Lodgepole pine site index in relation to synoptic measures of climate, soil moisture and soil nutrients

by G. Geoff Wang[1], Shongming Huang[2], Robert A. Monserud[3] and Ryan J. Klos[4]

Lodgepole pine site index was examined in relation to synoptic measures of topography, soil moisture, and soil nutrients in Alberta. Data came from 214 lodgepole pine-dominated stands sampled as a part of the provincial permanent sample plot program. Spatial location (elevation, latitude, and longitude) and natural subregions (NSRs) were topographic variables that might be considered as synoptic measures of climate. Soil moisture regimes (SMRs) were used as synoptic measures of soil moisture supply. Soil nutrient regimes (SNRs) were used as synoptic measures of soil nutrient supply. Simple measures of geographic location (elevation, latitude, longitude) carried the most predictive power, explaining between 33% and 37% of the variation. Site index decreased with elevation, increased with latitude, and had a quadratic relationship with longitude. The Lower Foothills NSR had higher site index (16.1 m) than the Upper Foothills (14.0 m), Montane (11.8 m) and Subalpine (10.3 m) NSRs. Soil moisture regime variables were not significant. Soil nutrient regime variables were also not important, although one was significant in conjunction with elevation, latitude, and longitude (41% explained variation). Standard errors of estimate ranged between 2.64 and 2.94 m for the various synoptic models. Interaction terms between synoptic variables were examined but were found to be non-significant.

Key words: site index, climate regime, soil moisture regime, soil nutrient regime, *Pinus contorta*

L'indice de station du pin lodgepole a été étudié en relation avec les mesures synoptiques de la topographie, de l'humidité et des éléments nutritifs contenus dans le sol de l'Alberta. Les données provenaient de 214 peuplements échantillons dominés par le pin lodgepole tirés du programme d'échantillonnage permanent de la province. La localisation spatiale (altitude, latitude et longitude) ainsi que les sous-régions naturelles constituaient des variables topographiques qui pouvaient être considérées en tant que mesures synoptiques du climat. Les régimes hydriques du sol ont été utilisés en tant que mesures synoptiques de l'apport en eau dans le sol. Les régimes d'éléments nutritifs ont été utilisés en tant que mesures synoptiques de l'apport en éléments nutritifs. Les mesures simples de la localisation géographique (altitude, latitude et longitude) comprenaient la plus forte puissance de prédiction, étant à l'origine de 33 % à 37 % des variations. L'indice de station décroissait avec l'altitude, augmentait avec la latitude et affichait une relation quadratique en fonction de la longitude. Les sous-régions naturelles des Lower Foothills affichaient un indice de station plus élevé (16,1 m) que dans le cas des sous-régions naturelles des Upper Foothills (14,0 m), de la zone montagneuse (11,8 m) et de la région subalpine (10,3 m). Les variables des régimes hydriques du sol n'étaient pas significatives. Les variables des régimes d'éléments nutritifs n'étaient pas importantes, même si l'une était significative en fonction de l'altitude, de la latitude et de la longitude (41 % de la variation expliquée). Les écart-types des estimés variaient entre 2,64 et 2,94 m selon les différents modèles synoptiques. Les effets d'interaction entre les variables synoptiques ont été étudiés mais ils ont été estimés comme étant non significatifs.

Mots-clés : indice de station, régime climatique, régime hydrique du sol, régime d'éléments nutritifs, *Pinus contorta*

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Introduction

Lodgepole pine (*Pinus contorta* Dougl. Ex Loud) is the most widely distributed species in western North America (Lotan and Critchfield 1990). The species includes several varieties, with *Pinus contorta var. latifolia* Engelm. found in Alberta. Although distributed in every forested natural subregion in Alberta (Alberta Environmental Protection 1994), lodgepole pine is mainly concentrated in the Lower Foothills, Upper Foothills, Montane and Sub-Alpine natural subregions. Although lodge-

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pole pine comprises about 20% of the mature standing timber in Alberta, it accounts for approximately 40% of the annual harvest in the province (Huang *et al.* 2001). Because of its widespread distribution and commercial value in the province, lodgepole pine has attracted a great deal of attention in growth and yield studies (Johnstone 1976, Dempster and Associates 1982, Huang *et al.* 2001).

Predicting forest growth and yield is of fundamental importance to forest managers. Knowledge of the potential productivity of a tree species is especially important when timber production becomes a major management objective. In North America, site index (determined by measuring heights and ages of free-growing, dominant/codominant trees in even-aged stands) has been commonly used by foresters as a measure of potential productivity (e.g., Carmean 1975, Monserud 1984). However, direct estimation of site index is not always possible, such as situations where the site is unstocked, stocked with trees unsuitable for site index measurement, or stocked with species other than the one of interest. In these cases, an indirect estimate using known characteristics of the site itself is an alternative. Many studies have attempted to integrate numerous site variables (i.e., various measures of geographical location, climate, topography, and soils) into a few synoptic ones, most commonly, climate, soil nutrient, and soil moisture regimes (e.g., Cajander 1926, Hills 1952, Major 1963, Krajina 1969). This approach has been best exemplified in British Columbia, where climate regime has been mapped as biogeoclimatic subzones or variants; field keys for classifying soil moisture regime and soil nutrient regime have been developed for most forest regions in British Columbia (Pojar *et al.* 1987). Sites with the same quality rating (in terms of climate, soil moisture and soil nutrient regimes) are considered to be biologically (Cajander 1926, Bakuzis 1969) or ecologically equivalent (Pojar *et al.* 1987).

To assist forest managers in selecting the most suitable species and silvicultural treatments, numerous studies have been conducted to link site index of different tree species to these synoptic measures of site quality (e.g., Green *et al.* 1989, Klinka and Carter 1990, Wang *et al.* 1994, Wang and Klinka 1996, Chen *et al.* 1998). These studies have found that synoptic measures of ecological site quality (e.g., climate, soil moisture, and soil nutrient regimes) are the best predictors when site index has to be predicted from site factors. However, this link between site index and synoptic measures of site quality has not been evaluated and applied in Alberta. A recent site index mapping study (Monserud and Huang 2002) indicated that lodgepole pine site index can be predicted across Alberta as a function of geographic variables such as elevation, latitude and longitude. However, it is not clear if synoptic variables, especially for soil moisture and nutrient regimes, can improve upon the result.

The main objectives of this study were (1) to examine the effects of synoptic measures of ecological site quality on lodgepole pine site index and (2) to develop regression models to predict lodgepole pine site index based on these synoptic measures.

Methods

The data

The permanent sample plot (PSP) data used in the study were obtained from the Alberta Land and Forest Division. These data were carefully collected throughout the inventoried areas of Alberta to provide representative information for a variety of densities, heights, species composition, stand structures, age, and site conditions (Alberta Forest Service 1988). A total of 213 PSPs, which were located in lodgepole pine dominated stands, were selected for the study. These PSPs were located within four natural subregions (NSRs) shown in Fig.1: Subalpine, Montane, Upper Foothills, and Lower Foothills. A summary of climate data is given in Table 1. The Lower Foothills NSR tends to have the warmest summer mean temperatures and greatest amount of growing degree days. The Upper Foothills NSR has the greatest amount of summer precipitation. The Montane NSR exhibits the warmest winter mean temperatures since it experiences the most frequent occurrences of chinook winds. The Subalpine NSR has the coldest summer and winter mean temperatures. It also has the least number of growing degree days and the greatest amount of winter and annual precipitation (Beckingham *et al.* 1996).

The 213 PSPs used in the study were located in even-aged lodgepole pine stands of fire-origin. Each PSP was 0.1 ha in size and was not subjected to any major disturbance since stand establishment (Alberta Land and Forest Service 2000). Among many data collected on each PSP, only spatial location (latitude, longitude and elevation), natural subregion (NSR), soil moisture regime (SMR), soil nutrient regime (SNR), and stem analysis data were used in the study. Elevation was either measured to the nearest meter using an altimeter, or interpreted from a province-wide digital elevation model (DEM) using a 100-m grid for the province. The soil moisture regime of each PSP was determined according to variables that affect soil water supply, including primary water source, slope position, soil texture, drainage, depth to impenetrable layer, surface humus depth, available water storage capacity, and slope gradient (Alberta Environmental Protection 1994). Similarly, the soil nutrient regime of each PSP was determined according to variables that affect soil nutrient supply, including bedrock source, soil texture, organic matter content, humus form, and soil reaction (Alberta Environmental Protection 1994).

Among the nine SMR classes (0 – very xeric, 1 – xeric, 2 – subxeric1, 3 – subxeric2, 4 – mesic, 5 – subhygric, 6 – hygric, 7 – subhydric, and 8 – hydric) defined by Alberta Environmental Protection (1994), five classes (SMRs 3 to 7) were represented in the study. Four classes (SMRs 0, 1, 2 and 8), were each represented by only one to three PSPs, and therefore were not included in the study or merged. Among the six SNR classes (1 – oligotrophic, 2 – submesotrophic, 3 – mesotrophic, 4 – permesotrophic, 5 – eutrophic, and 6 – hypereutrophic) described in Alberta Environmental Protection (1994), three (SNR classes 2–4) were represented in the study. SNR 6 was absent from the data, SNR 1 was represented only by one PSP, and SNR 5 had three PSPs. The distribution of the 213 lodgepole pine stands by natural subregion, moisture and nutrient classes is shown in Table 2.

Site index was determined based on stem analysis data. At each sample location, a minimum of three dominant trees were selected and felled following the standard procedures of Alberta Forest Service (1988). Each felled tree was sectioned at stump height (0.3 m), breast height (1.3 m), 2.8 m above the ground, and at equal lengths of 2.5 m thereafter to the top of the tree. Ring counts were measured at the top of each section.

Table 1. Summary of climate characteristics for four natural subregions (NSRs)

	Lower Foothills (11)	Upper Foothills (10)	Montane (9)	Subalpine (8)
Summer[a]				
Mean typical temperatures (°C)	12.8	11.5	11.9	9.4
Minimum typical temperatures (°C)	6.9	5.9	5.1	3.8
Maximum typical temperatures (°C)	18.3	16.7	18.9	14.7
Total precipitation (mm)	295	340	210	263
Growing degree days	1008	752	773	558
Number of days <0 °C	8	13	16	28
Winter[b]				
Mean typical temperatures (°C)	-7.8	-6.0	-5.5	-8.9
Minimum typical temperatures (°C)	-14.3	-12.5	-11.3	-14.5
Maximum typical temperatures (°C)	-2.1	0.5	-0.2	2.8
Total precipitation (mm)	60	60	93	146
Annual				
Total precipitation (mm)	464	538	440	568
Mean temperature (°C)	3.0	3.0	3.5	1.3

Source: Beckingham *et al.* (1996) and Alberta Environmental Protection (1994). [a]Summer is defined as May, June, July, and August; [b]Winter is defined as November, December, January, and February. The four natural subregions are shown in Fig. 1.

The height-age pairs from sectioned trees were plotted tree-by-tree to determine whether the individual height-age curve was relatively smooth and undisturbed. Several trees that showed obvious sign of suppression at young ages were removed from the analysis. Site index, defined as the tree height at breast height age 50 years, was obtained for each tree and averaged for each stand (Huang *et al.* 1997).

Data analysis

We began with a preliminary examination of the data, focusing on the largest synoptic classes, as well as those with the largest interspersion across different types of synoptic classes (Wang and Klinka 1996). The goal was to examine the limiting effect of each individual factor on lodgepole pine site index. Specifically, the effect of topography (measured by NSR, latitude, longitude, and elevation) on lodgepole site index was examined based only on PSPs with two fixed SMR classes (4 and 5) and one fixed SNR class (3). This combination of classes yielded 93 PSPs, nearly half the data. Based on this constrained data set, analysis of variance was used to compare site index across NSRs and regression analyses were used to relate site index to elevation, latitude and longitude. Similarly, the effect of soil moisture on site index was examined using the PSPs with SNR = 3 (n = 123), and the effect of soil nutrients on site index was examined using only the PSPs with SMR = 4 and 5 (n = 139). Based on these two constrained data sets, analysis of variance and analysis of covariance (with elevation as a covariate) were used to compare site index across SMRs and SNRs.

Based on a preliminary analysis of variables that were significantly related to lodgepole pine site index, regression analysis was used to develop site index prediction equations based on all 213 PSPs — the full dataset. Three dummy variables were assigned for the four NSRs and two dummy variables were assigned for the three SNRs because only (*k-1*) dummy variables were needed to distinguish *k* classes. SMRs were not significantly related to lodgepole pine site index. The following regression models were estimated:

Table 2. Distribution of 213 lodgepole stands according to natural subregion (NSR), soil moisture regime (SMR), and soil nutrient regime (SNR) with number of PSPs in parentheses

NSR	SMR	SNR
Subalpine (23)	3 (22)	2 (60)
Montane (13)	4 (20)	3 (123)
Upper foothills (73)	5 (119)	4 (30)
Lower foothills (104)	6 (40)	
	7 (12)	

Note: SMR 2 to 7 are, respectively, subxeric1, subxeric2, mesic, subhygric, hygric, and subhydric. SNR 2 to 4 are, respectively, submesotrophic, mesotrophic, permesotrophic, and eutrophic.

[1] $SI = b_0 + b_1\,(NSR9) + b_2\,(NSR10) + b_3\,(NSR11)$

[2] $SI = b_0 + b_1\,(NSR9) + b_2\,(NSR10) + b_3\,(NSR11) + b_4\,(SNR2)$

[3] $SI = b_0 + b_1\,(ELE)$

[4] $SI = b_0 + b_1\,(ELE) + b_2\,(LAT) + b_3\,(LON) + b_4\,(LON2)$

[5] $SI = b_0 + b_1\,(ELE) + b_2\,(SNR2)$

[6] $SI = b_0 + b_1\,(ELE) + b_2\,(LAT) + b_3\,(LON) + b_4\,(LON2) + b_5\,(SNR2)$

where NSR9, NSR10 and NSR11 are the Montane, Upper Foothills and Lower Foothills natural subregions, respectively; SNR2 = soil nutrient regime 2; ELE = elevation; LAT = latitude; LON = Longitude; LON2 = longitude squared, and b_0 to b_5 are model parameters to be estimated. Soil nutrient regime 3 was not used because it was not significant. Finally, we also examined interaction effects among the various synoptic variables (i.e., NSR x SMR, NSR x SNR, SMR x SNR, NSR x SMR x SNR) whenever sample size was adequately large. All statistical analyses were completed using SYSTAT (version 5.0) statistical software package (Wilkinson 1990).

Perhaps a word about pseudoreplication is in order here. Hurlbert (1984) created quite a stir by pointing out the prevalence of pseudoreplication in field ecology, and that it invalidated statistical inference. Replicates or sample plots that are

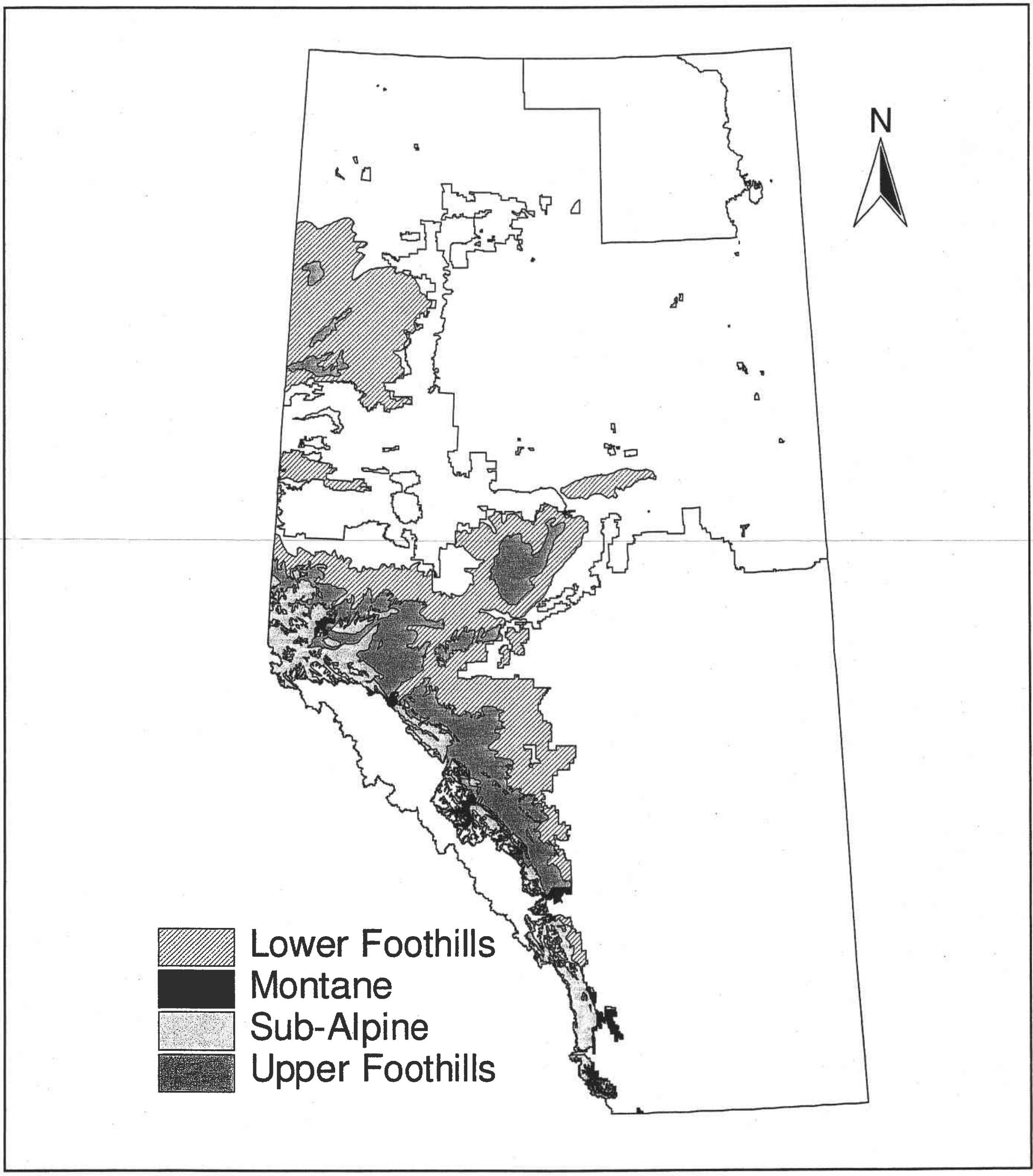

Fig. 1. Locations of the four natural subregions in Alberta.

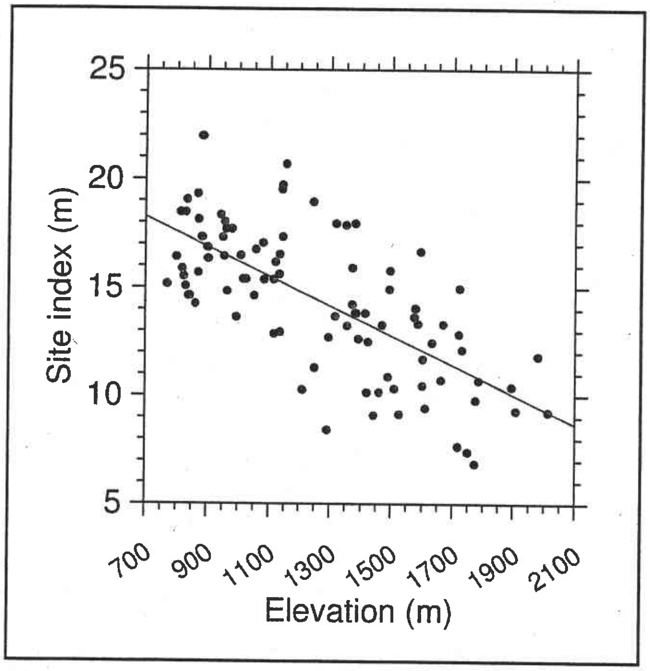

Fig. 2. The relationship between lodgepole pine site index and elevation based on 93 plots with SMR = 4 and 5 and SNR=3 ($R^2 = 0.475$, $p < 0.001$).

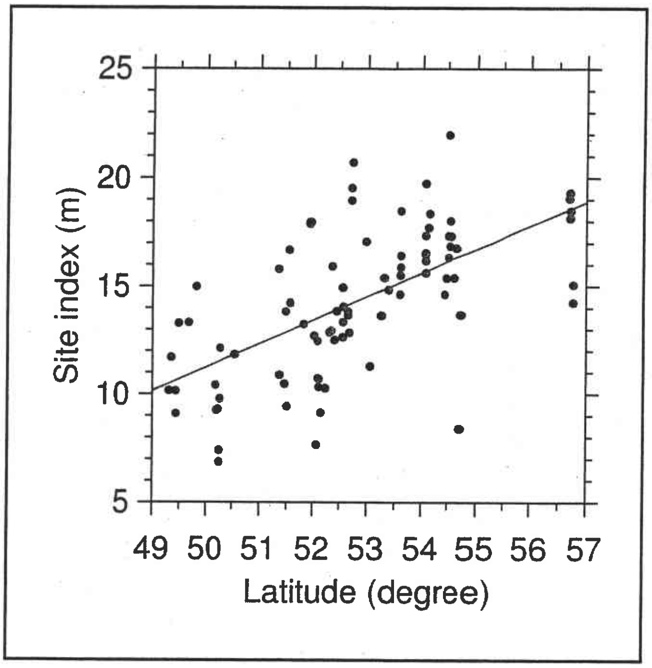

Fig. 3. The relationship between lodgepole pine site index and latitude based on 93 plots with SMR = 4 and 5 and SNR=3 ($R^2 = 0.356$, $p < 0.001$).

not independent are pseudoreplicates, which artificially increase sample size, bias hypothesis tests, and give a false sense of the power of the test of the experiment (Hurlbert 1984). In short, the strength of the experimental evidence is overstated (Hargrove and Pickering 1992). The existence of a spatial environmental gradient is a common cause (Monserud 2002). Almost all geographic datasets such as ours suffer varying degrees of this problem. The real message in Hurlbert's warning about pseudoreplication is that statistical interpretation should be rather conservative, because the correlation structure could serve to effectively reduce degrees of freedom (sample size). We indeed take this conservative approach, focusing our analysis strongly on synoptic variable combinations that have a large sample size. Our inventory plot data are not random samples derived from an experimental design. Rather, the inventory plot network was designed to faithfully represent the region rather than to fill synoptic strata equally. There is surely confounding among site effects, natural subregions, and the various soil moisture and nutrient regimes. We use analysis of variance primarily as a preliminary screening tool, and therefore rely on regression analysis to estimate prediction models with the full data.

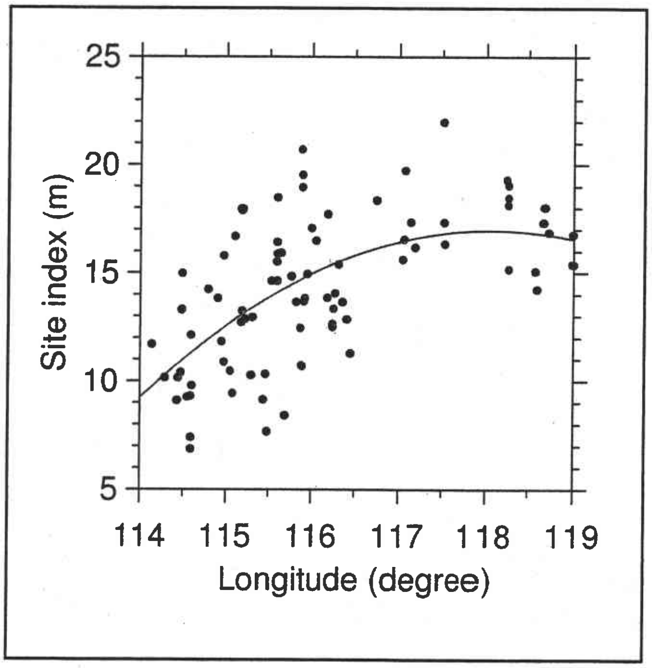

Fig. 4. The relationship between lodgepole pine site index and longitude based on 93 plots with SMR = 4 and 5 and SNR=3 ($R^2 = 0.362$, $p < 0.001$).

Results

Based on the 93 PSPs with SMR = 4 and 5 and SNR = 3, the effect of topography and NSR on lodgepole pine site index was examined. Site index decreased linearly ($p < 0.001$) with elevation, with 47% of its total variation explained (Fig. 2). Site index increased linearly ($p < 0.001$) with latitude, with 35% of its total variation explained (Fig. 3). Site index had a quadratic relationship ($p < 0.001$) with longitude, with 35% of its total variation explained (Fig. 4). Site index differed significantly among the four NSRs (Fig. 5). The Lower Foothills NSR had higher ($p < 0.001$) site index (16.1 m) than the Upper Foothills (14.0 m), Montane (11.8 m) and Subalpine (10.3 m) NSRs. The Upper Foothills NSR also had higher ($p < 0.005$) site index than the Subalpine NSR. Considering the location of each natural subregion, it appears that site index increases with distance from Rocky Mountain range because of decreasing elevation. In fact, when elevation was used as a covariate, no difference ($p = 0.309$) in site index was found among natural subregions based on analysis of covariance.

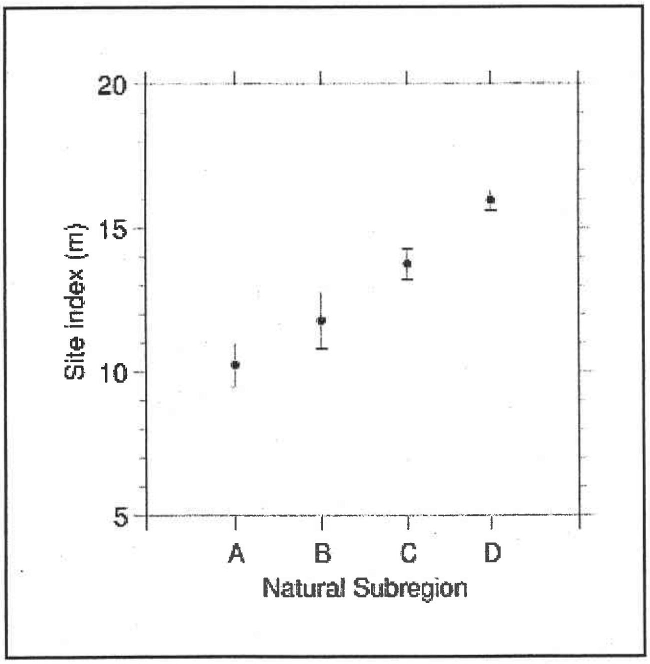

Fig. 5. The relationship between lodgepole pine site index and natural subregions (A = Subalpine, B = Montane, C = Upper Foothills, D = Lower Foothills) based on 93 plots with SMR = 4 and 5 and SNR = 3 ($R^2 = 0.352$, $p < 0.001$).

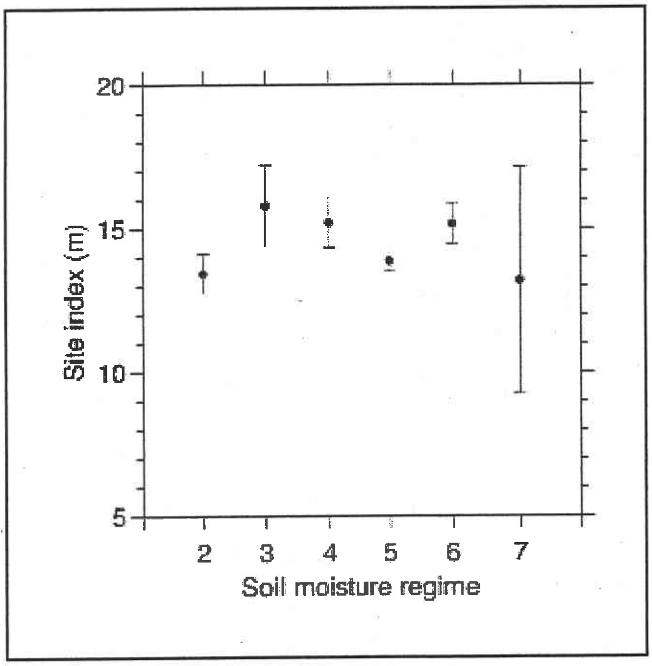

Fig. 6. The relationship between lodgepole pine site index and SMR based on 123 plots with SNR=3 ($R^2 = 0.041$, $p = 0.421$).

A total of 123 sites, all with SNR values of 3, were used to examine the effect of moisture regime on lodgepole site index. No significant difference in site index was found among SMRs with ($p = 0.422$) or without ($p = 0.709$) elevation as a covariate. The large standard error associated with SMR = 7 was due to small sample size (n = 3) (Fig. 6).

A total of 139 sites, with SMR = 4 and 5, were used to examine the effect of soil nutrient regime on lodgepole pine site index (Fig. 7). With SNR changing from 2 to 3 to 4, lodgepole site index increased from 12.8 to 14.2 to 15.2 m. However, this difference was not statistically significant ($p = 0.064$). When elevation was used as a covariate, the effect of SNR on site index became significant ($p = 0.025$), with lower site index associated with SNR = 2.

Based on the above preliminary results, topographic factors (NSR, elevation, latitude, and longitude) and one soil nutrient regime categorical variable (SNR2) were used to develop regression equations for predicting lodgepole pine site index based on all 214 plots (equations 1–6; Table 3). It was found that natural subregions (NSR) explained 27% of the total variation in site index (equation [1]). NSR together with SNR2 explained 30% of the total variation of site index (equation [2]). Elevation, latitude, and longitude together explained 37% of the total variation in site index (equation [4]). Elevation together with SNR2 also explained 37% of the total variation in site index (equation [5]). Adding SNR2 into [4] improved the prediction of site index, with 41% of the total variation in site index explained by equation [6] (Table 3). Residual plots obtained from equation [6] indicated that equation [6] fit the data well (Fig. 8). The standard error of the estimates in these models ranged from 2.64 to 2.94 m.

The influence of topography, soil moisture, and soil nutrient regimes on lodgepole pine growth might possibly interact with each other in more complex ways than captured by models [1]-[6] above. The interactions of the various synoptic factors on lodgepole pine site index, if significant, would have additional utility in predicting site index across large areas. However, the only test on interaction that was allowed by the full data set was between NSR and SNR, and their interaction was not significant ($p = 0.555$). When SMRs 6 and 7 were excluded (n = 161), NSR did not interact with SMR ($P = 0.167$) and SNR ($p = 0.229$). Based on data from the Upper Foothills and Lower Foothills natural subregions (total 177 PSPs), NSR did not interact with SMR ($p = 0.903$) and SNR ($p = 0.403$).

Discussion

This study suggests that lodgepole site index in Alberta is strongly associated with geographic factors, weakly associated with soil nutrient regime, and not related to soil moisture regime. In a recent study based on a large data set collected across the natural distribution range of lodgepole pine in Alberta, Monserud and Huang (2002) also found that geographic factors (elevation, latitude, longitude) were significant predictors of lodgepole pine site index. Using a much larger network of stem analysis plots (nearly 1000), they mapped lodgepole pine site index across Alberta with a thin-plate smoothing spline using only elevation, latitude, and longitude; root mean square residual was 1.16 m (Monserud and Huang 2002). Similarly, a study for inland Douglas-fir in northern Idaho and northwestern Montana, Monserud *et al.* (1990) also reported that elevation together with latitude and longitude explained 39% of the total variation in site index. In addition to confirming the importance of geographic variables, results from this study also indicate that (1) natural subregions are good pre-

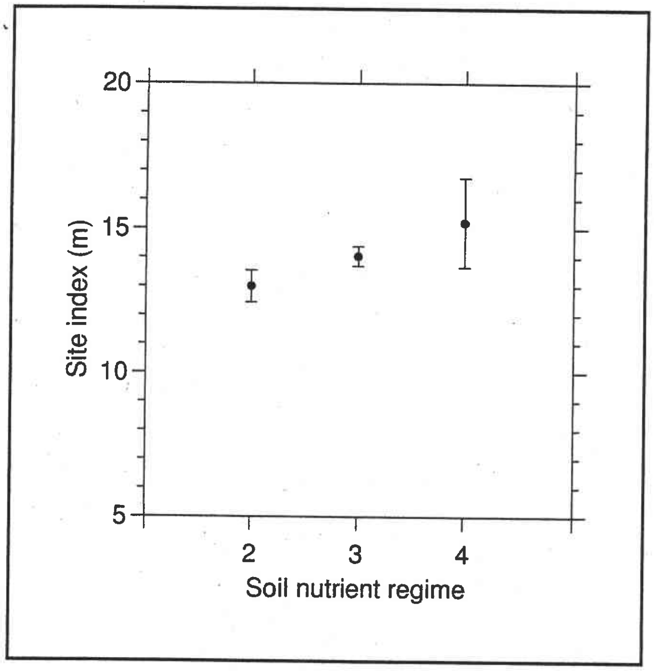

Fig. 7. The relationship between lodgepole pine site index and SNR based on 136 plots with SMR = 3 ($R^2 = 0.040$, $p = 0.064$).

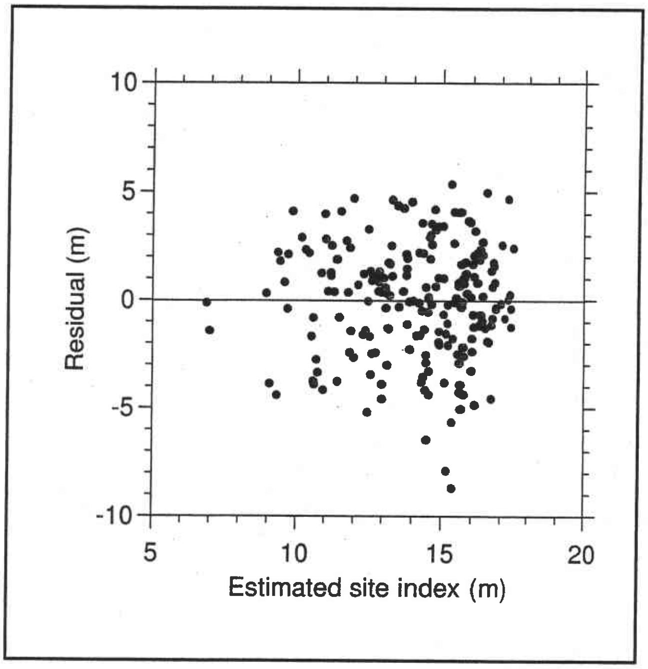

Fig. 8. Residual Analysis for Equation [6] (Table 3).

dictors and that (2) the addition of synoptic variables of soil moisture and nutrients explained only a minor component of the variation in site index.

The results shown in Table 3 suggest that with every 100 m increase in elevation, lodgepole pine site index decreases about 0.6 m. This outcome is similar to that found by Monserud and Huang (2002). Lower temperature and shorter growing season at higher elevation (Table 1) is likely responsible. The increase in site index with increasing latitude, although not expected, can be easily explained by the fact that plots with higher elevation (in Subalpine and Montane NSRs) are also associated with lower latitudes. The simple correlation coefficient between elevation and latitude was -0.79. In a study conducted in northern British Columbia, Chen *et al.* (1998) also reported that trembling aspen site index decreased with elevation but increased with latitude, and latitude was negatively correlated with elevation (-0.89).

The quadratic relationship between lodgepole pine site index and longitude (Fig. 4) reflected the fact that elevation decreases with longitude when moving away from Rocky Mountains towards the northeast; the highest longitude was associated with high elevation in the southern end of the Rocky Mountain range in Alberta (Fig. 1). Given the large differences in climate (Table 1) among the natural subregions, the significant effect of NSR on lodgepole site index is expected. The relative moist and warm climate in the Lower Foothills NSR supported the best lodgepole pine site index, while the coldest climate in the Subalpine NSR had the lowest lodgepole pine site index. The effect of NSR disappeared when differences in elevation among NSRs were adjusted, which further confirmed the importance of elevation on lodgepole site index in Alberta.

Many previous studies have concluded that predicting site index from soil and topography variables over a large geographic area is problematic. For example, Holmes and Tackle (1962) examined lodgepole pine stands in western Montana and reported that 89% of the variation in the height of dominants was explained by stand characteristics alone and the addition of soil factors did not improve the height predictions. Monserud *et al.* (1990) examined a large number of edaphic factors in a soil-site study for inland Douglas-fir in northern Idaho and northwestern Montana. They determined soil profile descriptions, numerous physical and chemical analyses, moisture availability, and physiographic site descriptors. The most striking aspect of their study was that the myriad of soil descriptors accounted for so little variation in site index (Monserud *et al.* 1990). After examining numerous soil properties, the standard error could only be reduced 0.3 m, a disappointing result in light of the considerable time and expense necessary for soil sampling (Monserud *et al.* 1990). The causes of these low soil–site correlations could not be conclusively determined, but the most likely explanations were *(i)* that the number of important site factor interactions occurring in this large and complex study area far exceeded the sample size, and *(ii)* failure to measure the true causes of site productivity (Monserud *et al.* 1990). Payandeh (1986) conducted a similar study in the seemingly more homogeneous environment of northern Ontario, with similar results.

Given that the promise of synoptic variables is to find a relatively small number of classification variables related to the underlying causes of productivity (moisture and nutrient regimes, and climate) that will be applicable over large geographic areas, the failure to find a strong relationship between site index and soil moisture and soil nutrient regimes in this study was unexpected. There are seemingly conflicting results between this study and that of Wang *et al.* (1994) and other synoptic analyses (e.g., Green *et al.* 1989, Klinka and Carter 1990, Wang *et al.* 1994, Wang and Klinka 1996, Chen *et al.* 1998). Wang *et al.* (1994) reported that similar topographic

Table 3. Regression equations of lodgepole site index (m at 50 years of breast height age) on natural subregion or spatial location, and soil nutrient regime (n = 214)

[1]	SI = 10.5 + 1.2(NSR9) + 2.8(NSR10) + 5.1(NSR11) $R^2 = 0.269$ SEE = 2.94 m
[2]	SI = 11.0 + 1.1(NSR9) + 2.7(NSR10) + 4.9(NSR11) – 1.42(SNR2) $R^2 = 0.304$ SEE = 2.88 m
[3]	SI = 21.8 – 0.006307(ELE) $R^2 = 0.332$ SEE = 2.80 m
[4]	SI = -3881.4 – 0.006609(ELE) – 0.5736(LAT) + 66.6484(LON) – 0.282(LON2) $R^2 = 0.372$ SEE = 2.72 m
[5]	SI = 22.0 – 0.006181(ELE) – 1.5(SNR2) $R^2 = 0.370$ SEE = 2.72 m
[6]	SI = -4097.2 – 0.006699(ELE) – 0.5938(LAT) + 70.4333(LON) – 0.2986(LON2) – 1.5(SNR2) $R^2 = 0.412$ SEE = 2.64m

Note: All models are significant ($p < 0.001$). NSR9, NSR10 and NSR11 are the Montane, Upper Foothills and Lower Foothills natural subregions, respectively; SNR2 = soil nutrient regime 2; ELE = elevation; LAT = latitude; LON = Longitude; LON2 = longitude squared; SI = site index, R2 = coefficient of determination; SEE = standard error of estimate.

variables (biogeoclimatic subzone, latitude, longitude, and elevation) were not associated with lodgepole site index in interior British Columbia. For soil moisture and nutrient regimes, Wang *et al.* (1994) reported that both SMR ($R^2 = 0.60$) and SNR ($R^2 = 0.45$) significantly affected lodgepole pine site index in British Columbia. The extremely weak effect of SNR ($R^2 = 0.040$, $p = 0.064$) and lack of influence of SMR ($p = 0.422$) on lodgepole pine site index in this study stands in contrast to the Wang *et al.* (1994) results. Several other synoptic studies on different species also found that SMR and SNR were the best predictors of site index (e.g., Green *et al.* 1989, Klinka and Carter 1990, Wang *et al.* 1994, Wang and Klinka 1996, Chen *et al.* 1998).

What are some differences between this and those other synoptic studies? The study of Wang *et al.* (1994) was much more limited in geographic variation. It only covered two biogeoclimatic subzones, with elevation on all sites < 900 m. The current Alberta study encompasses an area several times larger, with more complex topography (elevation ranged from 500 to 2100 m), and a larger number of natural subregions. Therefore, significant effects of topography on lodgepole pine site index in the Alberta study are not surprising. Failure to find a strong relationship between site index and soil moisture and soil nutrient regimes in this study suggests that the fallacy of the traditional soil-site studies may also apply to synoptic variables. For examples, Monserud *et al.* (1990) found that a large sample size covering a large and diverse study area contributed to the poor showing of edaphic variables in predicting site index. The sheer size of the study area increases the scientist's difficulty in finding a single set of soil-site factors that are strongly related to growth (Stone 1984). Recall Broadfoot's (1969) enormous sample size of 739 plots covering six southern states. Broadfoot (1969) regarded the sheer size of his study area as one of the reasons leading to an unsuccessful study. He found significant soil-site relations on small portions of his study area, but they did not generalize to his entire study area. Too many factors were interacting and varying.

A second difference is that many soil-site studies in general and synoptic studies in particular are carefully designed to control variation. Often, sample size is relatively small, and study area is limited. In contrast, the current study simply used the PSP inventory plot network, which is designed to be representative of growing conditions and natural variation across the province. It is understandable that scientists try to control or reduce variation in a study, in hopes of detecting a significant effect related to the variable of interest (site index). Monserud (2002) cautions that the lack of uniform conditions across the landscape, especially in mountainous terrain, means that results from small experimental plots or relatively small and uniform study areas may not generalize to the forest landscape with the same precision (Hobbs 1999). Studies that intentionally sample the natural variation across large, diverse study areas and with a large sample size accept the trade-off of a larger variance to gain greater assurance that the experimental results will generalize better to the population as a whole (Monserud 2002).

The ultimate test for any site index prediction equation developed through a research project is its success in application in the field when applied by foresters for operational purposes. The regression models developed in this study accounted for 37% to 41% of the total variation in lodgepole pine site index, with 2.64 to 2.94 m in the standard error of estimate. This level of precision in site index prediction might not be appropriate for forest management or silvicultural decision-making at the stand level. However, considering that easily-obtained topographic variables were the most significant predictors, models developed in this study should be useful for forest management planning at the regional scale, where assessment of regional potential of forest productivity is often needed without detailed site-specific information.

Conclusion

Simple topographic variables (elevation, latitude, longitude, natural subregion) accounted for almost all of the explainable variation in lodgepole pine site index in Alberta. Variables representing the soil moisture regime and soil nutrient regime (SMR and SNR) obtained from the existing classification system used in the provincial PSP program were not very useful in explaining additional variation. Furthermore, interactions among synoptic variables were not significant.

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References
Alberta Environmental Protection. 1994. Ecological land survey site description manual. Canadian Forest Service, Alberta Land and Forest Service Edmonton, Alberta. 165 p.

Alberta Forest Service. 1988. Alberta phase 3 forest inventory: tree section manual. Alberta Forest Service Publ. T/168, Edmonton, Alberta.

Alberta Land and Forest Service. 2000. Permanent sample plot field procedures manual. Forest Management Division, Alberta Land and Forest Service, Edmonton, Alberta. 102 p.

Bakuzis, E.V. 1969. Forestry viewed in an ecosystem perspective. *In* G.M. Van Dyne (ed.). The ecosystem concept in natural resource management. pp. 189–258. Academic Press, New York.

Beckingham, J.D., I.G.W. Corns and J.H. Archibald. 1996. Field guide to ecosites of west-central Alberta. Natural Resources Canada, Canadian Forest Service, Northwest Region, Northern Forestry Center, Edmonton, Alberta. Spec. Rep. 9.

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

Cajander, A.K. 1926. The theory of forest types. Acta For. Fenn., 2: 11–108.

Carmean, W.H., 1975. Forest site quality evaluation in the United States. Adv. Agron. 27: 209–269.

Chen, H.Y.H., K. Klinka and R.D. Kabzems. 1998. Site index, site quality, and foliar nutrients of trembling aspen: relationships and prediction. Can. J. For. Res. 28: 1743–1755.

Dempster and Associates. 1982. Interim yield tables for lodgepole pine regenerated after logging in Alberta. Edmonton, Alberta, Canada. 62 p.

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.

Hargrove, WW, and J. Pickering. 1992. Pseudoreplication: a *sine qua non* for regional ecology. Landscape Ecology 6(4): 251–258.

Hills, G.A. 1952. The classification and evaluation of site for forestry. Research Report 24, Ontario Department of Lands and Forests, Toronto. 41 p.

Hobbs, R.J. 1999. Clark Kent or Superman: where is the phone booth for landscape ecology? *In* J.M. Klopatek and R.H. Gardner (eds.). Landscape Ecological Analysis: Issues and Applications. pp. 11–23. Springer-Verlag, New York.

Holmes, J.R. and D. Tackle. 1962. Height growth of lodgepole pine in Montana related to soil and stand factors. Montana State University, School of Forestry, Bozeman. Bull. No. 21.

Huang, S., S.J Titus and G. Klappstein. 1997. Development of a subregion-based compatible height-site index-age model for young and mature lodgepole pine in Alberta. For. Mgmt. Res. Note No. 6, Land and Forest Service, Tech. Pub. No. T/353.

Huang, S., D. Morgan, G. Klappstein, J. Heidt, Y. Yang and G. Greidanus. 2001. Yield tables for seed-origin natural and regenerated lodgepole pine stands. Alberta Sustainable Resource Development Tech. Rep. Pub. No. T/485, Edmonton, Alberta, Canada. 193 p.

Hurlbert, S.H. 1984. Pseudoreplication and the design of ecological field experiments. Ecol. Monogr. 54(2): 187–211.

Johnstone, W.D. 1976. Variable density yield tables for natural stands of lodgepole pine in Alberta. Can. For. Serv. For. Tech. Rep. 20, Edmonton, Alberta, Canada. 110 p.

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

Krajina, V.J. 1969. Ecology of forest trees in British Columbia. Ecol. Western North Am. 2: 1–146.

Lotan, J.E. and W.B. Critchfield. 1990. *Pinus contorta* Dougl. ex. Loud. or Lodgepole pine. *In* R.M. and B.H. Honkala (tech. coords.). Silvics of North America: 1. Conifers, Burns. pp. 302–315., Agriculture Handbook 654, USDA For. Serv., Washington D.C.

Major, J. 1963. A climatic index to vascular plant activity. Ecology 32: 485–498.

Monserud, R.A. 1984. Height growth and site index curves for inland Douglas-fir based on stem analysis data and forest habitat type. For. Sci. 30: 943–965.

Monserud, R.A. 2002. Large-scale management experiments in the moist maritime forests of the Pacific Northwest. Landscape and Urban Planning 59: 159–180.

Monserud, R.A. and S. Huang. 2002. Mapping lodgepole pine site index in Alberta. *In* A. Amaro, D.D. Reed and P. Soares (eds.). Modelling Forest Systems. pp. 23–30. CABI Publishing, Wallingford, United Kingdom.

Monserud, R.A., U. Moody and D. Breuer. 1990. Soilsite relations for inland Douglasfir. Can. J. For. Res. 20: 686–695.

Pojar, J., K. Klinka, and D.V. Meidinger. 1987. Biogeoclimatic ecosystem classification in British Columbia. For. Ecol. Manage. 22: 119–154.

Payandeh, B. 1986. Predictability of site quality from soil factors and lesser vegetation in northern Ontario forest types. Great Lakes Forestry Centre, Canadian Forest Service, Inf. Rep. 0-X-373.

Stone, E.L. 1984. Site quality and site treatment. *In* E.L. Stone (ed.). Forest soils and treatment impacts. pp. 41–52. Department of Forestry, Wildlife, and Fisheries, University of Tennessee, Knoxville.

Wang, G.G. and K. Klinka. 1996. Use of synoptic variables in predicting white spruce site index. For. Ecol. Manage. 80: 95–105.

Wang, Q., G.G. Wang, K. Klinka and K.D. Coates. 1994. Use of site factors to predict lodgepole pine and interior spruce site index in the Sub-Boreal Spruce zone. Res. Note No. 114, Ministry of Forests, Victoria, B.C. 26 p.

Wilkinson, L. 1990. SYSTAT: The system for Statistics. Systat Inc., Evanston, IL. 677 p.