Research Report

B.C. Journal of Ecosystems and Management

Height growth and site index models for Pacific silver fir in southwestern British Columbia

Bernhard Erich Splechtna[1]

Abstract

Following an exploratory examination of the variation in the height growth pattern using a single-valued ratio, conventional polymorphic and climate-specific height growth and site index models were developed for Pacific silver fir (*Abies amabilis* [Dougl. *ex* Loud.] Forbes). The models were developed from stem analysis data obtained from 67 study plots, which were located over the entire elevation-continentality range of the species in southern coastal British Columbia. When tested against an independent data set consisting of 31 plots, the climate-specific models improved height and site index prediction compared to the conventional polymorphic models. The previously available model for Pacific silver fir was biased. It overestimated height before, and underestimated it beyond, the index age. It also underestimated height on low-productivity sites and overestimated it on high-productivity sites. In consequence, when this model was used to estimate site index from top-height and breast-height age, it underestimated site index before, and overestimated it beyond, the index age. Similarly, site index was overestimated on low-productivity sites and underestimated on high-productivity sites. The climate-specific models developed in this study are recommended for height and site index estimation of Pacific silver fir stands within a range of breast-height age from 15 to 160 years in southern coastal British Columbia.

Contact Information

1 Institute of Forest Ecology, BOKU University, Peter Jordan Strasse 82, A-1190 Vienna, Austria
E-mail: b.splechtna@utanet.at

Volume 1, Number 1, 2001
http://www.siferp.org/jem/2001/vol1/no1/art5.pdf

Introduction

Accurate estimates of forest productivity are needed for sustainable forest management in order to determine annual allowable cut and rotation period, and to make tree species selection decisions. As harvesting progresses increasingly into high-elevation forests, growth and yield information for these forests is urgently needed to accommodate forestry decision making.

Despite climatically unfavourable conditions, high timber volumes have accumulated in the high-elevation old-growth coastal forest of British Columbia over several centuries. However, the time needed to produce economically feasible and ecologically sustainable second-growth timber crops is unknown. Existing growth and yield information for these forests is limited to investigations of early growth performance (Arnott *et al.* 1995) or to different geographic areas (Hoyer and Herman 1989; Murray *et al.* 1991).

Notwithstanding recognized limitations (e.g., Monserud 1984a), site index (top height at reference age 50 years at breast height) is the most commonly used index of forest productivity in North America. Together with height growth models, site index is widely used in models designed to estimate forest- and stand-level yields (e.g., Mitchell 1975; Wykoff and Monserud 1987; Pretzsch 1994; Sterba 1995). Accurate estimates for site index and height depend on how well the models estimate the height growth pattern (i.e., the trajectory of height over age) of the top-height trees of a stand. However, height growth patterns vary with site (e.g., Carmean 1956, 1972; Assmann 1970; Beck 1971; Marschall 1976).

To account for differences in height growth pattern with site, height growth is commonly modelled by polymorphic functions. These functions allow different shapes of height growth curves for each site index (e.g., Curtis 1964; Heger 1968; Beck 1971; Carmean 1972; Curtis *et al.* 1974a; Alemdag 1991; Thrower and Goudie 1992; Chen *et al.* 1998). This approach assumes that the same height growth pattern will be followed regardless of which factors lead to a certain level of height growth (site index class). However, some studies found different height growth patterns for the same site-index class of the same tree species (e.g., Monserud 1984b; Klinka *et al.* 1996). Hence, site factors were incorporated into polymorphic models to make them site-specific (e.g., Monserud 1984b; Milner 1988). Such site-specific models showed increased precision compared to conventional polymorphic models (Monserud 1984b; Vander Ploeg and Moore 1989), and indicated that height growth patterns varied with climate, soils, or genetics (Monserud 1984b; Monserud and Rehfeldt 1990; Wang *et al.* 1994). In contrast, some authors concluded that conventional polymorphic curves described height growth patterns sufficiently (e.g., Beck 1971; Carmean 1972; Alemdag 1991). Therefore, a decision on whether or not to develop and use site-specific curves must be based on:

- the observed differences in height growth pattern,
- the improved performance of site-specific models compared to conventional polymorphic models, and
- the desired level of precision.

> *. . .[this research] develops accurate height growth and site index models for Pacific silver fir in coastal southern British Columbia and . . . evaluates the improvement of height and site index estimates over the currently used model.*

Pacific silver fir (*Abies amabilis* [Dougl. *ex* Loud.] Forbes) is a major component of the high-elevation coastal forests together with mountain hemlock (*Tsuga mertensiana* [Bong.] Carr.) and yellow-cedar (*Chamaecyparis nootkatensis* [D. Don in Lamb.] Spach). In contrast to the latter two species, Pacific silver fir also occurs on low-elevation sites. The height growth curves that have been used in British Columbia for both height and site index estimation of Pacific silver fir were developed from low-elevation data (191 sectioned trees) on Vancouver Island (Kurucz 1982). Since the height growth pattern may be significantly different between low- and high-elevation sites, the validity of these curves for low site-index classes (15 and below) is uncertain. The only existing curves developed for high-elevation sites are from a different (warmer) climatic region in the Washington and Oregon Cascades, and are based on data from only 40 sectioned trees (Hoyer and Herman 1989). Considering the small sample size, it is uncertain whether the data reflected the "true" variability of Pacific silver fir height growth pattern. Moreover, the validity of these curves for British Columbia is questionable as many studies have shown that the transferability of curves of the same species from one region to another is limited (e.g., Marschall 1976; Monserud 1985; Thrower and Goudie 1992; Chen *et al.* 1998).

The objectives of this study were to develop accurate height growth and site index models for Pacific silver fir in coastal southern British Columbia and to evaluate the improvement of height and site index estimates over the currently used model. To achieve these objectives, I:

- examined the changes in height growth pattern with soil and climate,
- developed conventional polymorphic models and site-specific models according to exploratory height growth pattern analysis, and
- compared performance of site-specific models to conventional polymorphic models and the currently used model using a set of independent data.

Materials and Methods

Sampling

The study area was restricted to the southern portion of the coastal forest south of the Port McNeill–Lillooett line (50°30′N) and west of Boston Bar (121°20′W), and included the entire native range of Pacific silver fir in southwestern British Columbia (Figure 1). Within the study area, the Insular and Coast Mountains extend in a north–south direction. These mountain ranges create an effective barrier to air movement between coastal and interior sites. Therefore, both a temperature gradient (with elevation) and a relatively steep continentality gradient (measured as difference between summer and winter temperature) exist (Klinka *et al.* 1989; Klinka *et al.* 1991; Nuszdorfer and Boettger 1994). Within the

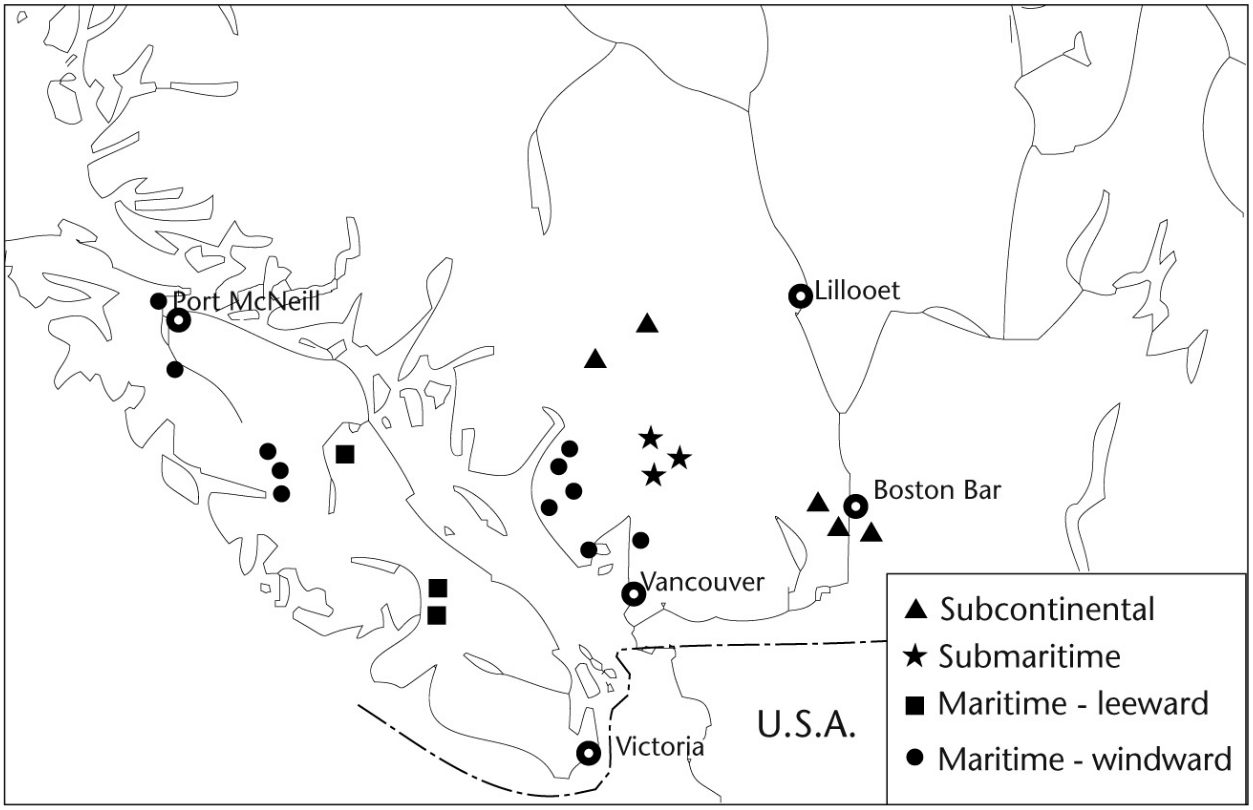

FIGURE 1. Continentality strata in the study area and general locations of study plots (dots represent location of more than one plot).

study area, Pacific silver fir extends from sea level to almost timber line, and from the hypermaritime region on the west coast of Vancouver Island to the subcontinental region on the leeward side of the Coast Mountains (Krajina 1969; Brooke *et al.* 1970; Klinka *et al.* 1989). Climatic differences associated with continentality are evident; for example, Pacific silver fir does not grow below 800 m on subcontinental sites of the study area, but occurs at sea level on hypermaritime sites.

Study stands were located in four continentality strata following the biogeoclimatic ecosystem classification system (Krajina 1965; Pojar *et al.* 1987) given in Klinka *et al.* (1989). However, in addition to subcontinental (SC), submaritime (SM), and maritime (M) strata, a fourth stratum (maritime leeward: ML) was defined. Located on the leeward side of the Insular Mountains, the ML stratum is characterized by warmer and drier summers than other maritime areas (Figure 1). Consequently, the maritime (M) stratum was designated as the maritime-windward (MW) stratum.

All study stands were naturally regenerated, unmanaged, fully stocked, relatively even-aged (ranging in age from 40 to about 300 years at breast height), and did not have a history of damage. They were distributed over a wide range of climatic conditions (measured by continentality stratum, elevation, and aspect) and soil moisture and nutrient conditions. The selected stands had an unknown, but obvious, history of stand-initiating disturbance by fire, wind, avalanche, or less frequently by timber harvesting. I assumed that the selected stands had grown under full light conditions except in the earliest stages, when competing vegetation or deep snow cover might have influenced tree growth. Many candidate stands were rejected from the sample because increment cores taken at breast height from dominant trees suggested suppression beyond breast height age. Despite these difficulties, 123 sample plots were established.

After randomly locating a sample plot of 0.04 ha in each stand, soil moisture regime (SMR) and soil nutrient regime (SNR) were estimated using a combination of topographic and soil morphological properties, as well as understorey vegetation (Green and Klinka 1994). Elevation was measured using a Thommen pocket altimeter, slope using a clinometer, and aspect using a compass. In each sample plot, the three largest diameter Pacific silver fir trees without observable damage were felled. Total height and length of the live crown were measured for each sample tree. Stem discs were cut at 30, 80, 130 cm above the ground, and then equally spaced discs at 100-cm intervals were taken to the top of each tree.

Data Analysis

Carmean's (1972) formula (see Dyer and Bailey 1987) was used to estimate the "true" tree height corresponding to the ring counts at the crosscuts. Height-over-age plots of every sampled tree were visually examined for patterns of suppression and release and growth anomalies beyond breast-height age. Suppressed trees were deleted from the analysis, and only the sample plots with two or three site trees were kept in the database. Consequently, 25 sample plots were deleted from the data set leaving data from 98 plots for model construction and testing (Table 1). The relatively high number of rejected plots emphasize that shade-tolerant Pacific silver fir is a very difficult species for site index estimation (Curtis *et al.* 1974a). Slight suppression, especially when subsequent release was gradual, was not always recognized when trees were cored before felling, but became apparent on height-over-age plots. The effect of a deep snowpack on the early growth of Pacific silver fir located on high-elevation sites added to the difficulties in distinguishing true suppression. I considered snow as a site factor, and retained a few plots where site trees showed release above breast height in the database. This was done only when:

- a deep and long-lasting snowpack was evident in the area (inferred from topography, height of epiphytic lichens, and observations of snowpack in late spring),
- a similar height growth pattern was observed in all site trees within the same plot, and
- similar stands in the same area showed a similar height growth pattern.

For every site tree, I obtained a record of heights at 5-year breast-height-age intervals by linearly interpolating between the height and age pairs that resulted from Carmean's formula. Average plot curves were computed as the arithmetic mean of these values. This provided height versus age data at 5-year intervals starting from age 5 years for each plot, and site index values for each plot as the

TABLE 1. General statistics for study plots according to the calibration, test, and all plots

	Breast height age (years)	Top height (m)	Site index at 50 years (m)
Calibration data			
N	67	67	67
Minimum	37	7.7	4.8
Mean	92	23.7	17.6
Maximum	312	55.0	36.7
Std. Deviation	51	8.6	7.9
Test data			
N	31	31	31
Minimum	36	8.9	4.6
Mean	82	22.0	18.2
Maximum	173	32.3	36.4
Std. Deviation	38	5.1	8.4
All data			
N	98	98	98
Minimum	36	7.7	4.6
Mean	89	23.1	17.8
Maximum	312	55.0	36.7
Std. Deviation	48	7.7	8.0

corresponding height at breast-height-age 50. A single, quantitative measure of height growth pattern for each plot was calculated as the ratio (*z*-ratio) between heights at breast height age 60 and 30 (Hoyer and Chawes 1980). This ratio was proposed by Zeide (1978) and has been used in numerous studies to characterize curve shape (Hoyer and Chawes 1980; Milner 1988; Wang *et al.* 1994). I used the *z*-ratio in an exploratory analysis to identify site factors that were related to height growth patterns. As not all trees had reached 60 years breast height age, the data set used contained data from 43 plots. Linear models were used to test the effect of climate (measured by elevation and continentality stratum) and edatope (any given combination of soil moisture regime and soil nutrient regime) on height growth pattern.

The height growth data beyond 100 years at breast height age were mainly from medium- and low-productivity, high-elevation plots. To achieve a more balanced sample distribution, I included only data up to 100 years of breast height age in the data set used to calibrate the height and site index models. This was a compromise between a completely balanced distribution and the desired range of data. Since validation of height and site index models is preferably done by using an independent data set (Marshall and Northway 1993; Nigh and Sit 1996), 31 plots were set aside as a test data set and 67 plots were used for model calibration (Table 1).

To find the most suitable function for estimating height growth, the three main types of functions commonly used to describe height growth of trees were fitted to the calibration data. These functions are:

- a conditioned logistic function (Thrower and Goudie 1992; Wang and Klinka 1995; Chen *et al.* 1998),
- a Chapman-Richards' function (Payandeh 1974; Carmean and Lenthall 1989; Thrower and Goudie 1992; Chen *et al.* 1998), and
- a conditioned Weibull function (Payandeh and Wang 1995).

Since two different least square problems are solved for height growth and site index models (Curtis *et al.* 1974b), two separate polymorphic models were fitted for estimating the height growth and site index of Pacific silver fir, respectively. When fitting the site index models, the data points associated with ages 5 and 10 were excluded because a strong relationship between top height and site index before breast height age 15 was not expected (Carmean and Lenthall 1989; Thrower and Goudie 1992). All non-linear models were fitted using the least square Marquart-Levenberg procedure of the SPSS™ program (SPSS Inc. 1993). The best polymorphic model was chosen based on fitting statistics (R^2 and MSE) and bias. Results from the height growth pattern analysis and the best height growth and site index model, were used to develop climate-specific height growth curves.

Three criteria were used to compare performance of polymorphic models to climate-specific models and currently used models: precision, bias, and potential for extrapolation beyond the calibration range. Precision was evaluated by the predicted mean squared error (PMSE); bias and extrapolation potential were assessed by examining residual plots by age and site index. The common procedure for testing site index models is to use every known pair of height and age to estimate site index; this is analogous to the procedure used for height models (e.g., Thrower and Goudie 1992; Chen *et al.* 1998). However, I decided to use only the originally measured top height of the trees at the time of sampling. This approach yields only one estimate per plot and eliminates the known problems caused by autocorrelation (Monserud 1984b; Nigh and Sit 1996). As this approach is closest to their application, I considered this to be the ultimate test for site index models, providing that a wide range in top height and age test data exists. In addition to the graphical examination of residuals, paired *t*-tests were used to detect significant differences between predicted and measured site indices.

Results

Examination of the Variation in Height Growth Patterns

Height growth patterns, as measured by *z*-ratios, were poorly correlated with site index ($r = 0.09$, $p = 0.57$, $n = 43$). Analysis of variance showed no significant difference in mean *z*-ratio between edatopes ($F = 2.2$, $p = 0.07$, $n = 43$). A significant relationship existed between height growth patterns and climate, although of the two tested variables in the model only continentality stratum was significant ($F = 3.49$, $p = 0.025$, $n = 43$), but elevation was not ($F = 0.06$, $p = 0.81$, $n = 43$). While no conclusion can be drawn about the true relationship between height growth patterns and site factors, this exploratory analysis clearly indicates that of the measured variables continentality stratum was most strongly related to height growth patterns.

Consequently, continentality strata were used in further analysis. Based on the results of the exploratory analysis, the maritime-windward and maritime-leeward strata were combined to form the maritime (M) stratum, and the submaritime and subcontinental strata were combined to form the submaritime/subcontinental (SS) stratum. Stands within these two strata showed significantly different height growth patterns (Figure 2). These two continentality strata were then used as dummy variables in height growth and site index models (equations [2] and [4]).

Height Growth Models

Based on examinations of residuals and fitting statistics ($R^2 = 0.98$, MSE = 1.13, $df = 994$), the conditioned logistic function was chosen as the baseline model:

$$H = 1.3 + (S - 1.3)\frac{1 + e^{[9.486 - 1.362\ln(50) - 1.18\ln(S - 1.3)]}}{1 + e^{[9.486 - 1.362\ln A - 1.18\ln(S - 1.3)]}}; \quad [1]$$

where: H = top height (m); S = site index (top height at 50 years breast height age); A = breast height age (years); e = the base of ln; and ln = natural logarithm.

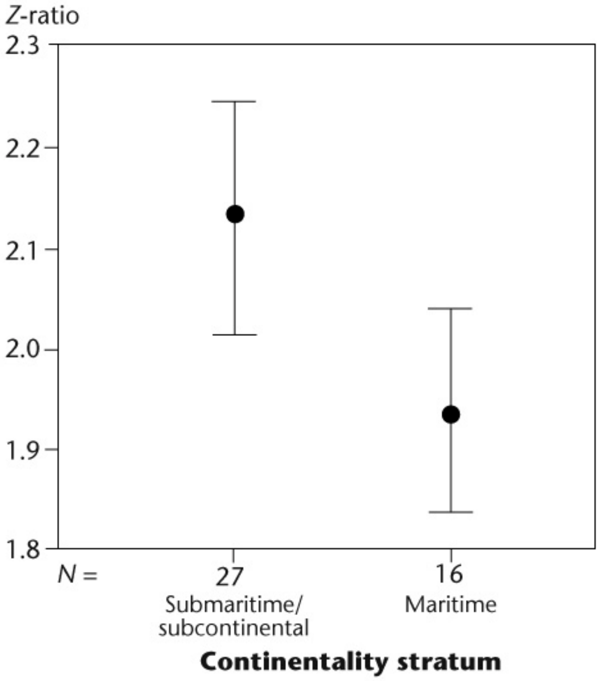

FIGURE 2. Mean *z*-ratios and confidence intervals (α = 0.05) for plots in the submaritime/subcontinental (SS) and maritime (M) continentality strata (*N* is the number of plots in each stratum used for the analysis).

Equation [1] was extended to accommodate variation in height growth pattern with continentality by using the two continentality strata as dummy variables, which resulted in:

$$H = 1.3 + M\left\{(S-1.3)\frac{1+e^{[8.704-1.306\ln(50)-0.980\ln(S-1.3)]}}{1+e^{[8.704-1.306\ln A-0.980\ln(S-1.3)]}}\right\}$$

$$+\,SS\left\{(S-1.3)\frac{1+e^{[9.761-1.549\ln(50)-1.109\ln(S-1.3)]}}{1+e^{[9.761-1.549\ln A-1.109\ln(S-1.3)]}}\right\}; \qquad [2]$$

where: H = top height (m); S = site index (top height at 50 years breast height age); A = breast height age (years); e = the base of ln; and ln = natural logarithm; and M and SS are either 0 or 1 depending on the plot location.

This climate-specific model showed a similar R^2 (0.98) to equation [1] and a slightly lower MSE (1.07, df = 991), indicating only a slight increase in precision. It yielded two sets of curves, one for each continentality stratum which displayed the greatest differences past the calibration range (> 100 years breast height age) (Figure 3). For all site-index classes, curves of the SS stratum were more sigmoidal than the curves of the M stratum. This implies that culmination of height growth occurs earlier and (potential) maximum heights reached for a given site-index class are lower in the SS stratum compared to the M stratum. Prior to the index age, height estimates in the SS stratum were always lower compared to the M stratum. Beyond the index age, however, differences in estimated heights varied with site-index class. For low site-index classes of 5 and 10 m, height estimates for the SS stratum were higher than for the M stratum; for site index classes of 15 and 20 m, little difference was evident between the curves of the two strata; and for site-index classes of greater than 25 m, the predicted heights were increasingly higher for the M than for the SS stratum. Within the tested range, the largest difference in top height between the two strata given by the model was about 4 m for site-index class 35 and breast height age of 160 years (Figure 3).

When tested against independent data within the calibration range, little difference in bias was evident between the models. The patterns of residuals versus age were similar for all four models up to the age class of 100 years (Figure 4A). Both models underestimated height for most age classes; however, this underestimation was only greater than two standard errors of the mean at age class 5 years. When residuals were plotted over site index classes, the climate-specific model [2] was only slightly biased for site index class 10 (mean bias = 0.1 m) (Figure 4B). Equation [1] was significantly negatively biased for site index classes 5 and positively biased for site index class 30 (Figure 4B). Model [2] (PMSE = 0.50, N = 486) was also slightly more precise than model [1] (PMSE = 0.69, N = 486).

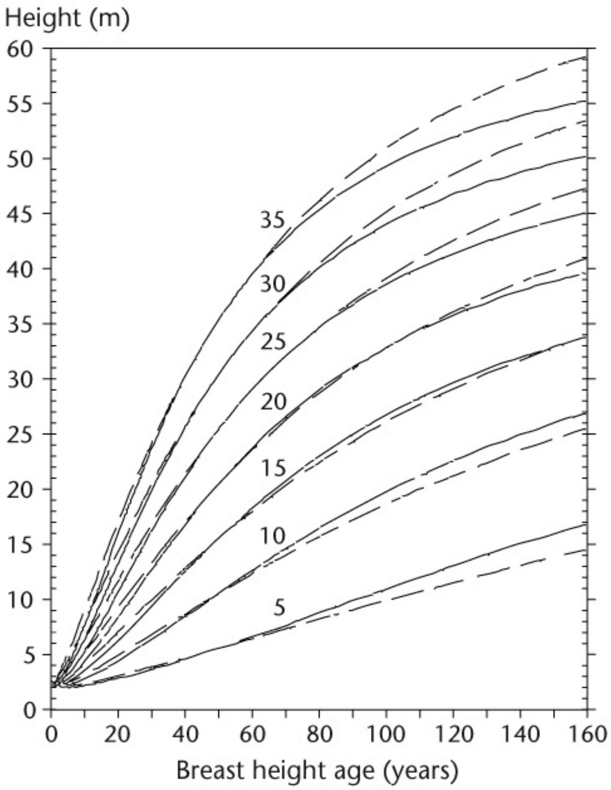

FIGURE 3. The plot of the climate-specific height growth curves from the selected model (equation [2]). Solid lines refer to the submaritime/subcontinental (SS) continentality stratum and dashed lines refer to the maritime (M) continentality stratum.

Past the calibration range, the climate-specific model (equation [2]) performed better than the conventional polymorphic model (equation [1]). The mean residuals never deviated from zero by more than 0.6 m and lay within two standard errors of the mean for all age classes. The conventional polymorphic model (equation [1]) yielded a large negative bias past 110 years (Figure 4A).

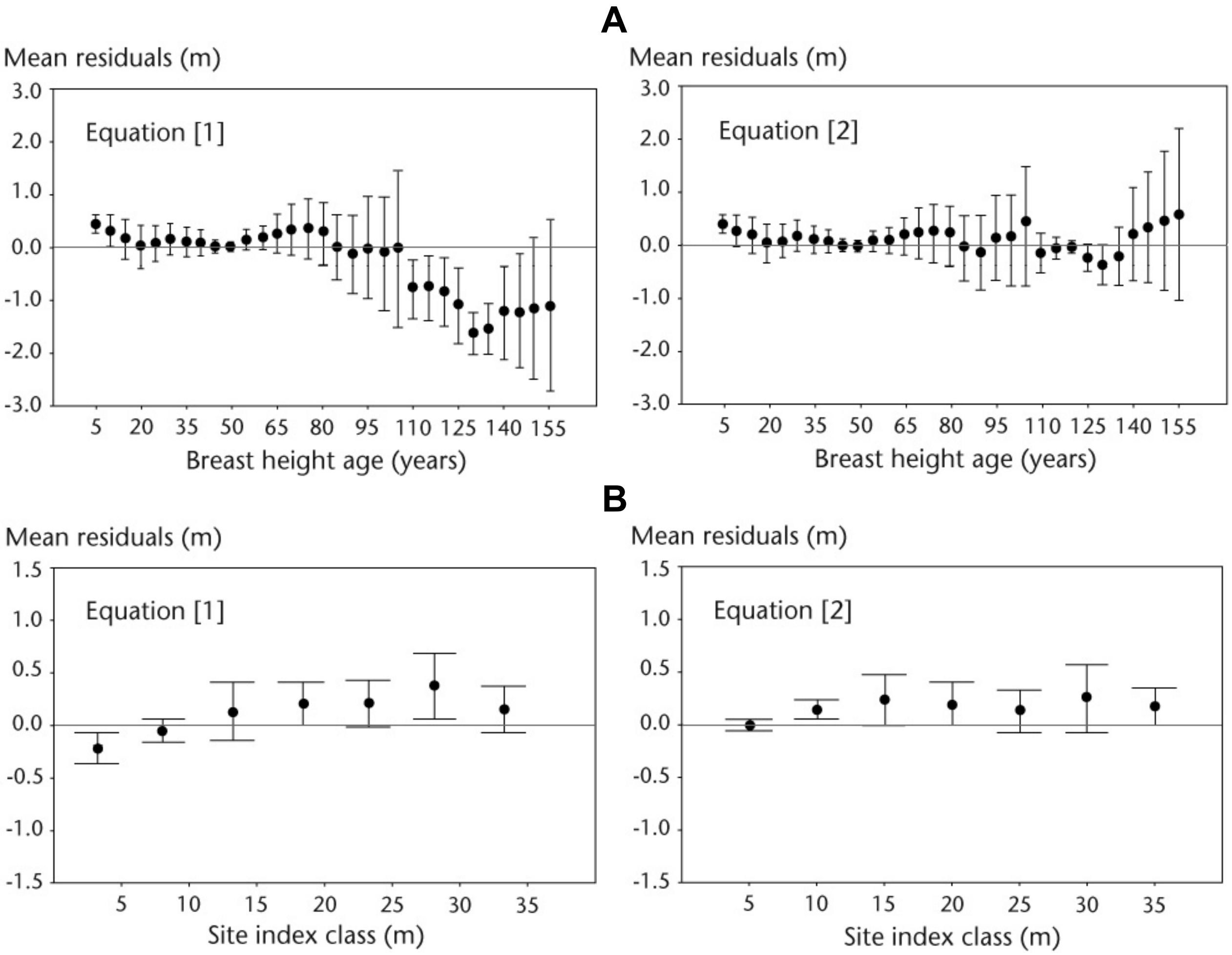

FIGURE 4. Validation of height models using the test data set. Mean and two standard errors by (A) breast height age and (B) site-index class for residuals of height models fitted by conditioned logistic (equation [1]) and the climate-specific function (equation [2]).

Site Index Models

After fitting the initially selected functions to the calibration data, the residuals for all the models showed a cubic pattern with breast height age. Therefore, several other functions were tried and finally an equation, previously used by Carmean and Lenthall (1989) and Thrower and Goudie (1992), was selected:

$$S = 1.3 + 0.694(50 - A)A^{-0.558} + 0.368(H - 1.3) + 31.771(H - 1.3)A^{-1} \quad ; \qquad [3]$$

where: S = site index (top height at 50 years breast height age); A = breast height age (years)*; and* H = top height (m); .

Although equation [3] also showed a slight cubic pattern with age, the mean residuals never deviated more than two standard errors from zero for any age class. Therefore, equation [3] was selected as the "best" conventional polymorphic model ($R^2 = 0.96$, MSE = 2.43, $df = 859$).

Using continentality strata, a climate-specific model was developed:

$$S = 1.3 + M\left\{0.694(50 - A)A^{-0.558} + 0.368(H - 1.3) + 31.771(H - 1.3)A^{-1}\right\} + SS\left\{0.592(50 - A)A^{-0.578} + 0.183(H - 1.3) + 41.659(H - 1.3)A^{-1}\right\}; \qquad [4]$$

where: S = site index (top height at 50 years breast height age); A = breast height age (years); H = top height (m); and M and SS are either 0 or 1 depending on the plot location.

The climate-specific model did not improve prediction when tested against the calibration data. A gain in accuracy was neither apparent from the fitting statistics ($R^2 = 0.92$, MSE = 2.33) nor from examination of residuals. However, when the independent test data were used for evaluation of potential differences between equations [3] and [4] in operational use, differences between the models were significant. Paired *t*-tests showed that estimates from equation [3] were significantly biased for the M stratum and that the climate-specific model [4] removed this bias (Table 2). Moreover, residual plots of the climate-specific model showed a better distribution of residuals (Figure 5). Equation [3] exhibited a decreasing variance of the residuals with site index as well as a tendency to underestimate site index for ages over 100 years. The climate-specific model [4] was also more precise as measured by a lower PMSE of 0.59 ($N = 31$) compared to the conventional polymorphic model [3] (PMSE = 0.73, $N = 31$). This gain in precision was mainly achieved by reducing the extreme values of the residuals by adjusting for continentality (Figure 5).

Applicability of the Existing Height Growth and Site Index Models for Pacific Silver Fir

When Kurucz's height growth model was used for prediction, height estimates were significantly biased. The residuals showed trends with age and site index class. This resulted in:

- overestimation of height before the index age and underestimation of height beyond the index age, and
- underestimation of height on low-productivity sites and overestimation of height on high-productivity sites (Figure 6).

When Kurucz's model was used to predict site index from top height and breast height age, a paired *t*-test showed a significant mean bias of –0.71 m ($\alpha = 0.01$, $N = 31$). This overall bias was attributed to a significant mean bias for the SS stratum, whereas, on average, the estimates of the M stratum were un-biased (Table 2). Residuals showed trends with both age and site index (Figure 7A). Site index was underestimated when top height was measured on the trees younger than the index age, but overestimated when top height was measured on the trees older than the index age. Similarly, site index was overestimated for low site-index classes and slightly underestimated for high site-index classes (Figure 7A).

Application of the model developed by Hoyer and Herman (1989) resulted in predictions that were significantly biased for the M stratum, as shown by paired *t*-tests (Table 2). Residual plots showed trends with both age and site index. The model underestimated site index using the trees younger than the index age and overestimated site index when using the trees older than 100 years; it also overestimated site index on low-productivity sites and underestimated on high-productivity sites (Figure 7B).

TABLE 2. Results of the paired *t*-tests using measured site index (SI) and predicted site index from polymorphic (SI [3]) and climate-specific models (SI [4] of this study and from Kurucz's models (SI [KU]) and Hoyer and Herman's models (S I[HO]).

	Continentality stratum[a]	Mean difference	Standard error	*t*	*df*	*p*
SI – SI [3]	M	0.338	0.148	2.277	17	.036
	SS	–0.330	0.280	–1.175	12	.263
SI – SI [4]	M	0.047	0.134	0.355	17	.727
	SS	0.193	0.278	–0.694	12	.501
SI – SI [HO]	M	0.451	0.130	3.473	17	.003
	SS	–0.616	0.293	–2.100	12	.057
SI – SI [KU]	M	–0.167	–0.231	–0.723	17	.480
	SS	–1.469	0.336	–4.368	12	.001

[a] M and SS refer to the continentality strata, maritime and submaritime/subcontinental, respectively.

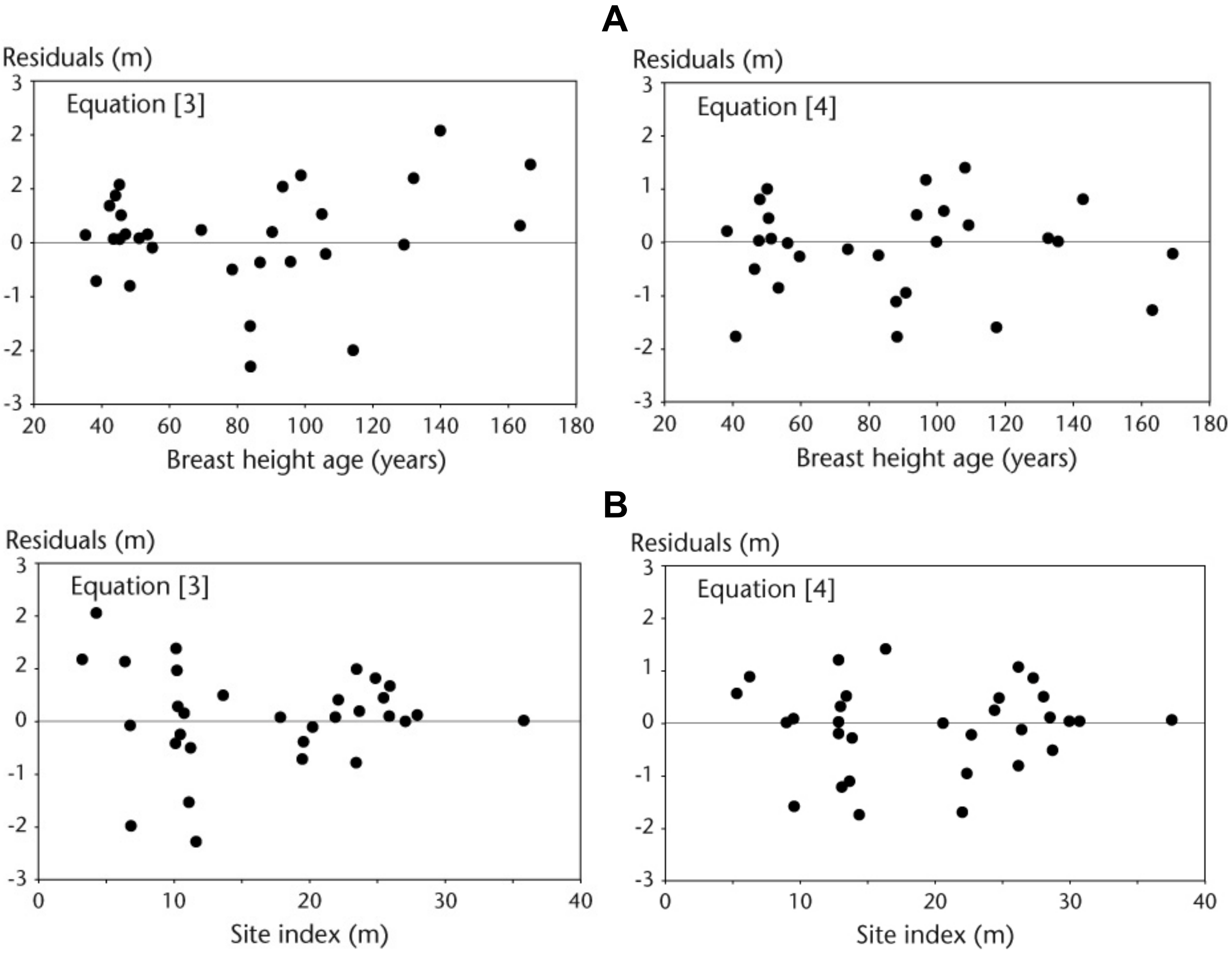

FIGURE 5. Residuals plotted by (A) breast height age and (B) site index for the polymorphic function (equation [3]) and the climate-specific function (equation [4]).

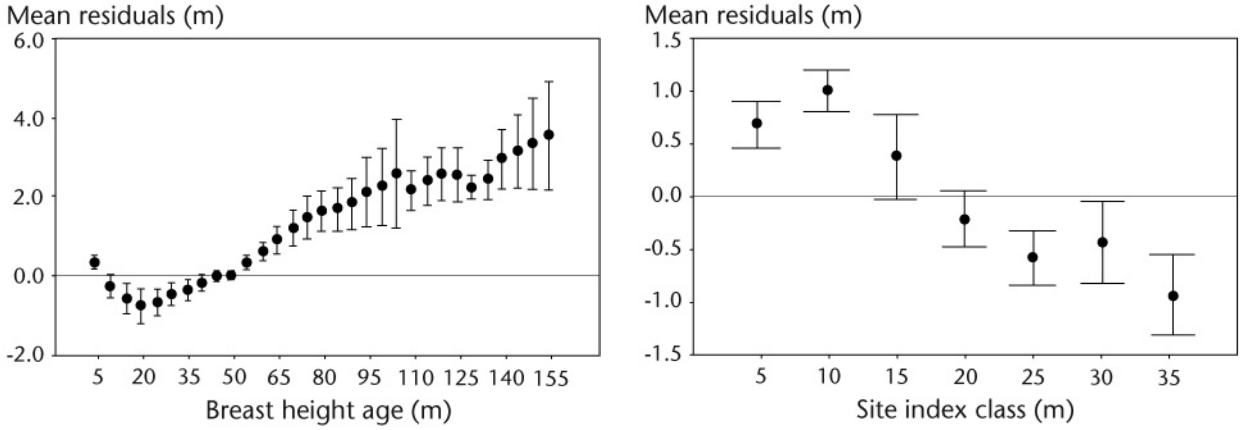

FIGURE 6. Mean and two standard errors of residuals (of predicted top height) by breast-height-age and site-index class as calculated from Kurucz's curve using the test data set.

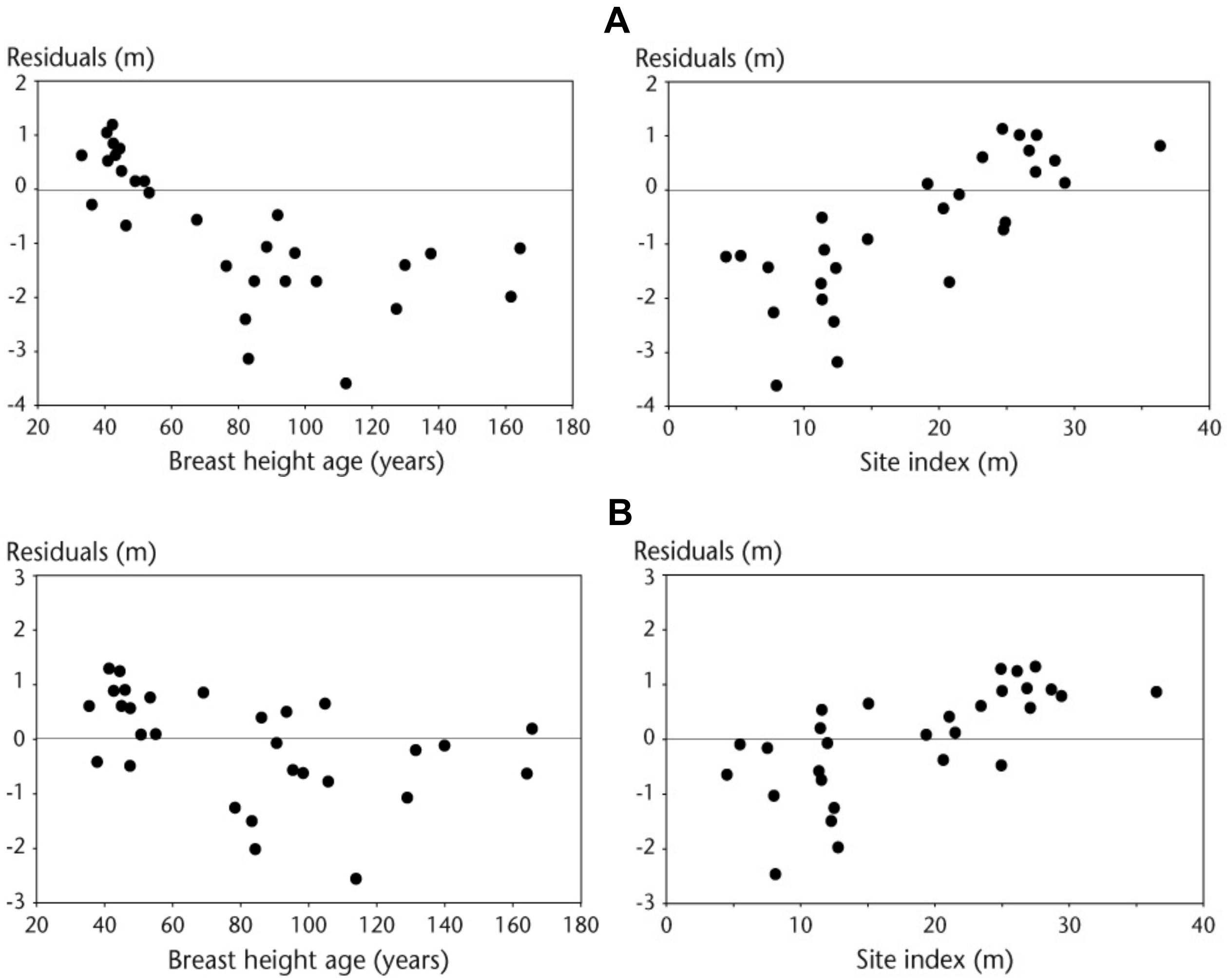

FIGURE 7. Residuals of predicted site index plotted by breast-height-age and site index calculated from (A) Kurucz's function and (B) the function from Hoyer and Herman.

Discussion

Differences in Height Growth Pattern between Continentality Strata

Differences in the height growth pattern between maritime and submaritime/subcontinental continentality strata were observed when height growth pattern was measured as a single-valued ratio (z-ratio). When the two continentality strata were used as dummy variables in climate-specific height growth and site index models, the resulting curves showed obvious differences in height growth pattern (Figure 3) and improved the accuracy of height and site index estimates (Figures 4 and 5, Table 2). A relationship between regional climate and height growth pattern was suggested for several tree species as height growth patterns have been found to vary from region to region (e.g., Marschall 1976; Monserud 1985; Thrower and Goudie 1992; Chen *et al.* 1998). The results also agree with several studies that reported relationships between climatic variables and height growth patterns (Hoyer and Chawes 1980; Milner 1988; Wang *et al.* 1994; Klinka *et al.* 1996).

However, numerous climatic and non-climatic factors may act and interact to produce height growth patterns. The association of continentality strata with variation in height growth pattern of Pacific silver fir may be indirect. Non-climatic factors that are associated with continentality strata may cause differences in height growth pattern; for example, differences in continentality may be associated with different populations of Pacific silver fir, which may have adapted different height growth patterns (Monserud and Rehfeldt 1990).

Application of Height and Site Index Models

The previously existing models to estimate height and site index for Pacific silver fir were significantly biased when applied to the entire study area (Figures 6 and 7). Consequently, estimates of yield for the coastal high-elevation forest based on these curves are likely to be incorrect. When the performance of the conventional polymorphic and climate-specific height growth and site index models was compared using an independent set of data, residual plots and the PMSE statistics showed that the climate-specific models were more accurate. The improvement over the conventional polymorphic models was mainly attributed to a reduced bias past the calibration range (Figures 4 and 5). This is consistent with the finding that differences between the height growth curves for the two continentality strata were largest between 100 and 160 years of age (Figure 3).

For Pacific silver fir stands growing in southwestern British Columbia, I recommend the application of the climate-specific models for height and site index estimation. The models should only be used within the age range of 15 to 160 years. Since the results of this study indicate that height growth patterns of Pacific silver fir vary with climate, caution must be used when the models are applied to stands growing in central or northern coastal British Columbia.

Acknowledgements

I thank James Thrower (J. Thrower and Associates), Peter L. Marshall, Han Y. H. Chen, and Karel Klinka (Faculty of Forestry, University of British Columbia) for useful comments and advice. I also thank the reviewers Robert Green, Al Wienscyk (SIFERP), Gordon Weetman, and John E. Barker (Faculty of Forestry, University of British Columbia) for their comments on the manuscript. I am grateful to D. Brisco, G. Bustard, and David New, University of British Columbia, for field assistance, as well as Lucia Gussner for assistance in laboratory analysis. Financial support for this study provided by Forest Renewal BC is gratefully acknowledged.

References

Alemdag, I.S. 1991. National site-index and height-growth curves for white spruce growing in natural stands in Canada. Canadian Journal of Forest Research 21:1466–1474.

Arnott, J.T., R.K. Scagel, R.C. Evans, and F.T. Pendl. 1995. High elevation regeneration strategies for subalpine and montane forests of coastal British Columbia. Can. For. Serv. and B.C. Min. For., Victoria, B.C. FRDA Report No. 229.

Assmann, E. 1970. The principles of forest yield study. Pergamon Press, New York, N.Y.

Beck, D.E. 1971. Height growth pattern and site index of white pine in the southern Appalachians. Forest Science 17:252–260.

Brooke, R.C., E.B. Peterson, and V.J. Krajina. 1970. The subalpine Mountain Hemlock zone. Ecology of Western North America 2:148–349.

Carmean, W.H. 1956. Suggested modifications of the standard Douglas-fir site curves for certain soils in southwestern Washington. Forest Science 2: 242–250.

_______. 1972. Site index curve for upland oak in central states. Forest Science 18:109–120.

Carmean, W.H. and D.J. Lenthall. 1989. Height-growth and site-index curves for jack pine in north central Ontario. Canadian Journal of Forestry Research 19:215–224.

Chen, H.Y.H, K. Klinka, and R.D. Kabzems. 1998. Height growth and site index models for trembling aspen (*Populus tremuloides* Michx.) in northern British Columbia. Forest Ecology and Management 102:157–165.

Curtis, R.O. 1964. A stem analysis approach to site-index curves. Forest Science 10:241–256.

Curtis, R.O., F.R. Herman, and D.J. DeMars. 1974a. Height growth and site index for Douglas-fir in high-elevation forests of the Oregon-Washington Cascades. Forest Science 20:307–316.

Curtis, R.O., D.J. DeMars, and F.R. Herman. 1974b. Which dependent variable in site index-height regressions? Forest Science 20:74–87.

Dyer, M.E. and R.L. Bailey. 1987. A test of six methods for estimating true heights from stem analysis data. Forest Science 33:3–13.

Green, R.N. and K. Klinka. 1994. A field guide for site identification and interpretation for the Vancouver Forest Region. B.C. Min. For., Victoria, B.C. Land Management Handbook No. 28.

Heger, L. 1968. A method of constructing site-index curves from stem analysis. Forest Chronicle 44:11–15.

Hoyer, G.E. and R. Chawes. 1980. Application of Zeide´s standardized growth curves and the two-point curve form estimation system to Pacific Northwest species. Department of Natural Resources, Olympia, Washington. Rep. No. 40.

Hoyer, G.E. and F.R. Herman. 1989. Height-age and site index curves for Pacific silver fir in the Pacific Northwest. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, Oreg. Research Paper PNW-RP-418.

Klinka, K, V.J. Krajina, A. Ceska, and M. Scagel. 1989. Indicator plants of coastal British Columbia. University of British Columbia Press, Vancouver, B.C.

Klinka, K., J. Pojar, and D.V. Meidinger. 1991. Revision of biogeoclimatic units of coastal British Columbia. Northwest Science 65:32–47.

Klinka, K., Q. Wang, R.E. Carter, and H.Y.H. Chen. 1996. Height growth/elevation relationships in subalpine forests of interior British Columbia. Forest Chronicle 72:1–6.

Krajina, V.J. 1965. Biogeoclimatic zones in British Columbia. Ecology of Western North America 1:1–17.

________. 1969. Ecology of forest trees of British Columbia. Ecology of Western North America 2:1–146.

Kurucz, J.F. 1982. Polymorphic site-index curves for balsam-*Abies amabilis* in coastal British Columbia. Woodlands Service Division, MacMillan Bloedel Ltd., Nanaimo, B.C. Research Project 933-3.

Marschall, J. 1976. Die neuen Fichtenertragstafeln für Österreich. AFZ 87:195–200.

Marshall, P. and S. Northway. 1993. Suggested minimum procedure for validation of growth and yield models and yield tables to be used in British Columbia. Report to the Forest Productivity Councils of B.C.

Milner, K.S. 1988. Constructing site specific height growth curves. *In* Proceedings IUFRO forest growth modelling and prediction conference. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minn. General Technical Report NC-120.

Mitchell, K.J. 1975. Dynamics and simulated yield of Douglas-fir. Forest Science Monograph No. 17.

Monserud, R.A. 1984a. Problems with site index: an opinionated review. *In* Symposium Proceedings: Forest land classification: experiences, problems, perspectives. J. Bockheim (editor). University of Wisconsin, Madison, Wis. pp. 167–180.

_______. 1984b. Height growth and site index curves for inland Douglas-fir based on stem analysis data and forest habitat type. Forest Science 30:943–965.

_______. 1985. Comparison of Douglas-fir site index and height growth curves in the Pacific Northwest. Canadian Journal of Forest Research 15:673–679.

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

Murray, D.M., D. Coble, and R.O. Curtis. 1991. Height growth of young Pacific silver fir and noble fir established on clearcuts in the Pacific silver fir zone of western Washington. Canadian Journal of Forest Research 21:1213–1221.

Nigh, G.D. and V. Sit. 1996. Validation of forest height-age models. Canadian Journal of Forest Research 26:810–818.

Nuszdorfer, F.C. and R. Boettger. 1994. Biogeoclimatic units of the Vancouver Forest Region. B.C. Min. For., Victoria, B.C. 1:250 000 map.

Payandeh, B. 1974. Nonlinear site index equations for several major timber species. Forest Chronicle 50:194–196.

Payandeh, B. and Y. Wang. 1995. Comparison of the modified Weibull and Richards growth function for developing site index equations. New Forests 9:147–155.

Pojar, J., K. Klinka, and D.V. Meidinger. 1987. Biogeoclimatic ecosystem classification in British Columbia. Forest Ecology and Management 22:119–154.

Pretzsch, H. 1994. Prospects of a model oriented forest yield science. Forstwissenschaftliches Centralblat 114:188–209.

SPSS Inc. 1993. SPSS for Windows™: Base System User's Guide, Release 6.0, Chicago, Ill.

Sterba, H. 1995. Forest decline and increasing increments: a simulation study. Forestry 68:153–163.

Thrower, J.S. and J.W. Goudie. 1992. Development of height-age and site-index functions for even-aged interior Douglas-fir in British Columbia. B.C. Min. For., Victoria, B.C. Research Note No. 109.

Vander Ploeg, J.L. and J.A. Moore. 1989. Comparison and development of height growth and site index curves for Douglas-fir in the Inland Northwest. Western Journal of Applied Forestry 4:85–88.

Wang, G.G.and K. Klinka 1995. Site specific height curves for white spruce stands based on stem analysis and site classification. Annales des sciences forestiéres 52:607–618.

Wang, G.G., P.L. Marshall, and K. Klinka. 1994. Height growth pattern of white spruce in relation to site quality. Forest Ecology and Management 68:137–147.

Wykoff, W.R. and R.A. Monserud. 1987. Representing site quality in increment models: a comparison of methods. *In* Forest growth modelling and prediction, Vol. 1, U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minn. General Technical Report NC-120.

Zeide, B. 1978. Standardization of growth curves. Journal of Forestry 75:289–292.