Jack pine site quality in relation to soil and topography in north central Ontario

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Site index for jack pine (*Pinus banksiana* Lamb.) was determined by stem analysis using dominant and codominant trees on each of 99 site plots located in mature, well-stocked, even-aged jack pine stands. Plots located on four major glacial soil groups showed a wide range of site index within each soil group. Separate multiple regression analysis showed that site index was significantly related to different soil and topographic features for each soil group: (*i*) for morainal soils shallow to bedrock (<1.0 m deep) ($R^2 = 0.83$), depth to bedrock and coarse fragment content; (*ii*) for deep morainal soils ($R^2 = 0.65$), depth to root-restricting layer, coarse fragment content, and clay content; (*iii*) for outwashed glacial sands ($R^2 = 0.65$), depth to root-restricting layer and slope steepness; and (*iv*) for glacial lacustrine soils ($R^2 = 0.75$), thickness of A horizon and pH of the BC horizon. These results indicate that site quality for jack pine on each of these four general soil groups is related to soil features associated with the quantity and quality of soil most favorable for root development. Results are illustrated by trend graphs, and site index prediction tables are given for each of the four soil groups.

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L'indice de qualité de station pour le pin gris (*Pinus banksiana* Lamb.) a été déterminé au moyen d'analyses de tiges sur des sujets dominants et co-dominants dans chacune des 99 places d'études localisées dans des peuplements denses et équiennes de pin gris. Les places d'études localisées dans quatre importants groupes de sols glaciaires ont montré une grande variation d'indices de qualité de station pour chaque groupe de sol. Des analyses de régression multiple séparées ont montré que l'indice de qualité de station était relié de façon significative aux propriétés topographiques et pédologiques de chaque groupe de sol: (*i*) pour les sols morainiques superficiels (<1,0 m de profondeur) ($R^2 = 0{,}83$), la profondeur de sol jusqu'à la roche-mère et le contenu en particules grossières; (*ii*) pour les sols morainiques profonds ($R^2 = 0{,}65$), la profondeur jusqu'à l'horizon induré, le contenu en particules grossières, ainsi que le contenu en argile; (*iii*) pour les sables glaciaires d'outwash ($R^2 = 0{,}65$), la profondeur jusqu'à l'horizon induré et la déclivité du terrain; et (*iv*) pour les sols glacio-lacustres ($R^2 = 0{,}75$), l'épaisseur de l'horizon A et le pH de l'horizon BC. Ces résultats montrent que la qualité de station du pin gris pour chacun des quatre groupes de sol est reliée aux caractéristiques pédologiques associées à la quantité et à la qualité du sol le plus favorable au développement des racines. Ces résultats sont illustrés par des graphes et on présente des tableaux de prévision de l'indice de qualité de station pour chacun des quatre groupes de sol.

[Traduit par la revue]

Introduction

Jack pine (*Pinus banksiana* Lamb.) is among the most widespread and most economically important forest trees in North America (Fowells 1965; Riemenschneider 1982). The annual harvest of jack pine in Ontario is only exceeded by that of spruce (*Picea mariana* (Mill.) B.S.P. and *P. glauca* (Moench) Voss) (Smyth and Ramsey 1984). The large area of jack pine in the boreal forest is related to a long history of natural wildfires (Larsen 1980; Rouse 1987). Jack pine very commonly regenerates in pure even-aged stands following wildfire because of prolific seed dispersal from serotinous cones found on older fire-killed trees. These pure even-aged stands are particularly common on frequently burned dry sites such as glaciofluvial sands and shallow to bedrock areas. Jack pine also commonly occurs following fires on morainal soils and occasionally on moist glacial lacustrine clay soils.

Intensive forest management for jack pine requires the ability to estimate site quality and the growth and yield associated with different levels of site quality. Armed with site quality and yield information, intensive management can be concentrated on productive forest lands capable of quickly producing large yields that may include valued poles and sawlogs.

Jack pine site quality in north central Ontario is easily estimated in older, even-aged, well stocked, undisturbed jack pine stands using Plonski's (1974) or Lenthall's (1986) site index curves. However, site quality is more difficult to assess when stands are composed of species other than jack pine, stands have only scattered jack pine of different age-classes, or jack pine stands are very young, partially or completely cut, or poorly stocked. Accordingly, forest managers require means for estimating jack pine site quality on all forest lands regardless of the condition or composition of existing forest cover.

The objective of this study is to identify relationships that exist between jack pine site index and features of soil and topography for land where jack pine presently occurs or may be managed in the future. Results of these soil–site analyses can be used for estimating site quality for jack pine where stands and trees are not suitable for directly estimating jack pine site index using site curves. These soil–site results also provide a quantitative basis for identifying features related to site quality that can be used in forest land classification programs now underway in northern Ontario (Nicks 1985; Sims et al. 1986).

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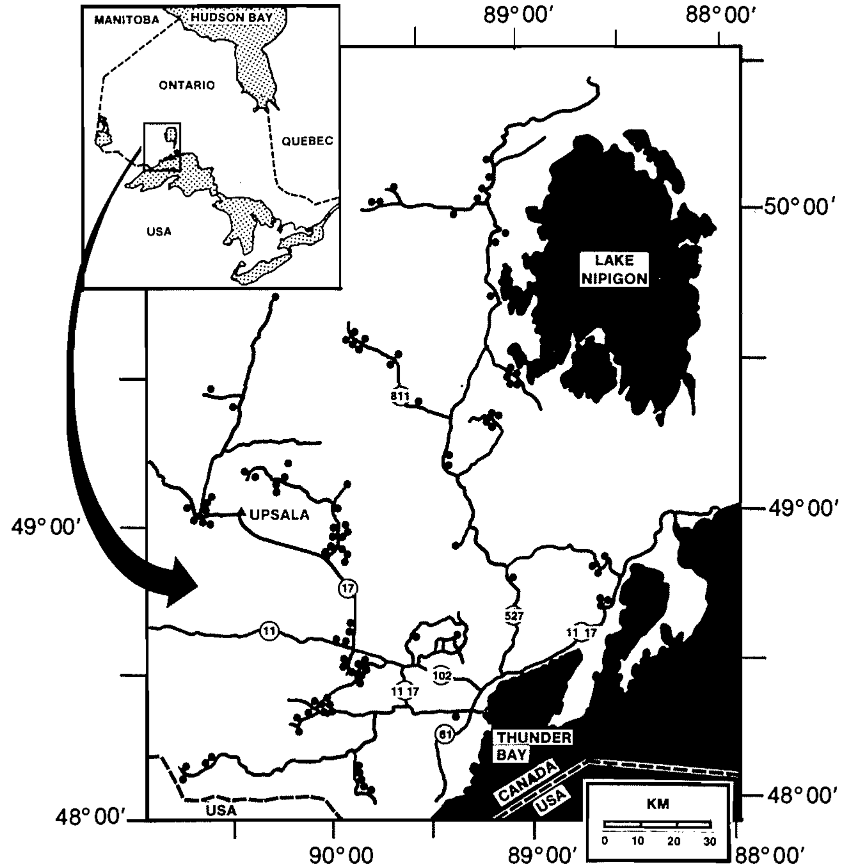

FIG. 1. Locations for 99 site plots used for studying soil–site relations of jack pine in north central Ontario.

Study area

A total of 141 site plots were located in north central Ontario in mature (older than 50 years), well-stocked, even-aged, undisturbed jack pine stands. Stem analyses using three to five dominant and codominant trees from each of these plots were used for developing polymorphic site index curves for jack pine (Lenthall 1986). Soil and topographic information also were taken from 99 of these site plots and were used as the basis for this soil–site study. Locations for these 99 plots are indicated in Fig. 1

Each plot was about 0.08 ha in size and plot locations were selected in well-stocked, even-aged portions of stands where microtopography was even and unbroken and where soil conditions were relatively similar. An effort was made to locate plots on four major glacial soil groups commonly found in north central Ontario: (*i*) morainal soils shallow (<1.0 m deep) to bedrock (20 plots); (*ii*) deep (>1.0 m deep) morainal soils (30 plots); (*iii*) outwashed glacial sands (31 plots); and (*iv*) glacial lacustrine soils (18 plots). Soil and site quality descriptions for these four general soil groups are as follows.

(*i*) Morainal soils shallow to bedrock: These soils have depths to bedrock of 1.0 m or less and have extremely variable amounts of coarse fragments. Areas having these shallow soils may also have pockets of deeper till between outcrops of bedrock or large boulders. Accordingly, soil conditions and site index can vary greatly depending upon depth and coarse fragment content. Site index can be good where deeper soils with few coarse fragments are found. In contrast, very poor site index occurs where soils are very shallow and contain many coarse fragments.

(*ii*) Deep morainal soils: These soils have depths to bedrock greater than 1.0 m and have large variations in content of coarse fragments. Content of silt and clay is variable and rooting depth is frequently restricted by basal till, gley, mottles, or a water table. Better site indices occur in areas having deep depths to a root-restricting layer and few coarse fragments. In contrast, poorer site indices occur where depths are shallow to a root-restricting layer and where large amounts of coarse fragments are found.

(*iii*) Outwashed glacial sands: These are outwashed or deltaic glacial sands that have few or no coarse fragments. Stratified sand or silty bands often occur in subsoils (B and C horizons) as a result of the sorting action of glacial meltwater. Rooting depth may be restricted because of very coarse sandy subsoils or gley and mottling where soils are imperfectly drained. Good site indices occur on level areas that are deep to root-restricting layers, whereas poorer site indices occur for steeper areas having shallow depths to a root-restricting layer.

(*iv*) Glacial lacustrine soils: These are clayey and silty soils deposited by glacial lakes. West and southwest of Thunder Bay, subsoils are usually acidic, have large amounts of clay, and are reddish in color. Other lacustrine deposits occur north of Thunder Bay where subsoils are less acid, silty, and greyish in color. Subsoils of all lacustrine soils have high bulk densities, low macropore space, few roots, and may be mottled or gleyed in poor and imperfectly drained areas. Surface layers (Ah, Ae horizons) of lacustrine soils vary greatly in thickness and have large amounts of organic matter and well-developed granular or subangular blocky structure. Exceptionally good site indices for jack pine occur where well-drained lacustrine soils have deep surface soil layers.

Methods

Site index determination

Three to five well-formed, uninjured, dominant, and codominant jack pine were selected for stem analysis on each of the 99 plots (Lenthall 1986). Trees were sectioned at the base, at 0.75, 1.3, and 2.0 m, then at each 1-m interval up to 13.0 m, and at 0.50 m thereafter. Age at each sectioning height was determined in the laboratory, and then average height–age curves were computed and graphed for each plot. These average height–age curves were used to determine site index as the average height of dominant and codominant trees 50 years after they reached breast height. Site index based on breast height age was used because Lenthall (1986) found that the dominant and codominant jack pine on these same plots had slow and erratic height growth below breast height followed by more rapid and consistent height growth after reaching breast height. Lenthall found that curves based on breast height age were more precise than curves based on total age.

Soil descriptions and analysis

Three 1-m^2 soil pits were dug on each plot to a depth of 1 m or to bedrock. A soil profile description was made for each pit according to standard Canadian methods (Day 1983). The following characteristics were recorded for each soil horizon: horizon depth and boundaries, texture class, size and distribution of coarse fragments, soil colour, mottle description, soil structure, soil consistence, and root abundance. Additional measurements included depths to bedrock, visible water table, water seepage, carbonates, mottles, gley, and soil depth having prominant and common roots.

Four major soil horizons (A, B, BC, C) were sampled in each of the three pits for laboratory analyses (McKeague 1978). For each horizon, samples from the three pits were composited and the composite sample was used to determine the following: percent gravel; percentages of sand, silt, and clay estimated by the pipette method; soil pH measured in 0.01 M $CaCl_2$; percent organic matter for the A, B, and BC horizons measured using the modified Walkley–Black method.

Statistical analyses

The four general soil groups represented four distinctly different soil populations. The shallow to bedrock moraines and deep moraines characteristically had large and variable amounts of coarse fragments. In contrast, the coarser textured outwashed sands had few or no coarse fragments but often had deeper rooting depths. The lacustrine clays and silts also had few or no coarse fragments but rooting depths were often limited by dense and less well-aerated subsoils. Statistical analyses were made separately for each of these four soil groups because each had distinctly different soil characteristics that might result in different relations between site quality and soil features (i.e., even though site index varied greatly within each soil group, the soil and topographic features associated with this site quality variation might differ, depending upon soil group).

Precision of soil–site regression equations can be confirmed by independently selected "check plots". Accordingly, check plots were randomly selected and withheld from the shallow to bedrock morainal soils, the deep morainal soils, and the outwashed glacial sands; no check plots were selected from the glacial lacustrine soils because of limited plot numbers for this soil group. Thus the shallow to bedrock morainal soils were represented by 16 computation and 4 check plots; the deep morainal soils had 25 computation and 5 check plots; outwashed glacial sands had 25 computation and 6 check plots; the lacustrine soils had 18 computation plots.

Multiple regression equations were developed for each of the four soil groups using the regression procedure of SPSSx (Nie 1983). These computed equations related site index (SI) to sets of soil and topographic variables; the coefficient of multiple determination (R^2) was used to estimate the precision of these analyses. Subsets of the independent variables to be used in the regression analyses were identified using "all-subsets regression by leaps and bounds" (Becker and Chambers 1984). This procedure selects the subset having the highest R^2 in which all variables significantly (0.10 level of probability) contribute to the R^2. Details of these statistical analyses are given by Schmidt (1986).

The regression equations from these analyses were used to compute SI values for each of the randomly selected check plots. Computed SI values were reasonably close[1] to SI values determined by stem analysis on the check plots. The regression equations were then recomputed with the check plots included. Theoretically, the inclusion of the check plots should produce equations having more precise estimates of the regression coefficients.

The final regression equations were computed combining both computation plots and the check plots. For each soil group the final equations were then used to compute trend graphs illustrating the relations between site index and statistically significant features of soil and topography. The equations for each soil group also were used to compute values for site index prediction tables designed for the field estimation of site index.

TABLE 1. Site index for jack pine on four general soil groups in north central Ontario

		Site index*			
Soil group	No. of plots	Mean	Range	SD	SEM
Shallow to bedrock† morainal soils	20	12.7	8.6–18.8	2.94	0.657
Deep morainal soils	30	17.7	13.9–22.4	2.05	0.274
Outwashed glacial sands	31	17.8	11.9–21.0	2.02	0.363
Glacial lacustrine soils	18	18.3	13.6–20.8	2.01	0.474
Total	99	16.8	8.6–22.4	3.05	0.307

*Site index is total height (m) of dominant and codominant trees at 50 years breast height age. Average site index for each plot is based on stem analysis from three to five dominant and codominant trees.

†Shallow to bedrock morainal soils have depths 1.0 m or less to bedrock.

Results

Site index ranged from 8.6 to 22.4 m for the 99 plots (Table 1). Site index within each of the four defined broad soil groups also varied greatly, resulting in no significant site index differences between soil groups. These results indicate that the four broad soil groups alone are too variable in site index and soil conditions for use in estimating site quality for jack pine. Thus for each soil group precise estimations of site index requires the identification of specific features of soil and topography that are significantly related to jack pine site index.

The features of soil and topography found to be significantly related to jack pine site index are given in the multiple regression equations computed for each of the four soil groups (Table 2). These final regressions combined both original computation plots and check plots; this combination resulted in only small, nonsignificant changes in the regression coefficients compared with those based on computation plots alone. Coefficients of multiple determination (R^2) also were relatively unchanged when check plots were combined with computation plots. R^2 values were unchanged, for the shallow to bedrock morainal soils, slightly improved for the deep morainal soils, slightly decreased for the outwashed glacial sands.

[1]For the shallow to bedrock soils the residuals between measured and computed site index were 1.7 m or less for three of the four check plots. For the deep morainal soils residuals were 0.9 m or less for the five check plots. For the outwashed glacial sands residuals were 1.5 m or less for five of the six check plots.

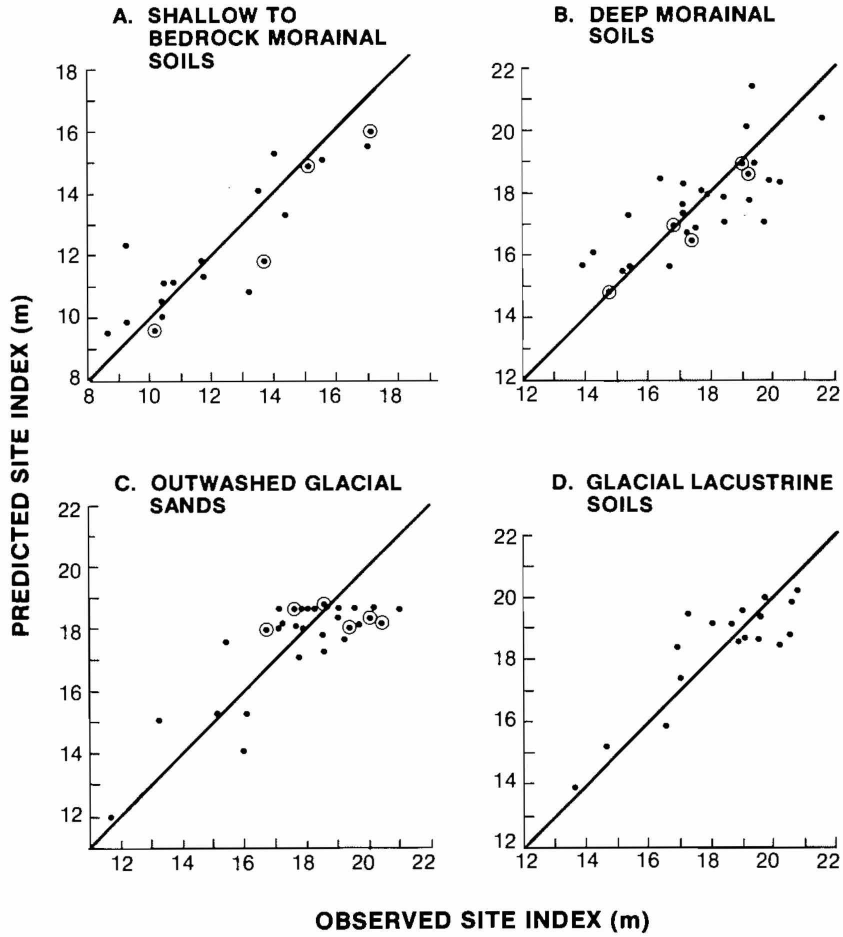

FIG. 2. Residuals showing differences between predicted and measured site index for plots established on four general glacial soil groups in north central Ontario. Check plots used to confirm preliminary regressions are denoted by circled symbols (⊙).

TABLE 2. Multiple regression equations expressing the relation between site index of jack pine and features of soil and topography for four general soil groups in north central Ontario

Soil group	No. of plots	Equation	R^2	SEE
Shallow to bedrock morainal soils	20	SI = 9.42 + 0.11DBR − 0.0006(DBR × CoFrag A)	0.83	1.28
Deep morainal soils	30	SI = 18.54 + 0.00051[DRL(100 − CoFrag C)] − 0.38 ClA	0.65	1.26
Outwashed glacial sands	31	SI = 17.56 + 0.10DRL − 0.73Slope − 0.0044 [DRL(20 − Slope)]	0.65	1.26
Glacial lacustrine soils	18	SI = 25.38 + 0.018 $(\text{ThA})^2$ − 0.24 $(\text{pH BC})^2$	0.75	1.07

NOTE: SI, site index is total height (m) of dominant and codominant trees at 50 years breast height age; DBR, depth to bedrock (cm); DRL, depth to root-restricting layer (cm) (e.g., basal till, coarse sandy subsoil, mottles, gley, water table, bedrock, or carbonates); ThA, thickness of A horizon (cm); CoFrag A, coarse fragments in A horizon (%); CoFrag C, coarse fragments in C horizon (%); ClA, clay content of A horizon (%); pH BC, pH of BC horizon; Slope, slope steepness (%).

The regression equations for each soil group have reasonably high R^2 values, indicating that these equations explain from 65 to 83% of the observed site index variation within each soil group (Table 2). In addition, site index estimated using these equations agrees well with site index actually measured on each of the computation and check plots. Figure 2 illustrates this close agreement between predicted and observed site index for plots on each of the four general soil groups.

The four regression equations (Table 2) were used to compute trend graphs illustrating the relationship between site index and the soil and topographic features that are significant for each soil group (Fig. 3). The four equations also were used to compute values in site index prediction tables for each of the four soil groups for the field estimation of site index (Table 3).

For each of the four glacial soil groups soil depth was found to be closely related to site index: depth to bedrock was significant for the shallow to bedrock morainal soils; depth to a root-restricting layer was significant for the deep morainal soils and outwashed glacial sands; and thickness of the A horizon was significant for the glacial lacustrine soils (Tables 2, 3; Fig. 3). For each soil group these depth relations can be interpreted as a measure of the quantity of soil most favourable for root development. Surface soil layers (Ah and Ae horizons) of undisturbed forest soils in north central Ontario, when compared with subsoil layers (B and C horizons), have large amounts of organic matter

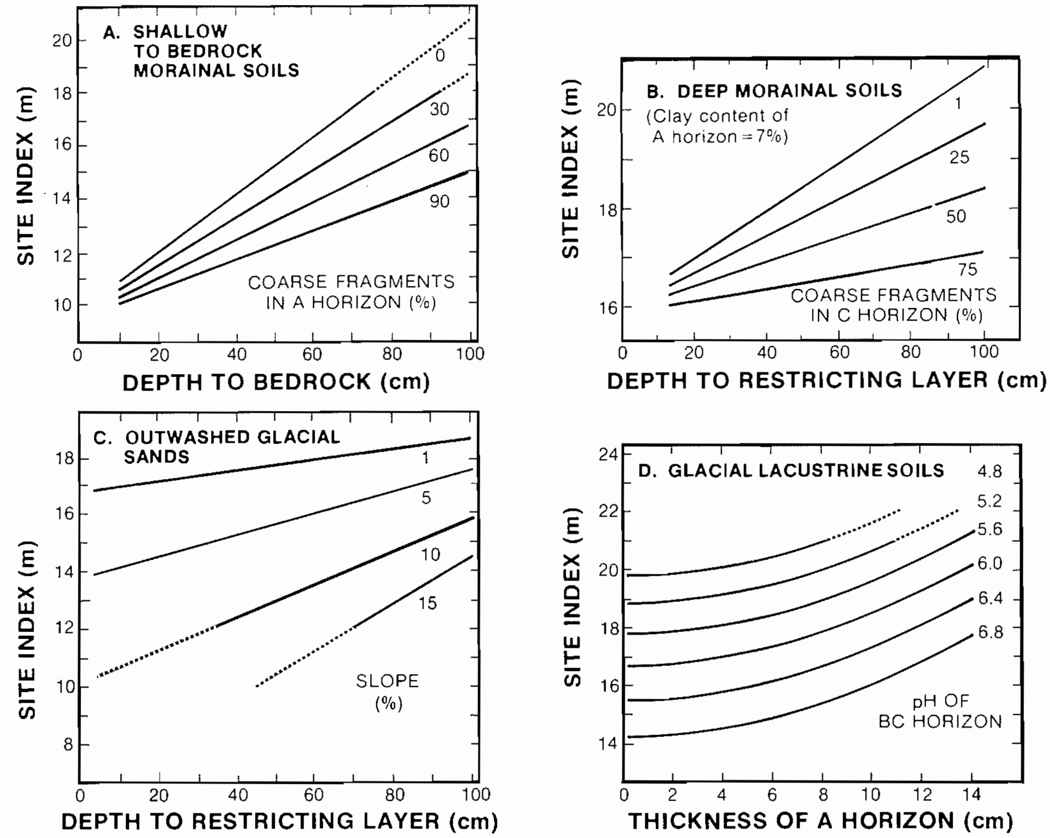

FIG. 3. Graphs illustrating the relationship between jack pine site indexes and features of soil and topography in north central Ontario. Features illustrated for these four glacial soil groups are significant based on multiple regression analysis.

and nutrients and excellent structure for soil aeration and water movement, hence favourable for the growth and functioning of roots. Accordingly, better site quality for undisturbed forest soils in north central Ontario is closely related to deeper favourable surface soil layers.

Coarse fragment content was significantly related to site index for the shallow to bedrock morainal soils and the deep morainal soils (Figs. 3A, 3B; Tables 3A, 3B). Coarse fragment content was not significant for the outwashed glacial sands and the lacustrine soil groups because these soils have few or no coarse fragments. Coarse fragments occupy soil volume that could otherwise be occupied by soil capable of furnishing moisture and nutrients for tree growth. Accordingly, large amounts of coarse fragments probably are associated with poorer site quality because coarse fragments reduce the volume of soil suitable for the development and functioning of tree roots.

The regression equation for deeper morainal soils includes a negative coefficient for the clay content variable, thus indicating that increased clay is associated with some decrease in site index (Tables 2, 3B). This relationship is unexpected because increased clay for coarse-textured soils should logically be associated with better tree growth resulting from greater amounts of available moisture and nutrients. Possibly this negative relationship with clay for deep morainal soils may be due to an association with other factors such as greater bulk density, less macropore space, and poorer aeration that could have a negative association with site quality.

For the outwashed glacial sands, site index decreased with increased slope steepness (Fig. 3C; Table 3C). The regression equation indicates that very good site indices occur on level areas that are deep to root-restricting layers. In contrast, steeper outwash sands with shallow depths to a root-restricting layer have much poorer site indices. A possible interpretation is that shallow sandy soils on steeper slopes have more rapid internal and lateral drainage; drier conditions thus result in poorer site quality.

For glacial lacustrine soils, site index decreased with increased pH of the BC horizon (Fig. 3D; Table 3D). Reasons for this decrease in site index are not obvious but possibly higher pH is indicative of the less acid grey lacustrine silts where site index is more variable and often poorer in contrast to the consistently good site indices observed on the more acid red lacustrine clays.

Discussion

Many forest soil-site studies have been published for other regions and for other North American and European forest species. These many soil-site studies are summarized by Coile (1952), Carmean (1975, 1982), Spurr and Barnes (1980), Pritchett and Fisher (1987), and Hagglund (1981). Soil-site studies for natural jack pine have been made in Minnesota (Pawluk and Arneman 1961; Frissel and Hansen 1965), in Michigan and Wisconsin (Shetron 1969, 1972*a*, 1972*b*; Hannah and Zahner 1970), in Northern Ontario (Chrosciewicz 1963), and in Saskatchewan (Jameson 1965). Soil-site studies also have been made for planted jack in Wisconsin (Wilde 1970; Wilde et al. 1951, 1964, 1965) and in New Brunswick (Hamilton and Krause 1985).

These soil-site studies show that results vary with different species, different regions, different soils, and topographic

TABLE 3. Site index* prediction tables for jack pine on four general glacial soil groups in north central Ontario

(A) Shallow to bedrock morainal soils

Depth to bedrock (cm)	Coarse fragments in A horizon 0–15%	15–30%	30–50%	50–70%
0–15	10.2	10.1	10.1	10.0
15–30	11.8	11.6	11.4	11.1
30–50	13.6	13.3	12.9	12.4
50–70	15.8	15.2	14.6	13.9
70–100	18.4	17.6	16.7	15.7

(B) Deep morainal soils

% clay in A horizon	0–30 cm depth†			30–70 cm depth			70–100 cm depth		
	10–40%‡	40–70%	70–100%	10–40%	40–70%	70–100%	10–40%	40–70%	70–100%
2–4	18.0	17.7	17.5	19.3	18.5	17.8	20.7	19.4	18.0
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

(C) Outwashed glacial sands

Depth to root-restricting layer (cm) §	Slope 0–3%	3–6%	6–9%	9–12%
0–30	16.7	14.8	12.8	10.8
30–60	17.3	15.7	14.1	12.5
60–90	17.9	16.7	15.5	14.3
90–120	18.4	17.6	16.8	16.0

(D) Glacial lacustrine soils

Thickness of A horizon (cm)	pH of BC horizon 4.8–5.3	5.3–5.9	5.9–6.5	6.5–7.0
0–4	19.3	17.9	16.2	14.5
4–8	19.9	18.5	16.8	15.1
8–12	21.1	19.7	18.0	16.2
12–16	22.8	21.4	19.7	18.0

*Site index is the total height (m) of dominant and codominant trees at 50 years breast height age.
†Depth to root-restricting layer (basal till, bedrock, mottles, gley, water table, till, or carbonates).
‡Percent coarse fragments in C horizon.
§Coarse sand, mottles, gley, and (or) water table.

and climatic conditions. However, generally we find that soil features closely related to site quality are those soil properties "...which influence the quality and quantity of growing space for tree roots" (Coile 1952). Topographic and climatic features can also be closely associated with site quality when topography and climate vary greatly within a study area. One reason for this association is that differences in topography and climate can be related to differences in soil moisture and nutrients, soil drainage, and local microclimate.

This preliminary soil–site study for jack pine in north central Ontario is for an area and for a species not previously studied using detailed stem analysis and sophisticated statistical procedures. Results of this soil–site study generally agree with previous soil–site studies and confirm Coile's views about the importance of quality and quantity of growing space for roots. This soil–site study also demonstrates that precision of soil–site analyses can be improved by stratifying diverse study areas into separate soil groups having similar geology and general soil profile characteristics.

A point of caution is that results from soil–site research apply only to the particular area studied and, further, only to the particular soil and topographic conditions sampled within that study area (Carmean 1975). Results of this soil–site study might also apply to other areas of northern Ontario having soil, topographic, and climatic conditions similar to the conditions that we studied in north central Ontario. However, these possible applications should be confirmed by independent testing. Of course more distant areas having greatly different soil, topographic, and climatic conditions would require separate soil–site studies.

Site index has been questioned regarding suitability as an index of forest site quality (Mader 1963; Carmean 1975; Monserud 1984). The major problem involves inaccuracies associated with older anamorphic site index curves developed using harmonizing methods. These inaccuracies are now well recognized and polymorphic site index curves based on stem analysis and nonlinear regression models are replacing many of the inaccurate older anamorphic site index curves.

Considerable efforts are still needed to link these newer, more precise polymorphic site index curves to more precise growth and yield tables and models. For example, if height growth of dominant trees on different sites is polymorphic, we might find that volume growth on these sites is also polymorphic. Furthermore, if site index curves based on breast height age are more precise than curves based on total age, we might find that volume growth models are also more precise when based on breast height age instead of total age.

The stem analysis procedures used in this study allowed us to directly observe site index on each plot rather than rely on estimations using questionable site index curves. Height–age curves based on stem analysis of dominant and codominant trees on each plot were used to directly observe site index; for our study, total height 50 years after reaching breast height was defined as site index. Thus we avoided the problems associated with estimating site index using older anamorphic site index curves or with curves based on total tree age. The stem analysis procedures we used probably result in much more precise site index values for each plot than are possible using older anamorphic jack pine site index curves (Plonski 1974), or even newer polymorphic curves computed using stem analysis from our plots (Lenthall 1986).

Our site index values are based on breast height age instead of the commonly used total age standard. The reason is that breast height age curves for jack pine are more precise than total age curves (Lenthall 1986); using breast height age avoids slow and erratic height growth below breast height that otherwise would contribute to less precise estimates of site index. Site studies for white spruce and red pine (*Pinus resinosa* Ait.) in north central Ontario reveal even more pronounced slow and erratic growth before reaching breast height than we found with jack pine. Thrower (1986) found little relationship between site index and years to breast height; site index curves computed for planted white spruce and red pine were thus based on breast height age, and growth intercepts were based on even higher starting points on the bole.

This preliminary soil–site study for jack pine has two major values for forest management in north central Ontario. First, our study provides a means for estimating site quality on lands having no usable trees for directly measuring jack pine site index. This is a recognized pragmatic goal of soil–site research for areas where trees are absent or where they are not suited for direct measurements of site index (Carmean 1975). For this goal the correlated site features need not be causative features; the most important considerations are that soil and topographic features be consistently correlated with site index, and that these features be easily recognized and measured in the field. Our multiple regression equations for four major glacial soil groups (Table 2) identify the significant soil and topographic features that are most closely related to jack pine site index. These equations are then used to construct site prediction tables (Table 3) designed for use in estimating jack pine site index in north central Ontario. Practicing foresters can make point estimates of site index merely by digging soil pits for observations of depth, coarse fragment content, and other features listed in these site index prediction tables. Thus these point estimates of site index using soil pits are comparable to point estimates obtained by directly estimating site index using dominant and codominant trees.

The second major value is that this preliminary soil–site study provides a quantitative basis for identifying soil and topographic features useful in landscape classification programs for north central Ontario that have the goal of classifying forest land productivity. Programs now underway in northern Ontario with such a goal are the "prime site" classification program (Nicks 1985) and the Forest Ecosystem Classification (FEC) program (Sims et al. 1986). Our soil–site study identifies specific soil and topographic features closely related to jack pine site index in north central Ontario. These same features could be used as a basis for defining or phasing soil units adopted by the prime site and FEC programs for north central Ontario.

For example, our results show that coarse fragment content and various depth expressions are major features closely associated with jack pine site index in north central Ontario. Thus, these features might be emphasized in landscape classifications that include interpretations for forest land productivity. Our results (Table 3) show that very poor site indices (SI <12 m) occur mostly on moraines that are very shallow (<30 cm) to bedrock. Poor site indices (SI 12–14 m) occur on moraines that are moderately shallow (30–50 cm) to bedrock; these poor site indices also occur on outwashed sands that are moderately shallow (<60 cm) to a root-restricting layer and that are on relatively steep ($>6\%$) slopes. In contrast, our results show that very good site indices (SI >20 m) are found on deep morainal soils that are deep to root-restricting layers and have few coarse fragments and relatively little clay in the A horizon; these exceptionally good site indices are also found on acid red lacustrine clay soils having deep A horizons. These examples illustrate that Table 3 and the soil–site equations (Table 2) can be used as a basis for defining soil depth, coarse fragment, and slope phases for use in landscape classification programs with the goal of classifying forest site quality.

Results from our relatively small and preliminary soil–site study can thus serve as a basis for designing landscape classification units suitable for classifying site quality of larger land areas. Designing these classification units still involves key questions about how easily these depth and coarse fragment values are recognized in the field and whether they occur in consistent and predictable patterns that can be used as the basis for landscape classification. However, these are questions requiring additional cooperative studies between forest soil–site investigators and forest soil surveyors. Our results can be further strengthened by additional plots representing soil groups such as the lacustrine clays for which there are presently minimum amounts of data.

Soil–site results should be considered only as correlations and not as evidence of cause and effect relations. Soil–site correlations are possible because certain soil, topographic, and climatic features are directly or indirectly related to materials (moisture and nutrients) and conditions (temperature, humidity) favourable for the growth of forest trees. The significant features determined by soil–site studies might be viewed as links in the many chains connecting tree response (site index) to causative factors such as moisture, nutrients, temperature, and light (Carmean 1975). Stone (1979, 1984) was concerned that soil–site correlations might be misinterpreted, particularly by those who emphasized moisture relations and neglected the nutritional role also involved in soil–site correlations.

Stone (1984) points out that we should be concerned not only with the site quality of a soil or a location but also with "What could it become?" Thus we should view forest site quality not as a fixed and unchangeable characteristic of forest land but as a measure of productivity that can either be improved by intensive management practices or be degraded by improper practices. For certain areas, forest site quality can be improved by practices such as fertilization, drainage, irrigation, or establishment of nitrogen-fixing vegetation. Site quality on certain areas also can be reduced by soil compaction and erosion, by excessive nutrient loss associated with severe fires, short rotation biomass harvesting, full-tree harvesting that removes nutrient-rich tree crowns from the area, and by severe site preparation that may remove slash, litter layers, and surface soil layers.

Increased emphasis on site quality evaluation is needed to parallel increased intensity of forest management. More knowledge about site quality is particularly needed for that vast area of forest land in the United States and Canada that will likely receive extensive management in the foreseeable future. Such lands will be managed on long rotations, only merchantable portions of trees will be removed, and fertilization or drainage will not generally be practiced. Accordingly, forest soils will be relatively unchanged except for occasional areas where unwise harvesting and site preparation practices cause physical and chemical soil damage. For these extensively managed lands site quality evaluation studies made in undisturbed natural stands probably will be applicable to the new natural forest that follows the harvesting of present stands.

More intensive forest management will require more detailed knowledge about the what, where, and why of forest site quality. The what of site evaluation requires precise quantitative standards such as more precise site index curves and more precise soil–site studies. The where requires the ability to accurately identify site quality for all portions of the landscape regardless of the kind or condition of forest cover. Knowing the what and where will thus enable us to better coordinate the various methods of site quality evaluation with forest landscape classification programs. But we need more than a knowledge of the what and where of site quality. We must have basic knowledge about the why of these observed site quality differences, which will enable us to develop practices for improving site quality, as well as practices for avoiding reductions in site quality. We should cooperatively apply ourselves to the task of acquiring more detailed knowledge about the what, the where, and the why of forest site quality and, furthermore, better define the forest growth and yield associated with differences in site quality.

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