RESEARCH REPORT

05

A Variable Growth Intercept Model for Spruce in the Sub-Boreal Spruce and Engelmann Spruce-Subalpine Fir Biogeoclimatic Zones of British Columbia

Gordon D. Nigh

1996

Province of British Columbia
Ministry of Forests Research Program

A Variable Growth Intercept Model for Spruce in the Sub-Boreal Spruce and Engelmann Spruce–Subalpine Fir Biogeoclimatic Zones of British Columbia

---

Gordon D. Nigh

Province of British Columbia
Ministry of Forests Research Program

Canadian Cataloguing in Publication Data

Nigh, Gordon Donald, 1956-
A variable growth intercept model for spruce in the sub-boreal spruce and Engelmann spruce-subalpine fir biogeoclimatic zones of British Columbia

(Research report ; 05)

Includes bibliographical references: p.
ISBN 0-7726-2679-0

1. Engelmann spruce - British Columbia - Growth - Mathematical models. 2. White spruce - British Columbia - Growth - Mathematical models. 3. Engelmann spruce - Yield - British Columbia. 4. White spruce - Yield - British Columbia. 5. Site index (Forestry) - British Columbia. I. British Columbia. Ministry of Forests. Research Branch. II. Title. III. Series: Research report (British Columbia. Ministry of Forests. Research Branch) ; 05.

SD 397.S77N53 1996   634.9′752′09711   C95-960410-3

Published by
Forestry Division Services Branch
B.C. Ministry of Forests
1205 Broad Street
Victoria, BC V8W 3E7
for
Research Branch
B.C. Ministry of Forests
31 Bastion Square
Victoria, BC V8W 3E7

Copies of this and other Ministry of Forests titles are available from
Crown Publications Inc.
521 Fort Street
Victoria, BC V8W 1E7

ABSTRACT

The variable growth intercept modelling technique is applied to three species of interior spruce in the Sub-Boreal Spruce and Engelmann Spruce–Subalpine Fir biogeoclimatic zones—Engelmann (*Picea engelmannii* Parry), white (*P. glauca* [Moench] Voss), and their cross. The variable growth intercept model allows foresters to estimate spruce site index from the first 1–30 years of height growth above breast height of a stand. Good results were obtained from the analysis of the model development data. However, testing indicated that the model may be biased (it underestimates site index). Nevertheless, interior spruce site index can be estimated with the model, but the model should be evaluated more thoroughly.

ACKNOWLEDGEMENTS

I would like to thank Pat Martin and Ralph Winter of the Silviculture Practices Branch for supporting this work and for making the model development data available, and Pat Martin, Amanda Nemec (International Statistics and Research Corp.), and Pat Salm (Weyerhaeuser Canada Ltd.) for reviewing this document. Thanks are also extended to J.S. Thrower and Associates Ltd. for collecting the data, and to the Resources Inventory Branch and Gaofeng Wang for supplying the test data. The funding to collect the model development data was provided by the Canada–British Columbia Forest Research and Development Agreement II.

CONTENTS

Abstract iii

Acknowledgements iv

Introduction 1

Data 1

Methods 2

Results 6

Discussion 9

Conclusions 18

Literature Cited 19

TABLES

1 Plot summaries **4**

2 Results of the analysis of the variable growth intercept model **7**

3 Formulated variable growth intercept model **9**

4 Results of Chow's test for data set compatibility **12**

5 Site indices as estimated from the variable growth intercept model, height, and breast height age **15**

FIGURES

1 Mean error versus breast height age for the variable growth intercept model and the height-age model **10**

2 Standard deviation of the errors versus breast height age for the variable growth intercept model and the height-age model **11**

3 Estimated site indices from the variable growth intercept model and the height-age model **13**

4 Inverted growth intercept model and the height-age model **16**

INTRODUCTION

Growth intercept models are becoming a vital tool to estimate site indices in British Columbia. These tools are primarily for silviculturists, but other foresters and researchers can use them as well. Growth intercept models estimate site index (top height at breast height age 50) from the early average growth above breast height of a tree species. Traditional (or fixed) growth intercept models predict site index from the annual growth above breast height averaged over a specified period (typically, five years). The advent of the variable growth intercept modelling technique generalizes this process (Nigh 1995a). Now, in theory, the number of years of height growth that the models can accept are not restricted, although it has been limited to 30 years. However, the models may be unstable, and hence unusable, if the growth period is too small. Variable growth intercept models are favoured over their fixed intercept counterparts because they are easier to use, more flexible, and are potentially more accurate (Nigh 1995a).

Because of the importance of interior spruce[1] as a major commercial species in the interior of British Columbia, a need existed for a spruce growth intercept model. The Silviculture Practices Branch of the B.C. Ministry of Forests had stem analysis and other related data collected, from which a fixed growth intercept model was constructed.[2] From these data a variable growth intercept model was developed for the Sub-Boreal Spruce (SBS) and Engelmann Spruce – Subalpine Fir (ESSF) biogeoclimatic zones of British Columbia. In general, the modelling technique closely follows that of Nigh (1995a), which should be consulted for additional details.

DATA

Forty-five 0.03 ha stem-analysis plots were established in spruce-dominated stands — 15 in each of the Prince George and Quesnel forest districts, 14 in the Lakes district, and 1 in the Morice district. All plots were in the SBS or ESSF biogeoclimatic zones. After locating the plots, three site trees were selected, felled, and measured. The height growth of these trees reflects the potential productivity of the site. The stems were split up the middle until at least the first nine annual nodes were identified from the terminal bud scars. The heights of these nodes were recorded. The stems were also sectioned at:

[1] Interior spruce species are white spruce (*Picea glauca* [Moench] Voss), Engelmann spruce (*P. engelmannii* Parry), and their cross (*P. engelmannii* x *glauca*).

[2] J.S. Thrower and Associates Ltd. 1995. Growth intercepts for interior spruce in north central British Columbia. Silv. Practices Br., B.C. Min. For., Victoria, B.C. Unpubl. rep. 19 p.

1. stump height (0.3 m);
2. breast height (1.3 m);
3. approximately every 5 years of growth between breast height and the height corresponding to 30 years breast height age;
4. approximately every 10 years of growth between the heights corresponding to 30 and 60 years breast height age; and
5. approximately every 20 years of growth for the remainder of the tree.

Heights and ring counts of each section were measured and other mensurational and ecological data were also collected. Full details of the data collection can be obtained from the final report.[3] Table 1 presents summary information about the plots, including biogeoclimatic site series, stems per hectare, basal area (m^2/ha), species composition, breast height age, top height, and site index.

[3] J.S. Thrower and Associates Ltd. 1995.

METHODS

The height of the sample trees at all breast height ages were linearly interpolated from the stem analysis data and adjusted for stem analysis bias (Carmean 1972; Newberry 1991). The individual tree height trajectories were plotted and 10 trees were deleted because they exhibited abnormal growth patterns, probably due to leader damage. After the deletions, each of the 45 plots still contained either two or three sample trees. The sample tree heights were averaged to give top height by plot and breast height age. The interpolation procedure assumes that, on average, the trees reach breast height midway through the growing season. The average annual height growth of the site trees in the plot (i.e., the growth intercept) was then calculated for breast height ages 1 to 30. Site index is the average height of the trees at breast height age 50 (Forest Productivity Councils of B.C. 1993; Nigh 1995b).

A simple linear model (equation 1) relates the growth intercept to site index.

$$SI = b_0 + b_1 \bullet GI_A + \varepsilon, \tag{1}$$

where: SI = site index (m at breast height age 50),

GI_A = growth intercept (cm/yr) corresponding to breast height age A

$= 100 \bullet (H - 1.3) \div (A - 0.5)$,

A = breast height age (years),
H = total tree height (m),
b_0, b_1 = model parameters, and
ε = random error.

Note that breast height age (A) is the number of annual growth rings at breast height. It is, on average, one-half year more than the number of years of growth above breast height (Nigh 1995b); hence, 0.5 is subtracted from A when calculating the growth intercept. Model (1) was fitted to the data using ordinary linear least squares regression for $A = 1, 2, \ldots, 30$. This resulted in a suite of sub-models that together constitute the variable growth intercept model. The data were also fitted to the power, or allometric, function (Sit and Poulin-Costello 1994), which had slightly poorer fit statistics (mean squared error and R^2).

The residuals (random errors) were analyzed to verify that the standard regression assumptions were met. The residuals were tested for normality (Shapiro and Wilk's [1965] W statistic) and homoscedasticity (Endrenyi and Kwong's [1981] F_k statistic). Homoscedasticity was also checked by plotting the residuals against the growth intercept.

The growth intercept sub-models were tested and compared with a height-age model for interior spruce.[4] This was done by assembling a test data set that consisted of stem analysis data from 96 plots in the SBS zone.[5] Three or four sample trees in each of the 0.04 ha plots were stem analyzed. These data were then processed in the same fashion as the model development data set to give site index and a set of growth intercepts for breast height ages 1 to 30.

I estimated site index from the fitted growth intercept model and the height-age model, and then plotted the mean error (actual SI – estimated SI) and the standard deviation of the error against breast height age. I also applied Chow's (Daniel and Wood 1980, p. 136) test to judge the compatibility of both the model development and test data sets. This technique uses the sums of squared errors from the fitting of the same model to the development, test, and combined data sets to test the hypothesis that both sets of data belong to that model. To show the smoothness of the transitions between the growth intercept and height-age models, site index was estimated from height and breast height age with the variable growth intercept and

[4] J.S. Thrower and Associates Ltd. 1994. Revised height-age curves for lodgepole pine and interior spruce in British Columbia. Res. Br., B.C. Min. For., Victoria, B.C. Unpubl. rep. 27 p. This model is not currently recommended for use in the province, but it likely will be in the near future.

[5] More information about these data can be found in Wang (1993) and Sylva Management Services Ltd. 1989. Stem analysis final report on interior Douglas-fir and white spruce. Resource Inventory Br., B.C. Min. For., Victoria, B.C. Unpubl. rep.

TABLE 1 *Plot summaries*[a]

Plot no.	Biogeoclimatic site series	Elevation (m)	Stems per ha	Basal area (m²/ha)	Species composition[b] (%)	Breast height age (years)	Top height (m)	Site index (m)
Quesnel Forest District								
1	SBSdw1/ 07	900	367	53.1	$S_{71}P_{15}F_{10}A_4$	104	33.3	21.6
2	SBSdw1/ 01	950	1500	57.3	$S_{80}B_{19}C_1$	62	28.3	24.5
3	SBSdw1/ 07	990	933	61.6	$S_{45}B_{18}F_{15}Ac_{13}P_6E_3$	88	32.9	24.6
4	SBSmw/ 06	710	600	33.8	$S_{84}A_9F_7$	51	26.2	26.1
5	SBSmw/ 07	890	933	39.8	$S_{52}A_{31}F_{14}P_3$	55	23.1	22.0
6	SBSmw/ 07	920	1467	56.8	$S_{64}P_{31}B_5$	67	26.2	21.2
7	SBSmw/ 08	930	1300	58.1	$S_{99}A_1$	52	26.4	25.8
8	SBSmw/ 01	990	667	42.3	$S_{78}F_{22}$	91	24.4	17.3
9	SBSdw1/ 01	1020	900	19.4	$S_{82}B_{18}$	60	20.2	17.9
10	ESSFwk1/ 01	1255	2367	43.1	$S_{79}B_{21}$	106	18.9	10.2
11	ESSFwk1/ 03	1300	3067	61.2	$S_{53}A_{36}B_{11}$	78	19.5	15.5
12	ESSFwk1/ 05	1345	2267	41.0	$S_{74}B_{23}P_3$	81	19.5	15.4
13	ESSFwk1/ 07	1290	1733	50.1	$S_{88}B_{12}$	93	21.9	14.5
14	ESSFwk1/ 01	1310	1967	56.8	$S_{62}B_{32}P_4Ac_2$	79	22.3	17.8
15	ESSFwk1/ 01	1330	2400	53.0	$S_{45}B_{33}P_{22}$	81	20.8	15.6
Prince George Forest District								
1	SBSwk1/ 01	890	967	25.7	$S_{93}B_7$	52	23.8	23.1
2	SBSwk1/ 01	965	1200	48.8	$S_{98}B_2$	68	23.9	20.4
3	SBSwk1/ 04	960	1100	33.3	$S_{89}P_7B_4$	63	20.3	17.0
4	SBSmw/ 09	910	3767	46.1	$S_{68}P_{30}A_1B_1$	54	16.1	15.1
5	SBSmw/ 01	915	3867	56.7	$S_{79}F_{18}B_3$	56	19.7	18.7
6	SBSmw/ 06	870	2300	58.4	$S_{77}F_{15}P_5A_3$	61	24.1	21.6
7	SBSwk1/ 03	970	1000	20.3	$S_{51}P_{36}B_{13}$	59	15.3	13.5
8	SBSwk1/ 01	970	1833	60.0	$S_{86}B_{14}$	71	26.6	21.7

9	SBSmk1/ 07	720	900	51.9	$S_{72}A_{25}P_3$	61	27.7	24.3
10	SBSmk1/ 07	710	2800	40.8	$S_{58}P_{24}B_{17}E_1$	64	18.2	15.2
11	SBSmk1/ 05	770	1400	57.3	$S_{89}F_7P_4$	59	23.1	20.7
12	SBSwk1/ 09	680	767	43.6	$S_{96}B_4$	61	29.1	24.6
13	SBSwk1/ 01	855	2533	47.0	$S_{77}P_{17}F_6$	49	20.7	21.0
14	SBSwk1/ 06	780	2200	39.8	S_{100}	65	18.0	15.1
15	SBSwk1/ 01	830	667	27.6	$S_{54}P_{30}B_{16}$	105	23.6	14.8
Lakes Forest District								
1	SBSmc2/ 06	855	900	51.7	$S_{97}P_3$	55	21.7	20.5
2	SBSmc2/ 02	730	1533	36.1	$S_{74}P_{26}$	94	20.5	14.0
3	ESSFmc/ 04	1200	1533	19.8	$S_{49}B_{30}P_{21}$	51	15.4	15.2
4	SBSdk/ 01	770	1833	29.0	$S_{89}A_7B_4$	93	21.2	14.3
5	SBSdk/ 03	975	3767	27.6	$S_{85}P_{14}A_1$	61	12.3	10.7
6	SBSdk/ 06	1170	2033	38.5	S_{100}	57	17.9	16.3
7	SBSdk/ 01	995	1967	32.3	S_{100}	57	15.4	13.9
8	SBSdk/ 06	1140	5367	50.3	$S_{98}A_2$	55	17.4	15.9
10	SBSdk/ 06	890	2300	29.8	$S_{58}A_{42}$	51	18.2	17.9
11	SBSdk/ 05	865	2367	36.6	$S_{90}A_7P_3$	62	19.7	16.5
12	SBSdk/ 01	845	2733	45.6	S_{100}	62	20.7	18.2
13	SBSdk/ 06	990	3867	43.4	$S_{91}A_6Ac_3$	51	18.9	18.6
14	SBSdk/ 01	990	2700	45.6	$S_{84}A_{16}$	60	21.3	19.2
15	SBSdk/ 01	920	1267	44.4	$S_{65}P_{35}$	56	21.5	19.8
Morice Forest District								
9	SBSmc2/ 01	955	3400	44.1	$S_{90}B_{10}$	55	19.5	18.4

---

[a] From J.S. Thrower and Associates Ltd. 1995. Interior spruce growth intercept project data package. Silv. Practices Br., B.C. Min. For., Victoria, B.C. Unpubl. rep.

[b] The following species abbreviations are used: S = interior spruce (*Picea glauca* [Moench] Voss, *P. engelmannii* Parry, *P. glauca* x *engelmannii*); P = lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.); B = balsam fir (*Abies lasiocarpa* [Hook.] Nutt.); F = interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco); A = trembling aspen (*Populus tremuloides* Michx.); Ac = cottonwood (*Populus trichocarpa* Torr. and Gray); E = paper birch (*Betula papyrifera* Marsh.); and C = western redcedar (*Thuja plicata* Donn).

height-age models for heights of 5, 10, 15, and 20 m. These estimates were then plotted against breast height age to observe the difference in estimated site index for the different models.

RESULTS

Table 2 presents the results of the analysis of the sub-models, including the parameter estimates, their standard error, the root mean square error, the W statistic for normality, and the F_k statistic for homoscedasticity. Table 3 shows the suite of 30 sub-models. The parameters for each sub-model were estimated from 45 observations. The root mean square error generally decreased as breast height age increased. This was expected since our ability to estimate site index from height and age improves as the trees approach the base age (50 years in British Columbia). The W and F_k statistics indicated that the residuals are normally distributed (except for the breast height age 25, 26, 27, and 28 models) and homoscedastic at the 95% significance level. As well, no trends in the residuals were detected when compared against the soil moisture and nutrient regimes, elevation, stems per hectare, and basal area.

The results of the validation, or testing, of the model are presented in Figures 1 and 2 and in Table 4. Figure 1 is a plot of the mean error (bias) versus breast height age, and Figure 2 shows the standard deviation of the errors versus breast height age. The plot of the mean error shows that the variable growth intercept model may be biased. This apparent bias increased until breast height age 11 and then decreased, although it is still statistically significant (based on a t-test) at age 30. The growth intercept model is more accurate than the height-age model up to breast height age five. Both models have approximately the same variation in error around the mean. Comparisons between the growth intercept model and the height-age model were not wholly valid because the test data made up approximately 75% of the height-age model development database. In this case, the optimism principle applies. This principle states that a model tested with the model development data will almost certainly indicate better performance than would be expected in practice (Picard and Cook 1984). To partially overcome this, the model testing was repeated with the model development data. This test showed that the bias and variability was greater in the height-age than in the growth intercept model.

TABLE 2 *Results of the analysis of the variable growth intercept model*

A	Parameter	Estimate	Standard error	Root mean square error	W[a]	F_k[a]
1				2.563	0.976	1.013
	b_0	7.867	1.400		(0.624)	(0.491)
	b_1	0.3516	0.04516			
2				2.545	0.973	1.066
	b_0	8.125	1.352		(0.512)	(0.457)
	b_1	0.3437	0.04361			
3				2.507	0.974	1.059
	b_0	8.155	1.316		(0.552)	(0.461)
	b_1	0.3448	0.04265			
4				2.538	0.984	1.141
	b_0	8.197	1.337		(0.884)	(0.412)
	b_1	0.3431	0.04333			
5				2.590	0.987	1.343
	b_0	8.270	1.373		(0.946)	(0.309)
	b_1	0.3369	0.04404			
6				2.508	0.987	1.012
	b_0	7.917	1.345		(0.948)	(0.492)
	b_1	0.3413	0.04225			
7				2.374	0.987	1.020
	b_0	7.414	1.290		(0.938)	(0.487)
	b_1	0.3496	0.03963			
8				2.256	0.985	1.122
	b_0	7.022	1.236		(0.904)	(0.423)
	b_1	0.3557	0.03734			
9				2.182	0.983	1.007
	b_0	6.700	1.210		(0.841)	(0.495)
	b_1	0.3599	0.03598			
10				2.128	0.982	1.725
	b_0	6.427	1.194		(0.832)	(0.179)
	b_1	0.3626	0.03499			
11				2.078	0.982	1.224
	b_0	6.125	1.183		(0.830)	(0.366)
	b_1	0.3664	0.03421			
12				2.022	0.984	1.221
	b_0	5.831	1.166		(0.880)	(0.368)
	b_1	0.3703	0.03330			
13				1.981	0.985	1.756
	b_0	5.595	1.155		(0.901)	(0.171)
	b_1	0.3732	0.03266			
14				1.954	0.982	2.012
	b_0	5.369	1.153		(0.826)	(0.120)
	b_1	0.3759	0.03231			
15				1.931	0.977	1.954
	b_0	5.125	1.156		(0.639)	(0.130)
	b_1	0.3792	0.03210			

continued on next page

TABLE 2 *Continued*

A	Parameter	Estimate	Standard error	Root mean square error	W[a]	F_k[a]
16				1.913	0.970	1.975
	b_0	4.921	1.159		(0.412)	(0.126)
	b_1	0.3817	0.03191			
17				1.891	0.965	2.166
	b_0	4.750	1.155		(0.287)	(0.098)
	b_1	0.3837	0.03160			
18				1.851	0.960	2.243
	b_0	4.512	1.143		(0.197)	(0.088)
	b_1	0.3878	0.03107			
19				1.817	0.957	2.242
	b_0	4.307	1.132		(0.151)	(0.088)
	b_1	0.3911	0.03060			
20				1.792	0.955	2.202
	b_0	4.180	1.122		(0.127)	(0.093)
	b_1	0.3929	0.03021			
21				1.749	0.952	2.242
	b_0	4.045	1.099		(0.092)	(0.088)
	b_1	0.3954	0.02949			
22				1.697	0.949	2.274
	b_0	3.909	1.069		(0.071)	(0.085)
	b_1	0.3981	0.02862			
23				1.646	0.947	2.359
	b_0	3.731	1.042		(0.063)	(0.076)
	b_1	0.4022	0.02786			
24				1.587	0.946	2.396
	b_0	3.472	1.015		(0.057)	(0.072)
	b_1	0.4083	0.02707			
25				1.526	0.944	1.202
	b_0	3.210	0.9854		(0.043)	(0.378)
	b_1	0.4147	0.02626			
26				1.467	0.942	1.224
	b_0	2.984	0.9550		(0.038)	(0.366)
	b_1	0.4203	0.02542			
27				1.400	0.943	1.233
	b_0	2.782	0.9166		(0.041)	(0.361)
	b_1	0.4254	0.02438			
28				1.325	0.944	1.285
	b_0	2.633	0.8690		(0.047)	(0.335)
	b_1	0.4293	0.02311			
29				1.248	0.947	1.417
	b_0	2.519	0.8186		(0.059)	(0.278)
	b_1	0.4323	0.02177			
30				1.172	0.950	1.613
	b_0	2.434	0.7682		(0.080)	(0.210)
	b_1	0.4349	0.02044			

[a] *P*-values for the test statistic are in brackets below the statistic.

TABLE 3 *Formulated variable growth intercept model*

A	Model	A	Model
1	$\widehat{SI} = 7.867 + 0.3516 \times GI_1$	16	$\widehat{SI} = 4.921 + 0.3817 \times GI_{16}$
2	$\widehat{SI} = 8.125 + 0.3437 \times GI_2$	17	$\widehat{SI} = 4.750 + 0.3837 \times GI_{17}$
3	$\widehat{SI} = 8.155 + 0.3448 \times GI_3$	18	$\widehat{SI} = 4.512 + 0.3878 \times GI_{18}$
4	$\widehat{SI} = 8.197 + 0.3431 \times GI_4$	19	$\widehat{SI} = 4.307 + 0.3911 \times GI_{19}$
5	$\widehat{SI} = 8.270 + 0.3369 \times GI_5$	20	$\widehat{SI} = 4.180 + 0.3929 \times GI_{20}$
6	$\widehat{SI} = 7.917 + 0.3413 \times GI_6$	21	$\widehat{SI} = 4.045 + 0.3954 \times GI_{21}$
7	$\widehat{SI} = 7.414 + 0.3496 \times GI_7$	22	$\widehat{SI} = 3.909 + 0.3981 \times GI_{22}$
8	$\widehat{SI} = 7.022 + 0.3557 \times GI_8$	23	$\widehat{SI} = 3.731 + 0.4022 \times GI_{23}$
9	$\widehat{SI} = 6.700 + 0.3599 \times GI_9$	24	$\widehat{SI} = 3.472 + 0.4083 \times GI_{24}$
10	$\widehat{SI} = 6.427 + 0.3626 \times GI_{10}$	25	$\widehat{SI} = 3.210 + 0.4147 \times GI_{25}$
11	$\widehat{SI} = 6.125 + 0.3664 \times GI_{11}$	26	$\widehat{SI} = 2.984 + 0.4203 \times GI_{26}$
12	$\widehat{SI} = 5.831 + 0.3703 \times GI_{12}$	27	$\widehat{SI} = 2.782 + 0.4254 \times GI_{27}$
13	$\widehat{SI} = 5.595 + 0.3732 \times GI_{13}$	28	$\widehat{SI} = 2.633 + 0.4293 \times GI_{28}$
14	$\widehat{SI} = 5.369 + 0.3759 \times GI_{14}$	29	$\widehat{SI} = 2.519 + 0.4323 \times GI_{29}$
15	$\widehat{SI} = 5.125 + 0.3792 \times GI_{15}$	30	$\widehat{SI} = 2.434 + 0.4349 \times GI_{30}$

The results of Chow's test for data set compatibility are given in Table 4. This test rejected the hypothesis that the development and test data sets belong to the same fitted sub-models for ages five and greater at the 95% significance level.

Figure 3 is a plot of estimated site index versus breast height age for the variable growth intercept (for breast height ages ≤ 30) and the height-age models (for breast height ages ≥ 30). The maximum difference in site index (over the four heights used in this analysis) between the models at breast height age 30 is approximately 1.15 m and occurs at a height of 10 m.

DISCUSSION

The variable growth intercept modelling technique works for interior spruce. The result of the data analysis is a suite of 30 sub-models that predict site index from average site tree height growth for breast height ages 1–30. This modelling technique has previously been applied to lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) (Nigh 1995a). As that report presents its features, advantages, and disadvantages, they will not be repeated here.

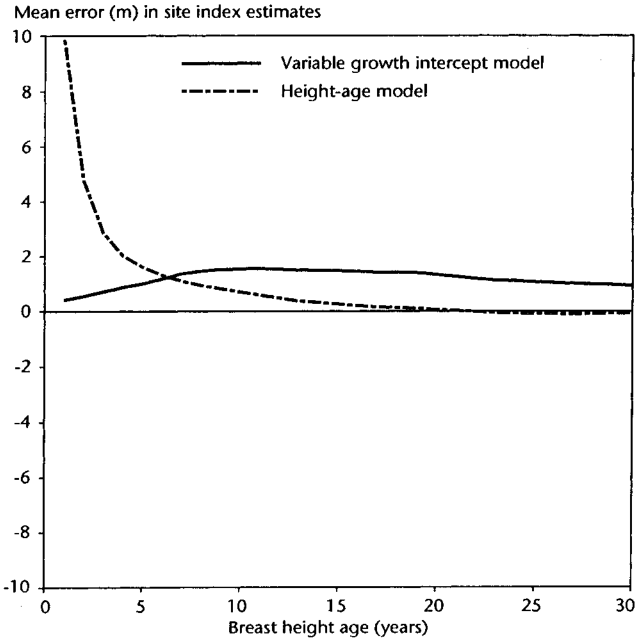

FIGURE 1 *Mean error (bias) versus breast height age for the variable growth intercept model and the height-age model.*

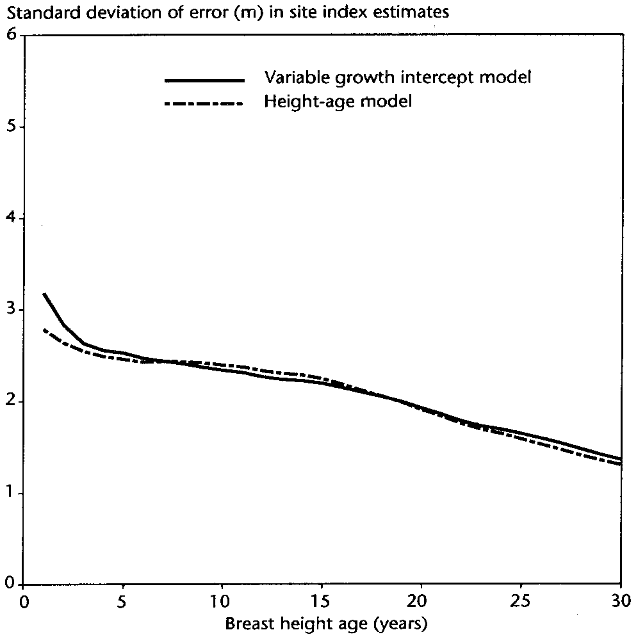

FIGURE 2 *Standard deviation of the errors versus breast height age for the variable growth intercept model and the height-age model.*

TABLE 4 *Results of Chow's test for data set compatibility*

A	Chow's statistic[a]	*A*	Chow's statistic[a]
1	2.592 (0.079)	16	5.756 (0.004)
2	1.227 (0.296)	17	5.790 (0.004)
3	0.942 (0.392)	18	6.042 (0.003)
4	1.719 (0.183)	19	6.233 (0.003)
5	2.710 (0.070)	20	6.114 (0.003)
6	3.637 (0.029)	21	5.909 (0.003)
7	4.588 (0.012)	22	5.702 (0.004)
8	5.106 (0.007)	23	5.581 (0.005)
9	5.393 (0.006)	24	5.625 (0.004)
10	5.521 (0.005)	25	5.778 (0.004)
11	5.624 (0.004)	26	5.896 (0.004)
12	5.708 (0.004)	27	6.075 (0.003)
13	5.576 (0.005)	28	6.332 (0.002)
14	5.649 (0.004)	29	6.610 (0.002)
15	5.753 (0.004)	30	6.784 (0.002)

[a] *P*-values for the test statistic are in brackets below the statistic.

Growth intercept models will most commonly be used during silviculture surveys. Standards for these surveys will be available (B.C. Ministry of Forests 1995). During a survey, sample plots are established and the top height tree(s) are identified. The total height and breast height age (number of annual growth rings at breast height) are recorded for each top

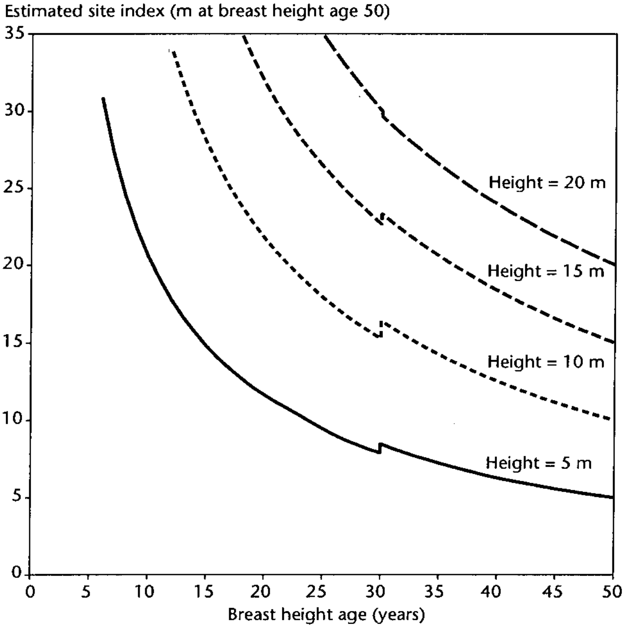

FIGURE 3 *Estimated site indices from the variable growth intercept model (*$A \leq 30$*) and the height-age model (*$A \geq 30$*).*

height tree. The site index for each tree is then found by either consulting the appropriate table to obtain site index directly (see, for example, Table 5), or by calculating the growth intercept (GI_A) with the following formula:

$$GI_A = (H - 1.3) \bullet 100 \div (A - 0.5).$$

The site index is then determined from this growth intercept and the sub-model corresponding to breast height age A. The site indices from the sample trees are averaged to calculate the site index for the plot. Both of these methods of obtaining site index assume that breast height is midway between two annual nodes. On average this assumption is valid, however, on any one tree it may be violated. This error can be reduced by increasing the number of sample trees.

Another method of obtaining the growth intercept is to accurately identify and measure the first ($A - 0.5$) years of growth above breast height from the annual whorls. This measured growth is divided by ($A - 0.5$) to get the average annual height growth (GI_A). Site index is then determined from the sub-model corresponding to breast height age A. This alternative method is more difficult to implement, but gives a more accurate growth intercept because it assumes that breast height does not lie midway between annual nodes. Therefore, this method is preferable when precise site indices are required from a few trees, for example, in research situations.

The growth intercept model can be inverted so that height is predicted from site index and age; that is, a height-age model is created.[6] This inverted model was compared to the latest height-age curves for interior spruce[7] and graphed up to 30 years breast height age for site indices of 10, 15, 20, 25, and 30 (Figure 4). The inverted model is quite different at young ages, as it shows more linear growth than the height-age curves.

To predict site index for young stands, growth intercept models are generally recognized as superior to height-age models. There are four reasons for this.

1. Growth intercept models are developed specifically for estimating site index, not height. Therefore, the site index estimates are optimized with the growth intercept model, but not the height-age model (Curtis et al. 1974).

[6] I do not recommend that the inverted growth intercept model be used as a height-age model. This exercise was done only for comparative purposes.

[7] J.S. Thrower and Associates Ltd. 1994.

TABLE 5 *Site indices as estimated from the variable growth intercept model, height, and breast height age*

bh age[a]	Top height (m)																					
(years)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Site index (m at bh age 50)																					
2	24.2																					
3	17.8	31.6																				
4	15.1	24.9	34.7																			
5	13.5	21.0	28.5																			
6	12.3	18.5	24.7	30.9																		
7	11.2	16.6	21.9	27.3	32.7																	
8	10.3	15.1	19.8	24.6	29.3	34.1																
9	9.7	13.9	18.1	22.4	26.6	30.8																
10	9.1	12.9	16.7	20.5	24.4	28.2	32.0															
11	8.6	12.1	15.5	19.0	22.5	26.0	29.5	33.0														
12	8.1	11.3	14.5	17.7	21.0	24.2	27.4	30.6	33.8													
13	7.7	10.7	13.7	16.6	19.6	22.6	25.6	28.6	31.6	34.6												
14		10.1	12.9	15.7	18.5	21.2	24.0	26.8	29.6	32.4												
15		9.6	12.2	14.8	17.4	20.0	22.6	25.3	27.9	30.5	33.1											
16		9.1	11.6	14.0	16.5	19.0	21.4	23.9	26.3	28.8	31.3	33.7										
17		8.7	11.0	13.4	15.7	18.0	20.3	22.7	25.0	27.3	29.6	32.0	34.3									
18		8.3	10.5	12.7	14.9	17.1	19.4	21.6	23.8	26.0	28.2	30.4	32.7	34.9								
19		7.9	10.0	12.1	14.2	16.4	18.5	20.6	22.7	24.8	26.9	29.0	31.2	33.3								
20		7.6	9.6	11.6	13.6	15.7	17.7	19.7	21.7	23.7	25.7	27.8	29.8	31.8	33.8							
21			9.3	11.2	13.1	15.0	17.0	18.9	20.8	22.8	24.7	26.6	28.5	30.5	32.4	34.3						
22			8.9	10.8	12.6	14.5	16.3	18.2	20.0	21.9	23.7	25.6	27.4	29.3	31.1	33.0	34.8					
23			8.6	10.3	12.1	13.9	15.7	17.5	19.3	21.1	22.9	24.6	26.4	28.2	30.0	31.8	33.6					
24			8.2	9.9	11.6	13.4	15.1	16.9	18.6	20.3	22.1	23.8	25.5	27.3	29.0	30.7	32.5	34.2				
25			7.8	9.5	11.2	12.9	14.6	16.2	17.9	19.6	21.3	23.0	24.7	26.4	28.1	29.8	31.5	33.2	34.9			
26				9.1	10.7	12.4	14.0	15.7	17.3	19.0	20.6	22.3	23.9	25.6	27.2	28.9	30.5	32.2	33.8			
27				8.7	10.3	11.9	13.5	15.1	16.7	18.4	20.0	21.6	23.2	24.8	26.4	28.0	29.6	31.2	32.8	34.4		
28				8.4	10.0	11.5	13.1	14.7	16.2	17.8	19.3	20.9	22.5	24.0	25.6	27.1	28.7	30.3	31.8	33.4	34.9	
29				8.1	9.6	11.2	12.7	14.2	15.7	17.2	18.7	20.3	21.8	23.3	24.8	26.3	27.9	29.4	30.9	32.4	33.9	
30				7.9	9.4	10.8	12.3	13.8	15.3	16.7	18.2	19.7	21.2	22.6	24.1	25.6	27.1	28.5	30.0	31.5	33.0	34.4

[a] Breast height (bh) age is the ring count at breast height.

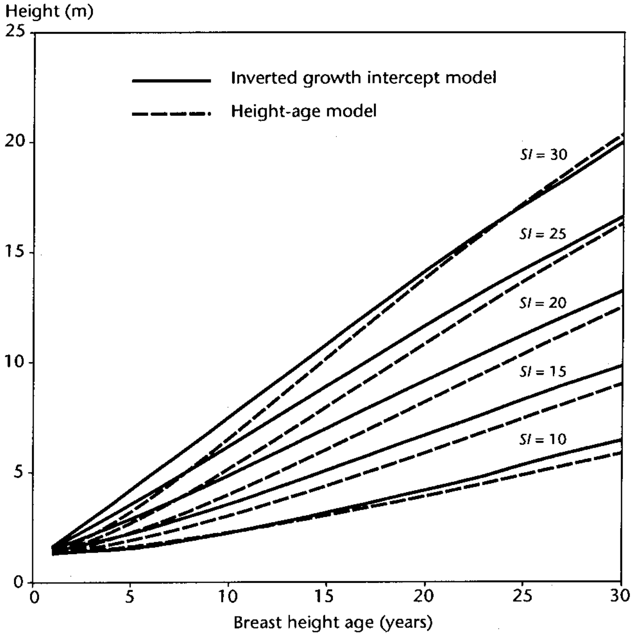

FIGURE 4 *Inverted growth intercept model and the height-age model.*

2. Growth intercept models are intended for young stands, whereas height-age models attempt to estimate height across a wide range of ages. The effect of this is evident in Figure 4, which shows the growth intercept model following the height growth pattern of young stands more closely than the height-age models.
3. The growth intercept model is not constrained to pass through the site index at index age, as is the height-age model. This allows the growth intercept model to be more flexible.
4. The errors in predicted site index associated with small deviations from the mean height growth pattern can be large near age zero with the height-age model (Nigh and Sit 1995). This is partially a result of the convergence of the curves at age zero. The growth intercept model is less sensitive to small deviations from the mean height. This can be seen in Figure 4, which shows that the inverted growth intercept model does not converge to breast height as fast as the height-age model.

I was concerned about the accuracy of the interpolation process to obtain heights. I addressed this concern by regressing site index on the growth intercepts calculated from the node measurements for breast height ages one to eight. This resulted in growth intercept sub-models that were practically the same as those obtained from the interpolated heights. I concluded that the interpolated heights were accurate.

The root mean square error is a guide to the error that can be expected from the model. The magnitude of approximately 95% of the errors in estimated site index will be roughly less than twice the root mean square error. This should be considered when scheduling a growth intercept survey. In general, the site index estimates will improve as the trees accumulate more growth. As well, annual fluctuations in climate will have a larger impact on growth intercepts calculated from only a few years growth. Therefore, site index estimates from growth intercepts are better on older trees.

The variable growth intercept model may be biased (Figure 1), causing site index to be underestimated. The bias may be in the model, the model development data, or the test data. The model is unbiased with respect to the model development data, as are all linear regression models with an intercept parameter

(Sen and Srivastava 1990). Therefore, either the model development or test data (or both) are biased. That is, the early height growth pattern of the trees, which determines their growth intercept, in the model development and test data are different for a given site index. This may be caused by the samples coming from different ecosystems, but is unlikely (Wang et al. 1994). Other possible sources of bias include selection criteria for sample trees and random chance. It is not possible to determine which data set is more representative of the typical height growth pattern of spruce in the SBS and ESSF biogeoclimatic zones at this time. Since the model development data set was selected specifically to develop a growth intercept model for managed stands, I assume that these data are more representative of managed spruce. Therefore, I recommend that the variable growth intercept model be used to estimate site index in juvenile stands of interior spruce in British Columbia. Although the model was developed with data from the SBS and ESSF zones, it can be applied interior-wide until models are developed for other zones. The potential bias should remain a concern to practitioners and modellers until it is fully resolved.

CONCLUSIONS

As with lodgepole pine, the site index for interior spruce can be estimated from its early height growth and a variable growth intercept model. A variable growth intercept model for interior spruce is presented here as a suite of 30 sub-models. The submodels can be somewhat cumbersome to use, so a simplifying table that overcomes this unwieldiness is given.

The variable growth intercept model may be biased. Further sampling and data analysis are required to verify or refute this bias, as well as to extend the biogeoclimatic range of the model. Until such a time, the model can be used to estimate site index in juvenile stands of interior spruce.

British Columbia Ministry of Forests. 1995. Growth intercept method for silviculture surveys. Silv. Practices Br., B.C. Min. For. Victoria, B.C.

Carmean, W.H. 1972. Site index curves for upland oaks in the central states. For. Sci. 18(2):109–20.

Curtis, R.O., D.J. DeMars, and F.R. Herman. 1974. Which dependent variable in site index-height-age regression? For. Sci. 20(1):74–87.

Daniel, C. and F.S. Wood. 1980. Fitting equations to data. 2nd Ed. John Wiley & Sons, Inc. Toronto, Ont. 458 p.

Endrenyi, L. and F.H.F. Kwong. 1981. Tests for the behaviour of experimental errors. *In* Kinetic Data Analysis. L. Endrenyi (editor). Plenum Press. New York, N.Y. 517 p.

Forest Productivity Councils of British Columbia. 1993. Minimum standards for the establishment and remeasurement of permanent sample plots in British Columbia. Resour. Inventory Br., B.C. Min. For. Victoria, B.C. 22 p.

Newberry, J.D. 1991. A note on Carmean's estimate of height from stem analysis data. For. Sci. 37(1):368–9.

Nigh, G.D. 1995a. Variable growth intercept models for lodgepole pine in the Sub-Boreal Spruce biogeoclimatic zone, British Columbia. Res. Br., B.C. Min. For. Victoria, B.C. Res. Rep. 02. 22 p.

________. 1995b. Compatibility improvements and bias reduction in height-age models. Res. Br., B.C. Min. For. Victoria, B.C. Res. Rep. 03.

________ and V. Sit. [1995]. Validation of forest height-age models. Can. J. For. Res. In review.

Picard, R.R. and R.D. Cook. 1984. Cross-validation of regression models. J. Am. Statist. Assoc. 79(387):575–83.

Sen, A.K. and M. Srivastava. 1990. Regression analysis theory, methods, and applications. Springer-Verlag. New York, N.Y. 347 p.

Shapiro, S.S. and M.B. Wilk. 1965. An analysis of variance test for normality (complete samples). Biometrika 52(3, 4):591–611.

Sit, V. and M. Poulin-Costello. 1994. Catalog of curves for curve fitting. Res. Br., B.C. Min. For. Victoria, B.C. Biom. Inf. Handb. No. 4. 110 p.

Wang, G.G. 1993. Ecological site quality, site index, and height growth of white spruce stands in the Sub-Boreal Spruce Zone of British Columbia. PhD thesis. Univ. B.C. Vancouver, B.C. 262 p.

________, P.L. Marshall, and K. Klinka. 1994. Height growth pattern of white spruce in relation to site quality. For. Ecol. Manage. 68:137–47.