported in other studies (Coile, 1952). There is no obvious biological explanation for the negative correlation of SI with the depth to the C horizon (DPC) for lacustrine sites.

Each of the final regression equations for the four landforms contains a soil depth variable. Equation F5 (Table 9) for bedrock sites includes the variable DBR; equation F8 (Table 12) for morainal sites includes the variable DRL; equation F11 (Table 15) for glaciofluvial sites contains the variable DMRL; and equation F16 (Table 18) for lacustrine sites includes the variable THA. The sign of the regression coefficients for each soil depth variable is positive, indicating an increase in SI with increasing soil depth.

Soil moisture has been viewed as the most important single factor in determining forest growth (Gaines, 1949). In this study, soil moisture was expressed in terms of soil moisture regime (MR) (Bates *et al.*, 1982). Soil moisture regime is coded on a scale from 0 (dry) to 6 (very moist) and is based on soil texture and depths to mottles or gley. MR is a qualitative variable and as such is not an appropriate variable for regression analysis. However, MR is the only measure of soil moisture available and was thus used in the analyses.

MR is positively correlated with SI for bedrock sites and negatively correlated for glaciofluvial and lacustrine sites. The variable MR did not account for a significant amount of variation, thus was not included in any of the final equations.

Soil water supply can be characterized by various laboratory measurements of available water. Pressure cell equipment can be used to estimate water retention at permanent wilting point and at field capacity (Ralston, 1964). These quantitative measures of soil moisture are more appropriate measures of soil moisture for regression analysis.

Soil moisture can also be expressed by quantitative measures of texture, soil depth, and depth to mottling. These quantitative measures are easily obtained in the field in contrast to field capacity and permanent wilting point that require laboratory analyses. Values for texture, depth, and coarse fragments are already included in the various regression equations (Tables 9, 12, 15, and 18).

Soil reaction may be indirectly related to tree growth (Lutz and Chandler, 1946). In this study, soil pH was measured for the four soil horizons. Soil pH for the B, BC, and C horizons were used as variables in the regression analyses (Table 8). The pH for the BC and C horizons of the glaciofluvial sites and the pH for the BC horizon of the lacustrine sites are negatively correlated with SI. This trend of decreasing SI with increasing soil pH is surprising because the opposite trend was expected. The regression equation (equation F16) for lacustrine sites contains the variable PHBC. The regression coefficient for PHBC is negative, indicating that SI decreases as PHBC increases.

Soil colour has been used as an indicator of other soil properties that are related to tree growth (Pritchett, 1979). In this study, soil colour was recorded for each horizon in terms of hue, value, and chroma using standard Munsell notation (Munsell Color Company, 1971). The soil colour variables are not continuous variables. It is not possible to use all 12 soil colour variables in the regression analyses, yet it is difficult to summarize soil colour in terms of fewer variables. The 12 soil colour variables were not used in the regression analyses with one exception. For lacustrine soils, the sites with the redder hues have higher SI values than the sites with yellower hues. Thus the hue of the C horizon (HUC) differentiates the red clays from the gray silts and therefore, the variable HUC has a strong negative correlation with SI for lacustrine sites (Table 8). There is no obvious reason why the red clays are better in site quality than the gray silts.

Soil nutrients can limit tree growth (Ralston, 1964). Certain measures of available soil nutrients (usually nitrogen, phosphorus, potassium, calcium, and magnesium) have been associated with tree growth. No nutrient analyses were carried out in this study, thus, nutrient variables were not be used in the regression analyses. It would be beneficial in future studies to obtain nutrient analyses. However, one must consider that the number of variables would increase substantially if nutrient variables were included. This would further increase the problems associated with multicollinearity and explaining variation by random chance.

Limiting the Number of Independent Variables

A major task in this study was to determine which of the 129 variables to use in the regression analyses. Various methods of limiting the number of variables could be used. One possibility is to subjectively select variables for regression analysis based solely on the investigators judgement. This is a quick method, but it relies heavily on the investigator's knowledge and may ignore potentially useful variables.

A second method of limiting the number of variables is to arbitrarily select variables based on specific criteria. This can be carried out in one step or a sequence of steps. In this study the number of variables were limited using a sequence of three steps. Thus, preliminary screening was conducted to eliminate variables having little or no relation to SI. A secondary screening was then made, and finally candidate variables were selected for regression analyses. At each step of the variable selection process, the selection of variables was based on satisfying specific criteria. A certain amount of judgement was used throughout the selection process.

A third method of limiting the number of variables involves choosing variables completely objectively based on specific objective criteria. Though this method is objective, it does not take advantage of the investigator's judgement and field experience.

A fourth method of limiting the number of variables involves the use of factor analysis. Factor analysis can be used to identify groups of inter-correlated variables within the candidate variable list and to rewrite the variable set to remove collinearity (Ebdon, 1977). Factor scores can be extracted by the analysis and the then used as variables in regression analyses. One major drawback of using factor scores for the regression analyses is the developed equations cannot be used in the field. For this reason, factor analysis was not used in this study.

Model Selection by Landform Type

Shallow to Bedrock

Only four of the screened variables (CLA, DBR, MR, and EXPBR) are significantly correlated with SI (Table 8) for the bedrock sites. It is surprising that CLA is negatively correlated with SI since greater clay content is usually associated with increased moisture and nutrient availability (Pritchett, 1979). However, CLA has a strong negative correlation with DBR and the association between CLA and SI may merely indicate that better sites are decper to bedrock and have less clay.

DBR has the highest simple correlation with SI. The correlation of SI with DBR is positive, indicating that a site with a greater depth to bedrock has a higher SI. This relationship was expected since depth to bedrock essentially defines the effective soil depth, and effective soil depth is associated with tree growth (Pritchett, 1979). MR is positively correlated with SI, indicating that moister sites have higher SI values. EXPBR is highly correlated with SI. The sites with greater than 30 percent exposed bedrock have a lower average SI than sites with little or no exposed bedrock. EXPBR is strongly correlated with DBR. SI is poorest on the shallow soils having a large amount of exposed bedrock while in contrast, better SI occurs on deeper soils having little or no exposed bedrock. It would appear that bedrock exposure is a good indication of shallower soils and thus lower SI values.

The variable DBR explains 75 percent of the variation in SI for the 16 bedrock plots used in the analysis (equation F1, Table 9). This one variable explains so much of the variation in SI that the addition of other variables does not significantly increase the R^2. Tree growth response to increasing root space is usually curvilinear (Ralston, 1964). Likewise, the relationship between SI and DBR may be curvilinear as indicated by equation F2 which contains a square root transformation of DBR. However, when an interaction term between DBR and CFRAGA is introduced into the equation a higher R^2 value is obtained with DBR alone than with the square root of DBR. Equations F2 and F3 indicate a curvilinear relationship between SI and DBR while, in contrast, equations F4 and F5 indicate a linear relationship. Equations F4 and F5 indicate that SI increases with an increasing depth to bedrock at a greater rate at lower coarse fragment contents than at higher coarse fragment contents (Figure 3).

Moraines

Seven of the screened variables were significantly correlated with SI (Table 8). CLA has the highest simple correlation with SI. As discussed for bedrock sites, the negative relationship of CLA with SI is unexpected. GRC and CFRAGC are negatively correlated with SI. This trend of higher site index with lower coarse fragment content has been found in other studies (Ralston, 1964).

Equation F6 contains three variables (DRL, CLA, and CFRAGC) and explains 60 percent of the variation in site index for the 25 plots used in the analysis (Table 12). Replacing the variables DRL and CFRAGC with an interaction term between the two variables increases the R^2 slightly (equation F7). SI increases as DRL increases at a greater rate for sites with lower CFRAGC values (Figure 4). Sites with a higher CFRAGC have lower SI. The positive relationship of SI with DRL is expected since better growth is associated with increased rooting depth (Pritchett, 1979). The negative relationship of SI with CFRAGC is also expected. An increase in coarse fragment content is usually associated with poorer tree growth (Ralston, 1964).

The regression coefficient for CLA indicates that as clay content increases SI decreases. The negative relationship of SI with CLA is difficult to interpret. As previously discussed, an increase in clay content is usually associated with an increase in moisture and nutrient availability and thus increased growth. The percent clay found in the A horizon of the sample plots is quite low, ranging from two to 11 percent. It is questionable whether the relationship of SI with CLA is real or a spurious relationship resulting from multicollinearity in the data set.

Glaciofluvial

Nineteen of the screened variables are significantly correlated with SI (Table 8). SLOPE has the highest simple correlation. The correlation is negative, indicating that higher SI values are associated with the lower slopes. There is no obvious reason for this strong relationship. The sample plots are either level or gently sloping, with slopes ranging from zero to 12 percent. These low slopes would not be expected to influence SI, and thus it would appear that some undetermined factor or factors associated with the sloping sites are related to the lower SI values.

It is surprising that the fine sand variables are negatively correlated and the coarse sand variables are positively correlated with SI. This suggests that sites with a higher coarse sand content and a lower fine sand content have higher SI. This trend contradicts the expected trend of coarser textured soils having poorer nutrient and moisture availability and thus poorer tree growth.

SI is positively correlated with SCDIF, indicating that the greater the difference in silt plus clay content from the surface to the subsurface, the higher the SI. Five depth variables (THAB, DPC, DMRL, DER, and DMR) are positively correlated with SI. This trend of increased SI with increased soil depth is expected.

MR is negatively correlated with SI, thus indicating that moist sites have lower SI. The pH of the BC and C horizons are negatively correlated with SI. This relationship of lower SI with higher pH values is unexpected since the higher pH values are usually associated with better nutrient availability (Pritchett, 1979).

Equation F9 (Table 15), includes the two variables (SLOPE and DMRL) explaining 66 percent of the variation in SI for the 25 plots included in the analysis. The addition of an interaction term between SLOPE and DMRL (equation F10) increases the explained variation to 71 percent. The equation indicates that SI increases with increasing DMRL and with decreasing SLOPE. However, the interaction term indicates that for steep slopes SI increases at a greater rate as DMRL increases, in contrast to gentle slopes where SI does not increase as much with increased DMRL (Figure 5). The positive relationship of SI and DMRL is expected since increased soil depth is usually associated with better tree growth. However, as previously discussed, the relationship between SI and SLOPE is difficult to interpret.

Equation F10 predicted SI for the six check plots reasonably well. However, all of the check plots have a SLOPE of zero. Thus, the SLOPE term in the equation was not well tested.

Equation F11 computed with the six check plots included, explains only 65 percent of the variation in SI. The decrease of six percent explained variation suggests two possibilities: (1) the relationship between SI, SLOPE and DMRL may be peculiar to the 25 computation plots, and not to the target population; or (2) the five check plots may not be representative of the plots included in the analysis.

Lacustrine

Twelve of the screened variables are significantly correlated with SI (Table 8) with PHBC having the highest simple correlation with SI. The negative correlation of PHBC with SI is unexpected. However, the red clays which have the higher SI values also have the lower PHBC values, thus correlation of PHBC with SI may be spurious.

HUC has the second highest simple correlation with SI. The correlation is negative indicating that sites with lower hue values (redder) have higher SI values. However, the red clay sites have a higher SI, and have lower PHBC values, higher THA values and higher clay content values. There is no obvious reason for the red clay sites to have SI values higher than the grey silts.

The clay content variables for all four horizons are positively correlated with SI. As expected the depth variables THA and DMRL also are positively correlated with SI. In contrast, the variable DPC is negatively correlated with SI. However, DPC is negatively correlated with HUC, indicating that the better SI red clay sites have shallower C horizons than do the poorer gray silts showing lower SI values. This may explain the negative correlation of DPC with SI.

Equation F12 includes THA and PHBC and explains 73 percent of the variation in SI. When both variables are squared, the amount of variation explained increases to 75 percent (equation F16). This indicates that both variables are expressing curvilinear relationships with SI. SI increases with increasing A horizon thickness (THA) and decreasing pH of the BC horizon (PHBC).

Evaluation of the Regression Equations

Carmean (1975) states that most successful soil-site studies explain 65 to 85 percent of the variation in site index. The "best" equations (equations F5, F8, F11, and F16) explain 83, 65, 65, and 75 percent of the variation in SI for bedrock, morainal, glaciofluvial, and lacustrine sites, respectively. Thus, the final equations for these four landforms explain variation in SI reasonably well by Carmean's standards.

The final regression equations for bedrock, moraine, and glaciofluvial sites predict SI reasonably well for their respective check plots. From these preliminary tests of the equations, it appears that the equations may be useful for predicting SI. The four equations are well-suited for field use and each of the equations contains three or fewer variables. All of the variables are field measureable, except for two: CLA for morainal sites, and PHBC for lacustrine sites. These two variables can be estimated by simple laboratory analyses.

Use of Regression Equations and Prediction Tables

Assuming that the sample plots used to compute the regression equations adequately represent the target populations, we can use these equations to predict SI for other plots. The following is a description of how the regression equations and prediction tables might be used to estimate SI on a specific plot. The standard errors of the estimate for bedrock, morainal, glaciofluvial and lcaustrine sites respectively are: 1.28, 1.26, 1.26, and 1.07 metres.

1. Check if the plot is relatively homogeneous in soil conditions. If substantial variation in soil and topographic conditions occurs over the plot, the equations cannot be used to predict SI.

2. Determine the landform of the plot: bedrock, moraine, glaciofluvial, or lacustrine (page 36).

3. Check if the site conditions on the plot meet the criteria specified for the landform (page 46). If the conditions do not meet the criteria, SI cannot cannot be predicted using the results of this study.

4. Obtain an estimate for each variable in the appropriate equation (equation F5, F8, F11, or F16). These estimates should be averages of three samples. Determine if the values fall within the range of the data used for computation, as shown on the trend graphs (Figures 2, 3, 4, 5, and 6). These equations should only be used within the range of the data.

5. Calculate SI using the appropriate prediction equation or use the appropriate prediction table (Tables 11, 14, 15, or 19).

This study has practical value for forest management in northwestern Ontario. The forest land in this area varies considerably as to its productive capacity for different species. Site quality estimation methods aid the forest manager in selecting the most productive and valued trees for each area of land (Carmean, 1975). The most productive land can be identified for more intensive management.

Site index can be estimated for land supporting even-aged, well-stocked, undisturbed stands using Plonski's (1981) or Lenthall's (1985) site curves. However, forest managers need site index predictions for land supporting stands that do not contain jack pine, or are uneven-aged, very young, partially or fully cut, or poorly stocked. This study has revealed preliminary relationships between the site index of jack pine and features of soil and topography for four landforms: bedrock, moraine, glaciofluvial, and lacustrine. Using the results of this study, jack pine site index may be predicted based on soil and topographic features for the four landforms.

COMPARISON OF THIS STUDY WITH PREVIOUS STUDIES

Sixteen papers were reviewed from the literature concerning soil-site studies for jack pine; 10 previous studies were conducted in natural stands and six were conducted in plantations. Only three soil-site studies for jack pine have been conducted in Canada, two in northern Ontario and one in Saskatchewan. The only soil-site study for jack pine in northwestern Ontario is reported by Chrosciewicz (1963). The relationships between jack pine growth and various site factors were not quantified in Chrosciewicz's study. Thus, this study in natural stands is the first soil-site study for jack pine conducted in northwestern Ontario where soil-site relationships are quantified.

The data for all previous studies were obtained exclusively from sandy sites. In this study, data were collected from four landforms: bedrock, moraines, glaciofluvial, and lacustrine. Thus, this study is the first to report soil-site relations for jack pine in northwestern Ontario on a variety of landforms and soil types.

The amount and type of data collected varies considerably between this and previous studies. Different site attributes were measured for different studies. Some researchers stressed chemical properties while others concentrated on physical soil properties. Soil physical properties were stressed in this study. The total number of plots used in the analyses for previous studies ranges from 12 to 83. A total of 84 plots were used for computation in the final analyses in this study.

In the older studies site index values were obtained by using published site index curves. Wilde *et al.* (1964; 1965) and Wilde (1970) used average annual height growth rather than site index as a measure of tree growth. In this study, actual site index was obtained from stem analysis and used as a measure of site quality.

The type of data analysis used in the previous studies varies greatly. Subjective descriptions of relationships between jack pine growth and site factors were often used, largely due to the lack of sophisticated analysis techniques and computer facilities. In more recent studies, the relationships are often quantified with the use of simple regression and multiple regression analyses. Multiple regression analysis was used in this study to derive equations relating site index to various soil and site features.

Various soil and site attributes have been identified as being related to jack pine growth in previous studies as well as in this study. Each study differs in aspects such as: location; soil and landform; amount and type of data collected; and method of data analysis. Thus, direct comparison of the results obtained from the studies are difficult. The specific soil and site attributes found to be related to site index of jack pine are particular to each study. However, the following general comparisons can be made.

For each of the four landforms in this study some measure of soil depth was found to have a positive relationship with site index. Shetron (1969, 1972a, and 1972b) also found a strong correlation between soil depth and site index of jack pine. SLOPE was found to be negatively correlated with site index in this work. Shetron (1972b) found the best soils for jack pine were located in low topographic positions.

A number of investigators found jack pine growth to be significantly related to some measure of sand content. However, in this study no sand content variables were included in the final equations. Shetron (1972b) and Hannah and Zahner (1970) report site index values to be greater in soils with finer textured lenses. Finer textured lenses were found on only a few sites in this sample and thus no relationship between these lenses and site index could be established.

A number of studies concluded that SI is related to soil chemical factors such as cation exchange capacity, total nitrogen, available phosphorus, and available potassium (Wilde *et al.*, 1964; 1965). No nutrient analyses were carried out in this study, thus soil nutrient relationships were not tested.

Though much variation exists between the soil-site studies for jack pine, all the studies have the same general aim, that is to identify relationships between jack pine growth and soil and site factors. The existing jack pine soil-site studies do not adequately reveal these relationships for the wide range of soil and topographic conditions where jack pine occurs. This study has revealed some preliminary soil-site relationships for jack pine growing on bedrock, morainal, glaciofluvial, and lacustrine sites in northwestern Ontario. Further study using a greater number of site plots may more precisely define these relationships.

SUMMARY AND RECOMMENDATIONS

Relationships between site index of jack pine in the Thunder Bay area and features of soil and topography were studied using multiple regression analyses. Separate regression equations were derived for each of four landforms: bedrock, moraines, glaciofluvial, and lacustrine. These data were examined in preliminary and final analyses.

PRELIMINARY DATA ANALYSES

Preliminary analyses using data from 95 plots plus an additional 24 check plots lead to the following conclusions:

1) Detailed descriptions of soil and topographic conditions on study plots results in a large number of independent variables available for regression analyses. Using such large numbers of independent variables in regression analyses can lead to equations that explain a large percentage of variation, but which may be due to random rather than systematic variation. A systematic method was used to limit the number of independent variables used in the regression analyses. The method used for limiting the number of variables was to select variables in a sequence of steps based on specific, defined criteria.

2) Many soil and topographic variables are not independent of each other. Regression results are ambiguous when strongly interrelated variables are used in the analyses. This problem of multicollinearity, was alleviated by selecting a small number of variables that are not strongly correlated with each other for the analysis.

3) Substantial variation in site quality and in soil and topographic conditions within the four broadly defined landforms is obviously apparent. In order to adequately model soil-site

relationships for such highly variable soil groups, it would be necessary to have more plots that cover the entire range of soil and topographic conditions occurring on each landform.

4) Largely due to the problems of numerous independent variables, multicollinearity, and highly variable landform groups, the preliminary regression equations cannot be accepted as valid models for predicting SI.

5) Equation P1 for bedrock sites and equation P4 for lacustrine sites (Table 6) predict SI reasonably well for the check plots (Table 7). In contrast, equations P2 and P3 for morainal and glaciofluvial landforms, respectively, do not predict SI well for the check plots. Since the preliminary equations appear to be invalid, it is not surprising that equations P2 and P3 do not predict SI well for the check plots.

FINAL DATA ANALYSES

The three problems described above in the preliminary analyses were somewhat alleviated in the final analyses: (1) the large number of independent variables were limited for regression analyses in a sequence of systematic steps; (2) the problem of multicollinearity was alleviated by selecting a small number of variables not strongly correlated with each other; and (3) the four highly variable landform groups were more precisely defined. The final analyses using data from 84 plots plus an additional 15 check plots lead to the following conclusions.

1) The most important soil feature for predicting SI for jack pine appears to be soil depth. Each of the final regression equations for the four landforms contains a soil depth variable.

2) The final regression equation for two of the four landforms contain interaction terms between a coarse fragment variable and a depth variable. Site index decreases with increasing coarse fragment content.

Bedrock

3) Jack pine SI in the Thunder Bay area can be estimated using equations F3 or F5 (Table 9) or site index prediction Table 11 on lands that meet the criteria specified for shallow to bedrock sites (page 46). Equations F3 and F5 explain 77 and 83 percent of variation in SI (Table 8) and have standard errors of the estimate of 1.45 and 1.28 metres, respectively.

4) Depth to bedrock (DBR) has the highest simple correlation with SI, explaining 75 percent of the variation in SI for the 16 computation plots. The relationship between SI and DBR is positive and curvilinear; that is, SI increases as depth to bedrock increases (Figure 2).

5) An interaction term (the product of DBR and coarse fragment content of the A horizon (CFRAGA)) was added to the equation with DBR alone; this interaction term increased the R^2 value significantly to 0.83 (Table 9). Thus SI increases with increasing depth to bedrock (DBR) but the increase is greater for soils having a smaller content of coarse fragments in the A horizon (CFRAGA) (Figure 3).

6) Equations F2 and F4 predict SI within 2.3 metres (maximum residual value) for the four check plots (Table 10).

Moraines

7) Jack pine site index in the Thunder Bay area can be estimated using equation F8 (Table 12) or site index prediction Table 14 on lands that meet the criteria specified for moraines (page 46). Equation F8 explains 65 percent of the variation in SI and has a standard error of the estimate of 1.26 metres.

8) Clay content of the A horizon (CLA) has the highest simple correlation with SI (Table 8) explaining 28 percent of the variation in SI. Though greater clay content is usually associated with better growth (Pritchett, 1979), CLA is negatively correlated with SI. Possibly this unexpected relationship is not a "true" one but a spurious relationship because of associations

with other features that are more directly related to SI.

9) The "best" equation (equation F8, Table 12) developed for moraines contains CLA and an interaction term (the product of depth to a restricting layer (DRL) and coarse fragment content of the C horizon (CFRAGC)). Thus SI increases with increasing depth to a restricting layer (DRL) but the increase is greater for soils having a smaller content of coarse fragments in the C horizon (CFRAGC) (Figure 4).

10) Equation F7 predicts SI within less than one metre of the observed SI (maximum residual value) for the five check plots (Table 13).

Glaciofluvial

11) Jack pine site index in the Thunder Bay area can be estimated using equation F11 (Table 15) or site index prediction Table 17 on lands that meet the criteria for glaciofluvial sites (page 46). Equation F11 explains 65 percent of the variation in SI and has a standard error of the estimate of 1.26 metres.

12) Percent slope (SLOPE) has the highest simple correlation with SI (Table 8) explaining 49 percent of the variation in SI. The correlation is negative, indicating that higher SI values are associated with gentler slopes. There is no obvious reason for this relationship.

13) The "best" equation (equation F11, Table 15) for glaciofluvial sites includes SLOPE, depth to a moist restricting layer (DMRL), and an interaction term (the product of SLOPE and DMRL). Thus SI increases with increasing depth to a moist restricting layer (DMRL) and with decreasing slope steepness (SLOPE). For steep slopes SI increases at a greater rate as DMRL increases, in contrast to gentle slopes where SI does not increase as much with increased DMRL (Figure 5).

14) Equation F10 predicts SI within 2.2 metres of the observed SI (maximum residual value)

for the six check plots (Table 16).

Lacustrine

15) Jack pine site index in the Thunder Bay area can be estimated using equation F16 (Table 18) or site index prediction Table 19 on lands that meet the criteria specified for lacustrine sites (page 46). Equation F16 explains 75 percent of the variation in SI and has a standard error of the estimate of 1.07 metres.

16) The pH of the BC horizon (PHBC) has the highest simple correlation with SI (Table 8), explaining 56 percent of the variation in SI. The negative correlation of PHBC is unexpected and may be a spurious relationship because of associations with other features that are more directly related to SI.

17) The "best" equation (equation F16, Table 18) for lacustrine sites contains PHBC and the thickness of the A horizon (THA). Thus SI increases with increasing thickness of the A horizon (THA) and with decreasing pH of the BC horizon (PHBC). Both THA and PHBC have curvilinear relationships with SI (Figure 6).

Evaluation of the Regression Equations

18) The "best" equations (equations F5, F8, F11, and F16) explain 83, 65, 65, and 75 percent of the variation in SI for bedrock, morainal, glaciofluvial, and lacustrine sites respectively.

19) The final regression equations for bedrock, moraine, and glaciofluvial sites predict SI reasonably well for the check plots, thus the final regression equations may be well-suited for field use in estimating SI for jack pine.

20) This study has practical value for forest managers in northwestern Ontario. Using the prediction equations and tables, jack pine site index can be estimated on land supporting stands that contain no jack pine, or are uneven-aged, too young to use conventional site

curves, partially or fully cut, or poorly stocked.

COMPARISON OF THIS STUDY WITH PREVIOUS STUDIES

Sixteen papers were reviewed from the literature describing soil-site relations for jack pine. A comparison of this study and these previous studies leads to the following conclusions.

1) This study is the first soil-site study for jack pine made in northwestern Ontario where soil-site relationships are expressed in quantitative terms.

2) This is the first soil-site study for jack pine on bedrock, morainal, or lacustrine sites.

3) This is the first study to use actual site index obtained from stem analysis. Most other studies use site index values obtained from older harmonized site index curves.

4) The specific soil and site attributes found to be related to the site index of jack pine differ greatly among these 16 studies as well as with this work. Thus, results can be considered as specific to each study; that is, the characteristics of each study area are unique as well as the research methods used in each study.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study has revealed some preliminary soil-site relationships for jack pine on bedrock, morainal, glaciofluvial, and lacustrine sites in northwestern Ontario. The following recommendations are made concerning further study.

1) The problems of numerous independent variables, multicollinearity, and highly variable soil commonly occur with all soil-site studies. Hopefully, the methods given here for dealing with these problems will be useful for future soil-site studies.

a) A more adequate method of limiting the number of independent variables must be developed. Variables were selected in this study by a sequence of steps based on specific criteria. This method is appropriate, but it is quite time consuming and could be improved.

b) The use of multivariate statistical techniques should be explored for use in soil-site studies. Many soil and topographic features are interrelated. Multivariate techniques eliminate the problem of multicollinearity. Factor analysis could also be used for limiting the number of independent variables.

c) The soil population for which a soil-site study is made should be precisely defined. If the defined soil population has much internal variation it then becomes necessary to obtain data from a large number of plots that cover the defined range of soil and topographic conditions. Quite clearly, the greater the internal variation of a soil population, the greater the number of plots needed to adequately model soil-site relationships. Substantial variation in soil and topographic conditions is apparent in the Thunder Bay area. The number of computation plots used in this study was limited. In future studies, the number of plots should exceed the number of independent variables.

2) Results from soil-site analyses should be adequately confirmed with an independent set of test plots. In this study, 4, 5, and 6 check plots were available for bedrock, morainal, and glaciofluvial sites, respectively; and no check plots were available for lacustrine sites. A greater number of check plots should be used for future testing of soil-site results.

3) The soil-site method is used to estimate the site quality for a small plot area in the same manner as individual trees are used for estimating site index. Methods are needed for applying these point estimates to larger spatial areas. Such methods would be particularly useful for developing systems of landscape classification and mapping.

4) Practical and economic limitations should be seriously considered in soil-site work. Soil and topographic data collection, laboratory analyses and statistical analyses can be very time-consuming and expensive and thus should be very carefully planned. The following is a list of

questions that have been faced by researchers in the past and should be considered in future soil-site work.

Study Area:

a) How should the boundaries of the study area be defined?

b) How should the soil population within the study area be stratified?

Stand and Plot Selection:

c) How should the stands be located; randomly or purposively? This will depend on the desired scope of inference.

d) How can the range of soil and topographic conditions within the defined soil population be adequately sampled?

e) How will the study plots be located within the stands?

Data Collection:

f) How will site quality be estimated; SI from published curves, stem analyses, or are there other measures of site quality that can be considered?

g) What soil and topographic features should be measured?

h) How will the soil data be collected; from one or more soil pits? How will soil pits be located; randomly or purposively?

i) Should soil samples be collected? How many soil samples should be collected from each plot? Should the samples be collected from all horizons, some horizons or from specified zones in the profile? Should horizon samples from each pit be separately analyzed, or should samples from the same horizons be combined?

Laboratory Analyses:

j) What physical analyses are required and which soil samples should be analyzed?

k) What chemical analyses are required and which soil samples should be analyzed?

l) Is there enough time and money available for the laboratory analyses? Are the required laboratory facilities available?

Data Analyses:

m) What data analysis method is most appropriate; multiple regression analysis, multivariate data analysis?

n) How many plots are needed for the verification of results?

Extrapolation of Results:

o) Can results of soil-site analyses be applied to areas outside of the study area? If so can criteria be developed that define how to apply soil-site results to these other areas?

p) How can soil-site results be used as a basis for developing systems of landscape classification that can accurately classify forest site quality?

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APPENDICES

APPENDIX I. Field Tally Sheet

1 GENERAL	SOIL-SITE STUDY	site index species	site index(m)	plot #
date(Y/M/D)	name(s)	soil category	tentative soil category	
topo map #	latitude	longitude	photos roll # picture #	soil samples

location

comments

lab analysis results

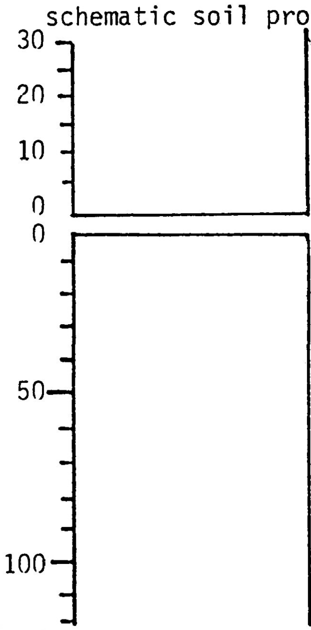
2 TOPOGRAPHY		diagram
slope length(m)	site position	
upslope length(m)	☐ crest ☐ upper	
slope(%)	☐ middle ☐ lower	
aspect(°)	☐ toe ☐ depression	
site surface shape ☐ cve ☐ cvx ☐ str	☐ level	

3 SOIL	SOIL-SITE STUDY	date(Y/M/D)	name(s)	plot #

1		2	3	4	5	6		7					8				9				10	11
lab sample				field soil texture <2mm		colour		mottles					structure				consist.				eff.	pH
	no.	horizon	horizon depth(cm)		moisture	aspect		aspect	colour	ab f c m	si f m c	co f d p	grade	class	kind	mod.	dry	moist	wet	plastic	deg	

2	12							13				14
	coarse fragment							roots				general comments
	%	Gr		Co		St		Ab	Si	Or	dist	
horizon	vol.	%	type	%	type	%	type	v f p a	v f m c	v n o b	in ex mx	

schematic soil profile



thickness of	moss	L	F	F/H	H	comments
sample 1						
sample 2						
sample 3						
sample 4						
sample 5						
average						

additional comments

	depth from surface to(in cm)	
	bedrock	
	carbonates	
	distinct mottles	
	prominant mottles	
	grey gley	
	bottom of zone of	
	maximum rooting	
	bottom of effective	
	rooting	

APPENDIX II: Average Plot Tally Sheet

SOIL-SITE STUDY: Pj ( )	date 84	name Schmidt	site index(m) bh tot	mode of dep. R G M L	soil samples	plot #

topo map # 5 2	latitude	longitude	photos roll photo	location

lab analysis

sample #	pit 1	pit 2	pit 3	horizon	depth	texture	colour	mottles colour	mottles ab	mottles si	mottles co	struct grade	struct class	struct kind	consist.	boundary	c. frag. total	c. frag. gravel	c. frag. cobbles	c. frag. stones	roots ab	roots si	comments
					-																		
					-																		
					-																		
					-																		
					-																		
					-																		
					-																		
					-																		
					-																		
					-																		

TOPOGRAPHY	
slope length(m)	
upslope length(m)	
slope(%)	
aspect(°)	
site surface shape: cvx str cve	
site position: crest, lower, level, upper, toe, middle, depression	
soil moisture regime	
soil drainage class	
pore pattern	
forest humus form	
soil classification	
method of excavation: shovel auger	
depth of pit(cm)	

DEPTH from surface(cm)	
bedrock	
water table	
seepage	
carbonates	
distinct mottles	
prominent mottles	
grey gley	
bottom of zone of..	//////
maximum rooting	
effective rooting	
visible rooting	
FEC soil type	
FEC vegetation type	
family part. size class	

schematic soil profile

30, 20, 10, 0

0, 50, 100

COMMENTS

cobbles-top	
cobbles-bottom	
cobbles-total	
stones-top	
stones-bottom	
stones-total	
depth to silt lenses	
depth to basal till	