LITERATURE REVIEW OF ECOLOGICAL PREDICTORS OF SITE PRODUCTIVITY

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DISCLAIMER

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FOOTHILLS MODEL FOREST MISSION

"to develop and recommend an approach to sustainability and integrated resource management through research and technology developed by means of collaborative partnerships".

RELATIONSHIP BETWEEN FOOTHILLS MODEL FOREST AND RESOURCE MANAGEMENT AGENCIES

The Foothills Model Forest represents a broad range of stakeholder groups with interest in Alberta's forests and how they are managed. However, Foothills Model Forest has no resource management authority or responsibility. The authority over, and responsibility for, the management of Alberta's public lands is vested in the Government of Alberta. The Government delegates certain rights and responsibilities to various resource industries and organizations which conduct their activities on public lands in Alberta. The Government of Alberta and other agencies and organizations will consider and respond to the recommendations of Foothills Model Forest from the perspective of their particular rights, responsibilities, obligations and stewardship commitments.

1. Introduction

Forest resource managers have developed a variety of methods for estimating forest site quality. Generally, these are grouped into two categories, direct and indirect.

Direct methods for evaluating site quality are widely used and accepted. They rely on some estimate of growth from existing forest trees.

One of the most direct measures of productivity for a site is total biomass or wood volume. This measure is, however, closely related to density, which is extremely variable in natural origin stands.

By far the most widely used measure of productivity is the site index relationship. Site index refers to the height a tree will attain on a given site at a base age (e.g., 50 years in Alberta). Site index is used extensively because it is relatively independent of stocking. This method, however, can only be applied to trees growing on a given site that have not been suppressed by overstorey competition. Site index is relatively useful in even-aged stands but is more difficult to use in mixed-age stands where some of the trees originated under overstorey cover. Since site index can only be determined directly for species growing on site, investigators have developed relationships to predict the site index of a species not on site by using between-species site index comparisons.

To accurately determine the site index, the trees should also be as old or older than the base site index age. This provides a direct estimate of site index. If trees younger than the base age are sampled, site index can be estimated using a site index relationship that is appropriate for the area. Researchers have been developing polymorphic site index curves that acknowledge the differences in growth pattern that a single species will display. In young stands, investigations have shown that a large number of samples are needed to define site index (Lloyd and Hafley 1977).

To facilitate the use of direct site productivity measures in juvenile stands, a method referred to as growth intercepts has been developed. Growth intercepts relate the early height growth of juvenile trees to an equivalent site index. Usually the first four to eight increments after breast height are correlated to the site index for a given stand.

Both site index and growth intercept measure the productivity expressed by the existing forest trees on the site; rather than the site's potential (Daubenmire 1984 and Kimmins 1987). Although site index is relatively independent of such factors as stocking, the influence of stocking, genetics and other incidents of stand history still have some impact on site index (Monserud and Rehfeldt 1990).

A final drawback to use of site index as a measure of productivity is that the overall variation in site index is relatively low. It can be difficult to statistically distinguish differences from the mean or average site (Grigal 1984).

Indirect measures of site productivity are extremely valuable because of their broad applicability. Indirect estimation of site productivity is based on ecological characteristics such as soil, vegetation and other site characteristics. Because they do not rely on the presence of an existing forest cover type, they can be applied to sites that are presently not forested. They can be used where the current forest cover did not develop as a free-growing stand and in juvenile stands. They also can be used to predict the productivity of species not presently on site (Carmean 1986, 1987).

This report reviews work that has been conducted on indirect measurement of site productivity. Most of the original reports consulted describe work conducted in British Columbia, Alberta, Ontario and the northwestern United States. The review is by no means exhaustive; rather, it summarizes the more important ecologically based productivity work with an emphasis on work that relates to species and ecological conditions similar to that found in the Foothills Forest.

For purposes of review, the material has been divided into soil/site based studies, vegetation based studies and ecosystem classification based studies.

2. Soil-Site Studies

The relationship between a site's soil and general landscape features and its ability to support forest growth has long been recognized.

Intuitively, soil and general site features should be closely related to site productivity. Soils are the medium through which trees receive their moisture and nutrients. Soil properties, in combination with general landscape features, affect soil aeration and the amount of moisture and nutrients available to the tree. Physical soil profile features even affect the pattern of root development of trees, while landscape position influences site microclimate.

Soil-based studies can be divided into two main types; those based on mapped soil survey units and those based on soil characteristics.

2.1 Mapped Soil Survey Studies

Mapped soil surveys are available for many areas in North America that support forest cover. It is not surprising, therefor, that investigators have tried to relate mapped soil units with forest productivity. Developing this type of relationship is especially appealing to forest managers because the soil units are mapped. This provides information on the extent and location of the units which is extremely valuable for planning purposes.

Much of the work examining relationships between soil mapping units and site index was conducted prior to the 1970s.

In the southern United States investigators such as Chandler et al. (1943) and Linnartz (1963) demonstrated significant correlations between soil series and site quality for loblolly (*Pinus taeda* L.), long-leaf (*Pinus palustris* Mill.), short-leaf (*Pinus echinata* Mill.) and slash pine (*Pinus elliottii* Engelm. var. *elliottii*). Phillips and Markley (1963) were similarly successful in correlating site quality of sweet gum (*Liquidambar styraciflua* L.) with soil series.

In contrast with the above studies, Carmean (1967) found that site quality, as measured by site index, did not differ significantly between soil types.

VanLear and Hosner (1967) examined the relationship between soil units and site quality, as expressed by site index, in yellow-poplar (*Liriodendron tulipifera* L.) in several counties in the southern United States. Four of the five soil mapping units examined had corresponding average site indices between 26.2 and 29.3 m while each unit had a standard deviation of at least 3.7 m and a standard error of approximately 1 m.

In South Africa, investigators found a poor relationship between soil series and site quality for a number of species (Schönau 1988). Evans (1974), however, was successful in identifying a relationship between site index of *Pinus patula* Schlect. & Cham. and soil 'set'. These soil 'sets' were developed specifically for describing forest plantations.

In west-central Alberta, Dumanski et al. (1973) studied the relationship between soil survey units and lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) productivity. The study area encompassed three distinct physiographic areas: the Alberta Plains, the Alberta Plateau-Benchlands and the Rocky Mountain Foothills. These physiographic areas are characterized by large differences in general soil characteristics as well as climatic differences. The study area, therefore, encompassed a wide variety of soil conditions. In addition to the soil mapping units, the study also examined two topographic characteristics, slope percent and aspect.

Three measures of site productivity were used in the evaluation, mean annual volume increment, periodic annual volume increment (PAI) and merchantable volume. The study was restricted to lodgepole pine stands which were considered fully stocked and were 60 to 110 years old. Of the three measures of productivity, only PAI produced soil groupings which were considered logical.

The effect of the topographic variables were examined for each physiographic unit. Sites characterized by sands and gravels were grouped separately. Aspect had a very slight effect on PAI in the medium to fine textured soils in all three physiographic regions. On the sand and gravel sites, however, northerly slopes were more productive than southerly slopes.

Optimal sites within the Alberta Plateau-Benchlands were associated with slopes of 20 to 30%. Steeper slopes had a marked decrease in PAI. In the Rocky Mountain Foothills, in contrast, productivity remained relatively constant, regardless of slope.

Two soil associations, Mayberne and Summit (Continental Till and Bedrock associations respectively), displayed the highest PAIs in the study area. The poorest productivity was associated with Erith and Fickle soil complexes which are composed of gleysolic and organic soils respectively. Table 1 outlines the results of this analysis.

Table 1. Mean and standard deviation for lodgepole pine PAI (m^3/ha) by soil association/complex (group differences significant at P=0.05) (from Dumanski et al., 1973).

Soil Association or Complex	Mean PAI (m^3/ha)	SD (m^3/ha)
Mayberne (Continental till) Summit (Bedrock)	7.76	5.20
Lendurm (Lacustrine) Marlboro (Cordilleran till) Maskuta (Bedrock)	4.54	2.30
Robb (Cordilleran till) Blackmud (Sand, gravel, loess) Lodge (Sand, gravel, loess) Jarvis (Sand, gravel, loess) Tri-Creek (Lacustrine)	3.91	1.75
Erith (Gleysolic) Fickle (Organic)	2.87	1.68

Based on the site indices of the Marlboro association, Dumanski et al. (1973) inferred ranking for all soil profiles in the study area (Table 2).

Table 2. Inferred ranking of soil profiles in the Hinton-Edson area (from Dumanski et al., 1973).

High	Bisequa Gray Luvisol "Bleached" Orthic Gray Luvisol Orthic Humo-Ferric Podzol
Intermediate	Orthic Gray Luvisol Dystric Brunisols Eutric Brunisols
Low	Brunisolic Gray Luvisol Eutric-Melanic Brunisol intergrades Gray Luvisols-Gray Brown Luvisol intergrades
Very Low	Gleysols Organics

In general, the utility of soil surveys for providing a broad, relative ranking of productivity is widely recognized (Crow and Rauscher 1984). More specific, quantitative relationships with soil survey units are, however, often difficult to establish.

Problems inherent in establishing quantitative relationships between soil units and productivity have been discussed in many papers.

Soil surveys are generally established for purposes other than for estimating forest productivity. The mapping units are not defined with respect to the soil characteristics which are important to tree growth (VanLear and Hosner 1967; Grigal 1984). Further, the soil characteristics which are important to tree growth will vary between species. Grigal (1984) suggests further soil surveys should incorporate characteristics such as surface horizon depth and coarse fragment percent since these are generally related to forest productivity.

Investigations often use soil survey information without considering topographic or landform characteristics. Grigal advocates including important topographic characteristics such as slope and aspect since these can have significant microclimatic effects. For example, a coarse textured soil on a northerly aspect may support a very productive site while on southerly aspects, the increased daytime heating may mean productive sites are restricted to finer textured soils. Very different combinations of soil and landform or topographic characteristics can result in similar growing conditions for tree species.

For certain species, difficulties in correlating soil units with productivity may arise because of the limited sites in which the species occurs (VanLear and Hosner 1967). Species which are ecologically restricted in range (e.g., to sites which have relatively good moisture and nutrient regimes) may be found within several different soil mapping units. Since the sites all show relatively good productivity, differences in productivity between the units would likely not be significant.

Finally, there are problems inherent in using site index, the most widely used indicator of productivity. It is generally recognized that a single species will display different growth patterns on different sites. To accommodate these differences, polymorphic site index curves have often been developed. Many investigations which have relied on site index as a measure of productivity did not, however, have access to appropriate polymorphic site index relationships (Daubenmire 1976 and Crow and Rauscher 1984).

2.2 Soil-Site Characteristic Studies

Extensive research has recently focused on the use of selected soil and site characteristics to evaluate forest tree productivity. This work has been facilitated, to a large extent, by improved electronic data analysis capabilities.

As early as 1935 investigators began evaluating the correlation between soil characteristics and site index (Coile 1935). These initial investigations showed that no single soil character of any horizon was well correlated with site index throughout the range of site index. Generally, site index was related to the amount of fine particles in the B horizon and by the thickness of the surface horizon. These early investigations also found that soil physical properties and topographic features were generally better for predicting site productivity than soil chemical properties (VanLear and Hosner 1967).

In Ontario, several studies have been conducted relating soil characteristics with site productivity for boreal species. The approach taken in Ontario is to develop separate relationships for different glacial landforms.

For jack pine (*Pinus banksiana* Lamb.), relationships were developed for shallow to bedrock, morainal, glaciofluvial and lacustrine soils. For shallow to bedrock soils, the depth to bedrock and the coarse fragments in the upper soil horizon proved to be important (Schmidt and Carmean 1988). For morainal soils the depth to the root restricting layer, clay content of the A horizon and coarse fragment content of the C horizon were all correlated to site index. On glaciofluvial soils the depth to the root restricting layer and slope were significantly related to productivity while on lacustrine soils the only factors related to productivity were the thickness of the A horizon and the pH of the BC horizon. Average site index for the shallow soil sites was 12.7 m while the range for the remaining sites is between 17.7 and 18.3 m. The standard error of the estimates was generally 1.26 to 1.27 m except for the lacustrine sites where the error associated with the soil-site regression was 1.07 m.

LeBlanc (1993) completed a similar study for jack pine in north eastern Ontario. For shallow morainal soils over bedrock, percent slope, thickness of the B horizon and the percent coarse fragments in the top 25 cm of the soil profile were related to site index. The r^2 of the resulting function was 0.78. In glaciofluvial soils, a function was developed based on depth to average rooting, depth to moisture restricting layer and percent silt in the B horizon ($r^2 = 0.51$). A somewhat better fit, $r^2 = 0.61$, was obtained for morainal soils based on depth to maximum rooting, pore pattern and percent sand and silt in the BC horizon.

LeBlanc also combined the data from Schmidt's study in north-central Ontario with that used in his north eastern Ontario study. The functions derived for the combined data were generally poorer than those developed for the separate data sets. These results indicated that different variables influence productivity in the two regions. The exceptions were shallow to bedrock soils and lacustrine soils which produced relatively strong relationship on the basis of the combined data.

In black spruce (*Picea mariana* (Mill.) B.S.P.) in north central Ontario, soils were again subdivided, this time into three categories: mineral, deep organic and peaty phase organic. Satisfactory relationships could only be developed for the two organic soil types. Significant characters in the deep organic sites included the thickness of the living moss and the microtopographic class. In the shallower peaty phase sites, the microtopographic class was again significant along with thickness of the Oh horizon and the clay content of the subsurface horizons (Buse and Baker 1991). Average site index was 9.3 m for the deep organic sites, 9.9 m for the peaty phase organic sites and 12.2 m for the mineral soil sites. The standard errors associated with the regression equations for the deep organic and peaty phase organic were 2.06 and 2.04 m respectively. This is much higher than the average difference in site index between the two types.

In the northwestern part of the province, the mineral soil sites were related to productivity through the thickness of the duff, the slope position, the depth to gleying, the depth to bedrock and moisture regime. On organic sites, the thickness of the Om layer, slope position, depth of the A horizon and the decomposition of the upper 25 cm of organic matter were all significantly related to productivity. The organic sites had average site indices of 10.0 m while the mineral soil sites averaged 13.9 m. The standard errors for the equations were 2.24 and 2.81 m respectively.

Soil-site studies involving white spruce (*Picea glauca* (Moench) Voss) in Ontario have been limited to plantations in the north central part of the province. Morainal, glaciofluvial and lacustrine soils were surveyed and separate relationships derived for each type. On morainal soils, the depth to the root restricting layer and the pH of the C horizon were both related to site index for planted white spruce (LaValley 1991). On glaciofluvial sites, only drainage class was a significant predictor for site index. On lacustrine soils, the type of clay (red versus gray), the hue of the C horizon and the depth to the root restricting layer were all significantly related to productivity. Standard errors for the equations ranged from 0.73 m for morainal soil (average site index of 7.4 m) to 0.74 m for lacustrine soils and 0.94 m for glaciofluvial soils (LaValley 1991). Average site indices ranged from a low of 7.4 m on morainal sites, 8.0 m on glaciofluvial site, to a high of 8.5 m on lacustrine sites.

Trembling aspen (*Populus tremuloides* Michx.) soil-site relationships were studied in northwestern Ontario. Soils were grouped by parent material into morainal, glaciofluvial and lacustrine types. Regression analysis indicated the depth to the root restricting layer was a significant factor in both the morainal and glaciofluvial soils (Li 1991). Additional significant characters in morainal soils were the silt and clay content of the A horizon and the coarse fragments in the C horizon. In the glaciofluvial soils, the only additional significant character was drainage class. In the lacustrine soils, the clay content of the C horizon and the depth to mottles were significant indicators or productivity (Li 1991). Average site indices for the sites ranged from a high of 20.6 m on lacustrine sites to a low of 18.8 m on morainal sites while the standard error for the equations ranged between 1.32 and 1.46 m. Clearly, the range of site indices surveyed was quite low and the errors associated with the equations is relatively large by comparison.

In a small study on 11 km^2 in Idaho, McGrath (1975) found elevation, effective rooting depth, wet consistency of the second horizon and texture of the third horizon to be significantly related to site index of interior Douglas-fir (*Pseudotsuga menziesii* var.*glauca* (Beissm.) Franco). For western larch (*Larix occidentalis* Nutt.), productivity as indicated by site index was related to the depth of the organic horizon and the pH of the fourth horizon. In contrast, productivity in grand fir (*Abies grandis* (Dougl. ex D.Don) Lindl.) was related to organic matter, nitrogen and colour of the first horizon and extractable magnesium in the second horizon.

Monserud et al. (1990) conducted a similar study for interior Douglas-fir over a much larger region of northern Idaho and northwestern Montana. On the basis of soil physical characteristic, a function relating productivity to parent material, bedrock, drainage class, soil depth and thickness of the C horizon was developed. This function, which relied on 13 variables, had an r^2 of only 0.16 and a standard error of 3.9 m. The standard deviation for site index for the entire study population was 4.3 m.

Broadfoot (1969) reports on studies relating soil properties to site productivity, as expressed by site index, for several southern hardwood species. Table 3 provides a summary of the results, by species.

Table 3. Significant soil characteristics for predicting site index (from Broadfoot 1969).

Species	Significant Variables	r^2	SE (m)
Sweetgum (*Liquidambar styraciflua* L.)	-clay and potassium within first 1.2 m	.34	2.4
Cherrybark oak (*Quercus flacata* var. *pagodaeforia* Ell.)	- depth of topsoil - depth to mottles - presence of fragipan	.39	2.7
Water oak (*Quercus nigra* L.)	- depth of topsoil - presence of fragipan - sodium	.32	2.4
Willow oak (*Quercus phellos* L.)	- clay within first 1.2 m - depth to mottles - presence of fragipan - inherent moisture	.43	2.7
Nuttall oak (*Quercus nuttallii* Palmer)	- silt and clay within first 1.2 m - soluble salts - available water capacity	.30	2.7
Green ash (*Fraxinus pennsylvanica* Marsh.)	- clay and pH within first 0.3 m - bulk density within first 1.2 m	.14	3.0
Cottonwood (*Populus deltoids* Barter. var. *deltoides*)	- silt, clay, pH and phosphorus within first 0.9 m	.45	3.0

One of the main problems associated with soil-site based productivity research has been the compensating effects between soil and site factors (Daubenmire 1976, Green et al. 1989, Peterson and Peterson 1992 and others). Different sets of soil and site conditions can produce ecologically equivalent sites for tree growth. The growing conditions on a site are the result of the interaction of a large number of individual characteristics.

Generally, soil-site studies are effective if diverse areas are stratified into areas with similar geology and general profiles (Schmidt and Carmean 1988). The drawback is, of course, that the results of any investigation is limited, in terms of applicability. Relationships developed are not transferable to other species and are not generally valid outside the original study area.

Most soil productivity research has concentrated primarily on soil physical properties. Soil chemical properties are difficult to use for a number of reasons. One difficulty lies in determining the relationship between soil chemical properties and nutrient uptake by vegetation. A nutrient is not always available for use by the vegetation. In 1979 Weaver and Forcella observed significant changes in soil chemical properties during different seasons, further limiting the applicability of chemical properties.

Use of either soil physical or chemical properties for productivity assessment is difficult to apply in the field because it often requires detailed soil surveying. Although this may be practical for certain applications, such as assessing a particular site, other applications such as mapping the units for planning is often not practical. This is especially true of soil chemical properties, which must be taken to the lab for analysis, rather than allowing for an assessment in the field.

3. Vegetation Indicators

The use of plant indicators to reflect forest site quality has been widely used in Europe (Daubenmire 1976) but its use in Canada and the United States has been limited. The theory behind the use of plant indicators as an index to site productivity is that the plants growing on a particular site provide a synthesis of all environmental characters that are important to plant growth, including the overstorey trees. Both the understorey and overstorey vegetation develop under similar environmental conditions and therefore, should be related.

The approach is generally most useful in temperate regions where the number of species is more restricted than in warmer regions. Species with high competitive value and a relatively narrow ecological amplitude are the best indicators (Daubenmire 1976 and Greer et al. 1989).

Corns and Pluth (1984) used vegetation indicators to augment a soil and landscape approach to predicting site index and mean annual increment for lodgepole pine and white spruce in west-central Alberta. Soil and landscape characters considered in the analysis included elevation, slope, aspect, thickness of the organic horizon, thickness, colour and structure of the A and B horizons, depth to mottles, drainage class, coarse fragment content and hydraulic conductivity. Vegetation characters considered in the analysis included litter cover, canopy cover, deadfall cover, regeneration density, lichen cover and cover of several species including *Ledum groenlandicum* Oeder, *Rosa acicularis* Lindl., *Calamagrostis canadensis* (Michx.) Beauv., *Rubus pubescens* Raf. and *Cornus canadensis* L. The results of their analysis are presented in Table 4.

For pine site index, the r^2 for the predictive equation increased from 0.49 to 0.71 with the inclusion of the vegetation characters. litter cover was significant, along with the percent cover of lichens, *Cornus canadensis* and *R. pubescens*. For white spruce, the r^2 increased from 0.58 to 0.91 with the inclusion of vegetative characteristics. Canopy and deadfall cover enhanced the prediction of site index, while litter cover did not. The percent cover of *C. canadensis* and *R. pubescens* also proved significant.

If mean annual increment was used as the measure of site productivity, the characteristics considered significant changed for both species.

Elevation showed a consistent negative relationship to productivity. As elevations increased, productivity decreased. Aspect was related to productivity in terms of mean annual increment, with maximum productivity tending to occur on north to northeast aspects.

Two vegetation characters, litter and deadfall cover, showed different relationships with productivity, depending on the species involved. Pine showed a negative relationship with litter cover, while in white spruce the trend was positive.

Unfortunately, the report does not indicate the standard errors associated with the resulting relationships, nor does it provide statistics for the predictive ability of the vegetative characteristics alone.

Table 4. Significant characters (P=0.05) in evaluating the site productivity of lodgepole pine and white spruce in west-central Alberta (from Corns and Pluth 1984).

Independent Variables	lodgepole pine SI	lodgepole pine MAI	white spruce SI	white spruce MAI
Topographic				
Elevation			neg	neg
Elevation (log)	neg			
Aspect (corrected)		pos		pos
Edaphic				
Consistence B horizon	neg	neg		
Value B horizon		neg		
Depth to mottles		neg		
Drainage class	neg		pos	
Hydraulic conductivity (log)				pos
Stone content				pos
Vegetational				
Litter cover (1/log)	neg	neg	pos	
Canopy cover		pos		pos
Deadfall cover		pos	neg	
Lichen cover	neg	neg		
Cornus canadensis cover	pos	pos	pos	
R. pubescens cover	pos			
L. groenlandicum cover			neg	neg
R. acicularis cover			neg	neg
Cal. canadensis cover				neg
Regeneration density	pos			pos

Like other indirect approaches to estimating site productivity, the use of vegetative characteristics is not without drawbacks.

Although vegetation does synthesize growing condition information (Daubenmire 1976), the conditions for understorey and overstorey growth may be significantly different. As an example, difference in rooting depth between understorey vegetation and the trees in the overstorey might mean vegetation indicators are not consistent with the overstorey on some sites. Also, understorey will be affected by the density of the overstorey because light conditions are dictated by overstorey density (Green et al. 1989). Relative abundance of many plants and presence of some species will be affected by light conditions.

Use of plant indicators is restricted to sites which have not been significantly disturbed (Schönau 1988). It can not be used in very young stands or on disturbed sites since the understorey vegetation will have been altered.

Finally, plant indicators do not provide any information regarding the physical site factors that are responsible for productivity differences (Crow and Rauscher 1984). This reduces its usefulness, to some extent, for forest management.

4. Ecosystem Classifications

Ecologically based forest management is becoming increasingly important in Canada and the United States. During the past twenty years, substantial progress has been made in the classification and inventory of ecological site units. In British Columbia, the ecological classification program is referred to as the Biogeoclimatic Ecosystem Classification System. The system integrates regional and local climate along with landscape, soil and vegetation characteristics. In the United States, a similar program has resulted in the identification of habitat types.

Alberta is still developing an ecosystem classification for the province. Ecological units referred to as ecosystem associations have been identified for west-central Alberta (Corns and Annas 1986). A similar classification, still in the draft stage, is also available for the southwestern portions of the province (AFS 1990).

Although there are difference in how these classifications were developed, they do have some basic similarities. They all attempt to synthesize climatic, landscape, soil and vegetation characteristics to describe ecological communities. Differences occur in the relative importance assigned to the different types of characteristics and, of course, to the way in which the units are identified and described. The classifications are all developed, however, on the principal that a relationship exists between the climate, landscape and soil and the resulting vegetation. This means differences in vegetation should be closely related to differences in climate and soil characters and vice versa.

Since ecological site units are supposed to represent the integration of a large number of site characters, it is only natural that interest has been shown in relating these units to site productivity.

Within Alberta, work of this type has been quite limited, primarily because of the lack of ecosystem classifications for most parts of the province. Correlations between site productivity and site units directly has generally been restricted to the information presented within the ecosystem classifications themselves. Both classifications document site productivity along with other ecological characteristics.

Li's 1991 study relating productivity of trembling aspen in northwestern Ontario to soil and site factors also examined the utility of the province's Forest Ecosystem Classification for predicting productivity. Productivity was subjectively grouped into 3 broad classes: high, moderate and low. The groupings proved insignificant.

In the United States, Monserud et al. (1990) examined the relation between site index of interior Douglas-fir and various environmental characteristics. Habitat series was able to predict site index with an r^2 or 0.39 and a standard error of 3.4 m. This was not improved with the addition of elevation, indicating habitat series and elevation were closely related. The addition of precipitation and longitude improved the r^2 of the predictive function to 0.42 and the standard error to 3.3 m.

In Canada, most of the work in developing site productivity relationships for ecological classification units has taken place in British Columbia, particularly in the coastal regions. The ecological classification for the area has been available and widely used for a number of years, providing the opportunity to examine its link with productivity.

Green et al. (1989) related site index of coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) in southwestern British Columbia to various ecological characteristics. Five site associations were distinguished from the 88 sample plots used in the analysis. These associations were defined on the basis of understorey vegetation. One association was further divided into 2 phases on the basis of soil characteristics, specifically particle size. The regression function predicting site index on the basis of site unit, had an r^2 of 0.85 and a standard error of 3.2 m. The addition of drainage and indicator species groups into the function improved the r^2 to 0.87 and the standard error to 3.0 m.

J. S. Thrower and Assoc. (1993) produced a summary of the research in British Columbia relating site index to the provincial Biogeoclimatic Ecosystem Classification (BEC). The summary lists numerous reports that have been published characterizing the site index of tree species for various BEC units. These are outlined in Table 5.

Research on the link between ecological classification and productivity in British Columbia has, in the past few years, dealt increasingly with the relationship between synoptic environmental variables, namely moisture and nutrient regime, and productivity. Ecological moisture regime defines, on a relative scale, the supply of moisture that is available to a site. It is derived from a broad assessment of site characteristics and integrates slope conditions, aspect, soil texture, surface organic layer and soil depth. Similarly, the nutrient regime integrates soil characteristics in an attempt to define, in relative terms, the nutrients that are available at a given site. It incorporates characteristics such as humus form, surficial mineral horizon, soil depth and texture, coarse fragment content and seepage/standing water. The two characteristics are closely tied to the BEC system, since the site units are related to specific moisture and nutrient regimes.

Kabzems and Klinka (1987a) examined nutrient regimes and their relationship to physical and chemical soil properties. They found a significant correlation in available nitrogen and nutrient regime. Subsequent work showed significant differences in site index of coastal Douglas-fir on the basis of moisture and nutrient regimes (Table 6) (Kabzems and Klinka 1987b). The study was based, however, on only 24 sample plots derived from six study areas.

Table 5. Reports summarizing site productivity to site units for various BEC zones in British Columbia (from J. S. Thrower and Associates 1993)

Author	Year	Species	BEC Zone
Green, R. N. and J. S. Thrower	1993	coastal Douglas-fir	Coastal Western Hemlock Coastal Douglas-fir Interior Douglas-fir
J. S. Thrower & Assoc.	1992	interior Douglas-fir	Sub-Boreal Spruce Interior Douglas-fir
Lloyd, D., K. Angove, G. Hope and C. Thompson	1990	codominant species combined	Interior Douglas-fir Sub-boreal Spruce
McLennan, D.	1989	lodgepole pine interior spruce	Sub-boreal Spruce
McLennan, D.	1990	ponderosa pine western larch interior Douglas-fir western white pine interior spruce subalpine fir western red cedar western hemlock	Interior Douglas-fir
McLennan, D. and A. Mamais	1992	amabilis fir western red cedar red alder western hemlock lodgepole pine sitka spruce yellow cedar mountain hemlock	Coastal Western Hemolock

(interior spruce - *Picea engelmannii* Parry/*P. glauca*; ponderosa pine - *Pinus ponderosa* Laws.; western white pine - *Pinus monticola* Dougl.; subalpine fir - *Abies lasiocarpa* (Hook.) Nutt.; western red cedar - *Thuja plicata* Donn; western hemlock - *Tsuga heterophylla* (Raf.) Sarg.; amabilis fir - *Abies amabilis* (Dougl.) Forbes; red alder - *Alnus rubra* Bong.; sitka spruce - *Picea sitchensis* (Bong.) Carr.; yellow cedar - *Chamaecyparis nootkatensis* (D.Don) Spach; mountain hemlock - *Tsuga mertensiana* (Bong.) Carr.)

Table 6. Douglas-fir site index mean (m @ 50 years) and standard deviations (in parentheses) for soil moisture and nutrient groupings (from Kabzems and Klinka 1987b). All differences are significant at P=0.05.

Soil Moisture	Soil Nutrient Regime			
Regime	Poor	Medium	Rich	Very Rich
Very Dry	17.8	22.2		
	(0.7)	(1.2)		
Dry		26.4	35.1	
		(1.3)	(1.8)	
Fresh			32.1	39.1
			(1.8)	(1.0)

Klinka and Carter (1990) examined the soil moisture and nutrient regime of 133 immature Douglas-fir stands in coastal British Columbia. Moisture regime, in combination with nutrient regime was able to predict site index with an r^2 of 0.84 and a standard error of 2.0 m. This was more successful than using other environmental variables.

Wang et al. (1992) converted field estimates of soil moisture and nutrient regime to actual soil moisture and nutrient regimes. Conversion of soil moisture regimes involved determining the potential and actual evapotransipiration and water deficit for each site. Soil nutrient regimes were converted on the basis of a number of characteristics, including pH of the forest floor and of the mineral soil, total phosphorus in the humus, etc. Relationships for these conversions were obtained from previous studies (Spittelhouse and Black 1981, Klinka et al. 1984 and Wang 1992).

Relationships for estimating site index were developed on the basis of actual soil moisture and nutrient regimes and site series. The best predictive equation derived was based on the soil moisture and nutrient regime, with an r^2 of 0.82 and a standard error of 1.4 m.

Results from studies involving the use of ecosystem classifications for predicting productivity have been mixed, with some successes and some failures. The site units synthesize a large number of climatic, landscape, soil and vegetation characteristics and should be related to productivity. Use of this approach is contingent, however, on the existence of an appropriate ecosystem classification.

The use of soil moisture and nutrient regime has proved useful for predicting productivity in some studies. This method does not require the existence of an ecological classification for an area. One of the main drawbacks to this approach is that deriving consistent soil moisture and nutrient estimates can be difficult since their assessment is somewhat subjective.

4. Summary

1. All indirect methods for estimating site productivity have their drawbacks. Productivity relationships developed for mapped soil surveys would be extremely valuable because they provide spatial information but they have been not been consistently successful. Use of other soil and site characteristics is usually effective but only for limited areas and often requires fairly detailed soil sampling for use in the field. Vegetation indicators are much easier to survey but are best used along with other soil and site characteristics. The conditions in which the understorey vegetation is growing can be different than that of the overstorey. Use of ecological units is often relatively effective but is not an option in areas which do not have an established classification. Finally, synoptic variables such as soil moisture and nutrient regime have proven valuable, but their assessment in the field is relatively subjective.

2. Indirect methods for estimating site productivity are best developed using as wide a range of information as possible. Landscape, soil and vegetation characteristics should all be examined for their predictive ability. Use of ecological classification units, where available, should also be considered, although likely in conjunction with other characteristics.

3. The landscape, soil and vegetation characters which have value as predictors of site productivity are quite specific in terms of applicability. They tend to apply to only a specific geographic area and vary considerably for different species within the area. This is one of the major drawbacks of using this type of indirect approach; relationships specific to each area and species need to be developed.

This specificity is a function of the different ecological conditions in different areas (e.g., in areas with fine textured soils, the presence of coarse fragments may improve drainage and subsequently growth; in areas with coarse textured soils, coarse fragments may result in very poor moisture and nutrient holding capacities and result in poorer growth rates). The growth requirements and typical conditions under which different species grow leads to species specific relationships (e.g., pine may do quite well on relatively well drained sites where conditions are too dry for good spruce growth).

Stratification of the area on the basis of broad landscape characteristics, for example parent material, has proved very useful in a number of studies.

4. Although the specific landscape, soil and vegetation characters which are strongly related to site productivity vary considerably between geographic areas and between species, they are generally related to soil moisture and nutrient availability. Characters which tend to have

predictive value often include aspect, parent material, soil moisture regime, soil nutrient regime, drainage and, where available, ecological unit or indicator plants. Different sets of these conditions can, however, result in similar ecological conditions for tree growth.

5. Literature Cited

Alberta Forest Service. 1990. Field guide to forest ecosystems of southwestern Alberta - first approximation. Alberta Forestry, Lands and Wildlife, Edmonton, Alberta.

Broadfoot, W. M. 1969. Problems in relating soil to site index for southern hardwoods. For. Sci. 15:354-364.

Buse, L. J. and W. D. Baker. 1991. Black spruce site quality key for the northwestern region of Ontario. Northwestern Ontario Forest Technology Development Unit Tech. Note TN-09.

Carmean, W. H. 1961. Soil survey refinements needed for accurate classification of black oak site quality in southeastern Ohio. Soil Sci. Soc. Amer. Proc. 25:394-397.

Carmean, W. H. 1986. Forest site quality research in the north central region. Pp. 62-67 *in* Wickware, G. M. and W. C. Stevens ed. Site classification in relation to forest management. Great Lakes For. Centre, Sault Ste. Marie, Ontario. Aug 27-29, 1985.

Carmean, W. H. 1987. Forest site quality evaluation in north central Ontario. Pp. 3-11 *in* Jones, R. K. ed. Approaches to the evaluation of forest productivity in Ontario. University of Guelph, April, 1987.

Chandler, R. F., P. W. Schoen and D. A. Anderson. 1943. Relation between soil types and the growth of loblolly pine and short leaf pine in east Texas. J. Forestry 41:505-506.

Coile, T. S. 1935. Relation of site index for shortleaf pine to certain physical properties of the soil. J. Forestry 33:726-730.

Corns, I. G. W. and D. J. Pluth. 1984. Vegetational indicators as independent variables in forest growth prediction in west-central Alberta, Canada. For. Ecol. Manage. 9:13-25.

Corns, I. G. W. and R. M. Annas. 1986. Field guide to forest ecosystems of west-central Alberta. Can. For. Serv., Northern For. Cent., Edmonton, Alberta.

Crow, T. R. and H. M. Rauscher. 1984. Forest growth models and land classification. Pp. 190-204 *in* Bockheim, J. G. ed. Forest Land classification: experiences, problems, perspectives. Univ. Wisconsin, Madison, Wisconsin.

Daubenmire, R. F. 1976. The use of vegetation in assessing the productivity of forest lands. Bot. Rev. 42:115-143.

Dumanski, J., J. C. Wright and J. D. Lindsay. 1973. Evaluating the productivity of pine forests in the Hinton-Edson area, Alberta. from soil survey maps. Can. J. Soil Sci. 53:405-419.

Evans, J. 1974. Some aspects of the growth of *Pinus patula* in Swaziland. Comm. For. Rev. 53:57-62.

Green, R. N., P. L. Marshall and K. Klinka. 1989. Estimating site index of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) from ecological variables in southwestern British Columbia. For. Sci. 35:50-63.

Green, R. N. and J. S. Thrower. 1993. Field guide insert for the estimation of coastal Douglas-fir site index from BEC site series. B. C. Min. For.

Grigal, D. F. 1984. Shortcoming of soil survey for forest management. Pp. 148-166 *in* Bockheim, J. G. ed. Forest land classification: experiences, problems, perspectives. Univ. Wisconsin, Madison, Wisconsin.

J. S. Thrower & Associates. 1992. Preliminary site index/ecosystem correlations for interior Douglas-fir in British Columbia. B. C. Min. For. Contract Rep., Minor Serv. Contract No. 82085.

J. S. Thrower & Associates. 1993. A summary of research relating site index and the biogeoclimatic ecosystem classification system in British Columbia. B. C. Min. For. Contract Rep., Minor Serv. Contract No. 112015.

Kabzems, R. D. and K. Klinka. 1987a. Initial quantitative characterization of soil nutrient regimes. I. Soil properties. Can. J. For. Res. 17:1557-1565.

Kabzems, R. D. and K. Klinka. 1987b. Initial quantitative characterization of soil nutrient regimes. II. Relationships among soils, vegetation and site index. Can. J. For. Res. 17:1565-1571.

Kimmins, J. P. 1987. Predicting the future productivity of Ontario's forests. Pp. 41-46 *in* Jones, R. K. ed. Approaches to the evaluation of forest soil productivity in Ontario. Univ. Guelph, Guelph, Ontario.

Klinka, K. and R. E. Carter. 1990. Relationship between site index and synoptic environmental factors in immature coastal Douglas-fir. For. Sci. 36:815-830.

Klinka, K., R. N. Green, P. L. Courtin and F. C. Nuszdorfer. 1984. Site diagnosis, tree species selection and slashburning guidelines for the Vancouver Forest Region. Land Manage. Rep. No. 25, B. C. Min. For., Victoria, B. C. 180 pp.

LaValley, R. R. 1991. Soil-site relations for young white spruce plantations in north central Ontario. M.Sc.F. Thesis. Lakehead University, Thunder Bay, Ontario. 117 pp.

LeBlanc, P. A. 1993. Soil-site relations for jack pine (*Pinus banksiana* Lamb.) in northeastern Ontario. Thesis. Lakehead University, Thunder Bay, Ontario. 168 pp.

Li, Y. 1991. Soil-site relations for trembling aspen (*Populus tremuloides* Michx.) in northwestern Ontario. Thesis. Lakehead University, Thunder Bay, Ontario. 125 pp.

Linnartz, N. E. 1963. Relation of soil and topographic characteristics to site quality for southern pines in the Florida parishes of Louisiana. J. Forestry 61:434-438.

Lloyd, D., K. Angove, G. Hope and C. Thompson. 1990. A guide to site identification and interpretation for the Kamloops Forest Region. B.. C. Min. For., Ld. Manage. Hdbk. No. 23. 399 pp.

Lloyd, F. T. and W. L. Hafley. 1977. Precision and the probability of misclassification in site index estimation. For. Sci. 23:493-499.

McGrath, C. L. 1975. Soil-site quality relationships on the University of Idaho Experimental Forest. Univ. Idaho, For. Wildlife and Range Exp. Stn., Moscow, Idaho. Note No. 22. (*Cited in* Monserud et al. 1990)

McLennan, D. 1989. Summary of site index statistics for lodgepole pine and interior spruce in ecosystems of the sub-boreal spruce and sub-boreal pine spruce biogeoclimatic zones. B. C. Min. For. Contract Rep., Minor Serv. Contract No. 12095.

McLennan, D. 1990. Site index of commercial tree species in biogeoclimatic groups and site classification units in the Nelson Forest Region. Unpublished Contract Rep. to the Min. For., Nelson For. Region, Nelson, B. C.

McLennan, D. and A. Mamais. 1992. Ecosystem classification and site index-site unit correlations for the CWHvm biogeoclimatic subzone near Prince Rupert, British Columbia. B. C. Min. For. Contract Rep., Minor Serv. Contract No. 98073.

Monserud, R. A., V. Moody and D. W. Breuer. 1990. A soil-site study for inland Douglas-fir. Can. J. For. Res. 20:686-695.

Monserud, R. A. and G. E. Rehfeldt. 1990. Genetic and environmental components of variation of site index in inland Douglas-fir. For. Sci. 36:1-9.

Peterson, E. B. and N. M. Peterson. 1992. Ecology, management and use of aspen and balsam poplar in the prairie provinces. For. Can. Northern For. Centre. Special Rep. 1. 252 pp.

Phillips, J. J. and N. L. Markley. 1963. Site index of New Jersey sweetgum stands related to soil and water-table characteristics. U. S. For. Serv., Northeastern For. Exp. Stn., Res. Paper NE-6. 25 pp.

Schmidt, M. G. and W. H. Carmean. 1988. Jack pine site quality in relation to soil and topography in north central Ontario. Can. J. For. Res. 18:297-305.

Schönau, A. P. G. 1988. Problems in using vegetation or soil classification in determining forest site quality. Pp. 3-11 in D. W. Cole and S. P. Gessel ed. Forest site evaluation and long-term productivity. Univ. Washington Press, Seattle.

Spittlehouse, D. L. and T. A. Black. 1981. A growing-season water balance model applied to two Douglas-fir stand. Water Resource Res. 17:1651-1656.

Wang, Q., G. Wang, K. D. Coates and K. Klinka. 1992. Use of site factors in the prediction of lodgepole pine and interior spruce site index in the SBS zone of the Prince Rupert Forest Region. Rep. for B. C. Min. For.

Wang, Q. 1992. Ecological and height growth analysis of some sub-boreal immature lodgepole pine stands in central British Columbia. Ph.D. thesis. Fac. For., Univ. British Columbia, Vancouver, B. C. 207 pp. (*cited in* Wang et al. 1992).

Weaver, T. and F. Forcella. 1979. Seasonal variation in soil nutrients under six Rocky Mountain vegetation types. Soil Sci. Soc. Am. J. 43:589-593.

VanLear, D. H. and J. F. Hosner. 1967. Correlation of site index and soil mapping units. J. Forestry 65:22-24.