RESEARCH REPORT

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A Growth Intercept Model for Coastal Douglas-fir

Gordon D. Nigh

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British Columbia

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ABSTRACT

This research develops a growth intercept model for coastal Douglas-fir. Forty-eight stem analysis plots were located in the Coastal Western Hemlock and Coastal Douglas-fir biogeoclimatic zones of British Columbia. Three Douglas-fir trees in each plot were selected for intensive sampling. These trees were cut down and the height at the end of each growing season was identified from the annual branch whorls. The top height growth of the plots was reconstructed and the site index and growth intercept for breast height ages one to 50 were calculated from the height-breast height age data. A model was then fitted to the site index and growth intercept data, resulting in a growth intercept model which consisted of 50 functions. Four refinements to the growth intercept modelling technique are introduced in this report. These eliminate deficiencies noted in other growth intercept modelling endeavours.

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INTRODUCTION

Growth intercept models are effective tools for estimating site index, particularly in juvenile stands. These models compute site index from the early average height growth of trees that are expressing the potential productivity of the site on which they grow. The growth intercept technique is easy to apply because early average height growth is calculated from common forest tree measurements (total height and breast height age), and the models are simple mathematical equations. Growth intercept models have been developed for coastal western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Nigh 1996a), Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Nigh 1996b), interior lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.) (Nigh 1995a), and spruce (*Picea glauca* (Moench) Voss, *P. engelmannii* Parry, *P. glauca* x *engelmannii*) (Nigh 1995b). Eventually, models should be available for all major commercial species in British Columbia.

This report describes the growth intercept model for coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*). Although growth intercept modelling has become fairly standardized (see above cited reports describing the technique for other species), four new model development techniques are presented in this report. These techniques improve the functional form of the model and improve the data collection and analysis procedures. While these improvements represent relatively minor adjustments to the modelling process, they are significant because they remove shortcomings that were recognized in previous modelling efforts.

DATA

The data collection procedures for the coastal Douglas-fir growth intercept model are briefly described in this section and are more fully discussed in the source report.[1] Forty-eight stem analysis plots were located in the Lake Cowichan, Port Alberni, Chilliwack, and Squamish areas. These plots were established subjectively in stands with Douglas-fir as the leading or major component. Exact plot locations were chosen so that they were ecologically uniform and included three suitable top height trees (largest diameter, undamaged, unsuppressed, vigorous). Plot

[1] J.S. Thrower and Associates Ltd. 1995. Coastal Douglas-fir growth intercept project data package. Report to Research Branch, B.C. Min. For., Victoria, B.C.

measurements were taken on an 11.28 m radius plot, but the sample trees were selected from a 10.75 m radius plot to conform with the sampling standards for top height. Plot measurements included the diameter at breast height (dbh) and species of all trees greater than 4 cm dbh. As well, a full ecological description of the plot was recorded, as were access notes. Summary statistics for the plots are in Table 1.

Three sample trees in each plot were felled and their total height was measured. The height of the annual whorls, from the tip of the tree to as far down the stem as possible, were recorded. In all cases, annual branch whorls were identified below breast height (1.3 m above the ground); hence the height of each tree at breast height age zero is known. Stem sections were taken periodically to confirm annual whorl counts with ring counts. Any discrepancies were resolved, sometimes by splitting the stem and identifying whorl heights from the terminal bud scars. This data collection technique was introduced by J.S. Thrower and Associates Ltd. It allows height growth to be reconstructed extremely accurately, but it is less reliable for species whose annual height growth is difficult to identify from branch whorls, such as western hemlock.

METHODS

With traditional stem analysis, section data was converted into height-breast height age data by linear interpolation and then corrected to remove stem analysis bias (Carmean 1972). Advances in data collection technology have greatly simplified the task of data preparation for analysis, making these data manipulations unnecessary. The heights of the sample trees are now averaged directly (by plot and breast height age) to give plot data from breast height age zero to the age of the youngest sample tree (equation 1).

$$[1] \qquad H_A = \frac{1}{3}\sum_{i=1}^{3} h_{i,\,A}\,,$$

where: H_A = plot height (m) at breast height age A, A = 1, 2, 3, . . . (yrs),
$h_{i,A}$ = height (m) of tree i at A, and
i = tree index number within the plot.

TABLE 1 *Summary information about the study plots*

	Biogeoclimatic information									
Plot	Zone	Subzone/ variant	Site series	SMR[a]	SNR[b]	Basal area (m^2/ha)	Stems per ha	Breast height age (yrs)	Height (m)	Site index (m)
Chilliwack										
CH-01	CWH	dm	05	4	D	62.7	1 450	52	41.3	40.3
CH-02	CWH	dm	01	3	B	42.3	900	51	39.1	38.3
CH-05	CWH	dm	07	5	D	71.6	650	54	45.3	42.8
CH-07	CWH	dm	03	2	B	46.3	1 700	50	24.9	24.8
CH-08	CWH	dm	06	5	C	55.0	700	49	38.8	39.2
CH-09	CWH	ds1	03	2	A	31.0	2 200	47	21.8	22.5
Lake Cowichan										
LC-01	CWH	vm1	01	4	C	72.2	675	56	44.0	40.4
LC-02	CWH	vm1	01	3	C	60.1	925	54	35.3	33.5
LC-03	CWH	xm	07	5	E	41.5	100	65	49.4	42.2
LC-04	CWH	xm	03	2	A	46.8	1 350	54	30.0	28.9
LC-05	CWH	xm	01	3	B	57.2	350	52	41.6	40.7
LC-06	CWH	xm	05	4	D	47.6	375	58	44.0	40.4
LC-07	CWH	xm2	01	3	C	62.9	850	53	42.7	41.2
LC-08	CWH	xm	01	3	B	57.9	650	53	37.5	35.9
LC-09	CWH	vm1	01	4	C	70.9	625	60	43.1	38.3

TABLE 1 *Continued*

	Biogeoclimatic information									
Plot	Zone	Subzone/ variant	Site series	SMR[a]	SNR[b]	Basal area (m^2/ha)	Stems per ha	Breast height age (yrs)	Height (m)	Site index (m)
LC-10	CWH	mm1	01	3	B	56.1	2 350	57	31.5	29.6
LC-11	CDF	mm	01	3	B	46.5	2 150	58	24.3	21.4
LC-12	CDF	mm	01	3	C	42.9	1 500	64	28.4	23.7
LC-13	CWH	xm	01	4	C	42.1	2 400	54	28.5	27.2
LC-14	CWH	xm	01	4	C	43.5	725	52	35.5	34.7
LC-15	CWH	xm	03	2	B	71.8	3 200	60	22.4	19.4
LC-16	CWH	xm	01	4	C	44.6	1 700	58	23.1	20.6
Port Alberni										
PA-01	CWH	xm	01	3	C	57.0	1 250	56	34.8	32.2
PA-02	CWH	xm	01	3	C	42.5	675	55	35.5	33.8
PA-03	CWH	xm	03	2	C	69.7	1 350	68	33.3	26.2
PA-04	CWH	xm	03	2	C	54.1	1 250	54	34.1	32.6
PA-05	CWH	xm	01	4	C	61.0	1 200	51	34.7	34.0
PA-06	CWH	xm	04	2	D	76.1	1 050	52	35.5	34.4
PA-07	CWH	xm	05	4	E	135.0	750	62	46.8	41.3
PA-08	CWH	xm	05	4	D	72.4	625	60	41.7	37.3
PA-09	CWH	xm	05	3	D	52.2	600	57	42.5	38.9
PA-10	CWH	xm	05	4	E	94.2	825	56	47.4	43.5

TABLE 1 *Concluded*

Plot	Biogeoclimatic information					Basal area (m^2/ha)	Stems per ha	Breast height age (yrs)	Height (m)	Site index (m)
	Zone	Subzone/ variant	Site series	SMR[a]	SNR[b]					
PA-11	CWH	xm	03	2	C	57.9	2 100	52	26.7	26.0
PA-12	CWH	xm	01	4	C	74.4	1 250	58	40.3	37.1
PA-13	CWH	xm	01	3	C	85.2	1 250	53	38.6	37.1
PA-14	CWH	xm	01	3	B	69.4	1 500	59	31.4	28.6
PA-15	CWH	xm	01	4	B	75.5	1 300	56	34.0	31.9
PA-16	CWH	xm	01	3	C	54.3	950	55	35.7	33.3
PA-17	CDF	mm	01	2	B	48.8	2 200	84	23.4	15.2
PA-18	CDF	mm	02	1	B	28.5	1 250	56	21.6	20.1
PA-19	CDF	mm	01	3	C	43.1	1 350	54	21.5	20.7
Squamish										
SQ-01	CWH	dm	07	5	D	79.3	675	70	56.2	45.7
SQ-02	CWH	dm	01	4	C	78.0	675	68	45.5	36.8
SQ-03	CWH	dm	05	4	D	80.9	850	70	49.1	39.8
SQ-04	CWH	dm	01	3	C	31.4	2 200	53	31.1	29.8
SQ-05	CWH	dm	01	3	B	85.6	2 400	53	33.7	32.4
SQ-06	CWH	vm1	03	2	C	76.6	1 500	71	38.6	30.3
SQ-07	CWH	vm1	03	2	C	44.4	725	71	38.1	29.2

[a] SMR – relative soil moisture regime (1 = xeric; 2 = subxeric; 3 = submesic; 4 = mesic; and 5 = subhygric).
[b] SNR – soil nutrient regime (A = very poor; B = poor; C = medium; D = rich; and E = very rich).

Growth intercepts were calculated by plot according to equation [2] for each breast height age from one to 50.

$$[2] \qquad GI_A = \frac{H_A - 1.3}{A - A_1} \times 100,$$

where: GI_A = growth intercept (cm/yr) for A = 1, 2, . . ., 50 (yrs),

A_1 = proportion of height growth (between zero and one) that occurred below breast height,

$$= \frac{1.3 - H_0}{H_1 - H_0}.$$

Previously, trees were assumed to reach breast height midway through the growing season, and therefore A_1 was always 0.5. This resulted in errors in the regressor (independent) variable (GI_A), violating the assumption that the regressor variables are known without error.[2] Subtracting the portion of growth between ages zero and one from the breast height age eliminates this problem. The denominator in equation [2]is now the precise number of years the tree has been growing since it reached breast height. This is another new development in the modelling technique.

The site index of the plot is the average height of the sample trees at breast height age 50 (equation 3).

$$[3] \qquad SI = \frac{1}{3} \times \sum_{i=1}^{3} h_{i,50},$$

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

Now, for each plot, a site index and growth intercepts for breast height ages one to 50 are available for further analysis.

The functional form of the growth intercept model is given in equation [4].

$$[4] \qquad SI = b_0 + b_1 \times GI_A^{b_2} + \varepsilon,$$

where: b_0, b_1, b_2 = model parameters, and

ε = random error.

This functional form was tried previously, although not all

[2] Other techniques for estimating parameters are available when the regressor variables have errors (Seber and Wild 1989).

three parameters were statistically significant. In this third new development, a theoretical value is assigned to parameter b_0 rather than one obtained empirically. The site index must be at least 1.3 m since the trees should attain this height if they are older than breast height age one. The smallest possible growth intercept (GI_A) is zero. Therefore, parameter b_0 must be 1.3 to correct the model when GI_A is zero. With this method of parameter value assignment, extrapolations below the range of the data are more reliable because the low end of the relationship is derived theoretically.

The data were fit to function [5] for breast height ages one to 50. This results in 50 growth intercept models, one for each age between one and 50. Previous growth intercept models had functions from breast height ages one to 30. After age 30, it was recommended that site index be estimated using the height-breast height age models. Making the transition from the growth intercept model to the height-breast height age models at breast height age 30 caused the estimated site index to jump, in some cases by more than a metre. This is easily and legitimately explained, but it may disconcert some practitioners. The problem is eliminated by extending the growth intercept functions to breast height age 50 because both types of model give virtually identical results at this age 50 (Mario Di Lucca, B.C. Ministry of Forests, pers. comm., 1996). Extending the functions to breast height age 50 is the fourth new development.

$$[5] \qquad SI = 1.3 + f(b_1) \times GI_A^{b_2} + \varepsilon$$

where: $f(b_1) = e^{b_1}$.

A preliminary analysis showed that parameter b_1 had excessive parameter-effects nonlinearity (Ratkowsky 1983) when it occurred in the model as a linear parameter (equation 4). When reparameterized (equation 5), the model behaves in a close to linear way. The following statistical tests were done at the 95% significance level on each function to ensure good statistical properties:

- Bias: a *t*-test shows whether the mean of the residuals is significantly different from zero.
- Normality: Shapiro and Wilk's (1965) *W* statistic tests the assumption that the residuals are normally distributed;

- Homoscedasticity: Endrenyi and Kwong's (1981) F_k test and a plot of residuals versus growth intercept examine the assumption that the variance of the residuals is constant.
- Intrinsic and parameter-effects nonlinearity: Bates and Watts' (1980) measures of nonlinearity indicate if the model behaves in a close to linear way.
- Parameter bias: Box's (1971) measure of parameter bias also indicates the linearity of the model.

Plot PA-03 was identified as an outlier during a preliminary analysis. The growth pattern of the sample trees in this plot had a marked slowing of growth of unknown cause at approximately breast height age 20. Consequently, this plot was deleted, leaving 47 plots (observations) for further analyses.

The residuals were regressed against biogeoclimatic zone, subzone/variant, site series, relative soil moisture and nutrient regimes, basal area, stems per hectare, breast height age, and top height to determine if any trends existed.

RESULTS

Table 2 presents the results of the data analysis and contains the parameter estimates, their standard error, and the root mean square error. The results of the tests for bias, normality, homoscedasticity, intrinsic and parameter-effects nonlinearity, and parameter bias are not shown but are summarized below:

- Bias: none of the models showed any evidence of bias.
- Normality: the models for breast height ages 2, 10, 30, 31, 32, 33, 37, and 38 showed slight ($0.005 < p < 0.05$) evidence of non-normality.
- Homoscedasticity: the models for breast height ages 37, 38, 39, 49, and 50 showed some evidence of heteroscedasticity based on the F_k test, but the residual plots indicated that it was not serious.
- Intrinsic and parameter-effects nonlinearity: all models had low measures of nonlinearity.
- Parameter bias: parameter bias was less than one percent except for the breast height age 11, 12, 13, 14, and 15 models.

The tests for bias, normality, and homoscedasticity show that the usual least-squares regression assumptions (Sen and Srivastava 1990) were, in general, met. The tests for nonlinear model behaviour show that the models behave in a close to

TABLE 2 *Results of the analysis of model (5) for breast height ages one to 50*

	Parameter		
A	Estimate	Standard error	Root mean square error
1	b_1: 1.360	0.2697	4.684
	b_2: 0.5382	0.06751	
2	b_1: 0.9344	0.2561	3.970
	b_2: 0.6330	0.06279	
3	b_1: 0.8956	0.2378	3.702
	b_2: 0.6328	0.05734	
4	b_1: 0.8527	0.2333	3.594
	b_2: 0.6358	0.05561	
5	b_1: 0.7825	0.2174	3.304
	b_2: 0.6474	0.05137	
6	b_1: 0.7097	0.2061	3.074
	b_2: 0.6593	0.04827	
7	b_1: 0.5697	0.1957	2.802
	b_2: 0.6882	0.04556	
8	b_1: 0.4694	0.1967	2.725
	b_2: 0.7076	0.04552	
9	b_1: 0.3624	0.1937	2.607
	b_2: 0.7296	0.04466	
10	b_1: 0.2360	0.1907	2.478
	b_2: 0.7570	0.04387	
11	b_1: 0.1442	0.1899	2.396
	b_2: 0.7760	0.04354	
12	b_1: 0.04220	0.1895	2.319
	b_2: 0.7981	0.04338	
13	b_1: -0.02816	0.1891	2.270
	b_2: 0.8135	0.04324	
14	b_1: -0.1085	0.1856	2.184
	b_2: 0.8310	0.04241	
15	b_1: -0.1264	0.1825	2.142
	b_2: 0.8343	0.04165	
16	b_1: -0.1782	0.1797	2.083
	b_2: 0.8457	0.04098	

TABLE 2 *Continued*

A	Parameter		Root mean square error
	Estimate	Standard error	
17	b_1: -0.2392	0.1747	1.992
	b_2: 0.8595	0.03985	
18	b_1: -0.2806	0.1720	1.941
	b_2: 0.8690	0.03922	
19	b_1: -0.3052	0.1670	1.876
	b_2: 0.8747	0.03809	
20	b_1: -0.3334	0.1588	1.777
	b_2: 0.8819	0.03624	
21	b_1: -0.3557	0.1537	1.710
	b_2: 0.8872	0.03508	
22	b_1: -0.3836	0.1463	1.621
	b_2: 0.8944	0.03342	
23	b_1: -0.3841	0.1393	1.549
	b_2: 0.8950	0.03183	
24	b_1: -0.3951	0.1325	1.472
	b_2: 0.8982	0.03031	
25	b_1: -0.4002	0.1281	1.422
	b_2: 0.9003	0.02932	
26	b_1: -0.4187	0.1252	1.384
	b_2: 0.9055	0.02870	
27	b_1: -0.4179	0.1214	1.345
	b_2: 0.9062	0.02785	
28	b_1: -0.4441	0.1162	1.279
	b_2: 0.9131	0.02668	
29	b_1: -0.4723	0.1140	1.245
	b_2: 0.9204	0.02620	
30	b_1: -0.4818	0.1108	1.208
	b_2: 0.9235	0.02549	
31	b_1: -0.4846	0.1062	1.158
	b_2: 0.9252	0.02445	
32	b_1: -0.5055	0.1019	1.107
	b_2: 0.9314	0.02351	
33	b_1: -0.5255	0.09429	1.021
	b_2: 0.9372	0.02177	
34	b_1: -0.5452	0.08788	0.9486
	b_2: 0.9428	0.02031	

TABLE 2 *Concluded*

	Parameter		
A	Estimate	Standard error	Root mean square error
35	b_1: -0.5736	0.08427	0.9034
	b_2: 0.9506	0.01950	
36	b_1: -0.5733	0.07865	0.8442
	b_2: 0.9516	0.01822	
37	b_1: -0.5971	0.07189	0.7680
	b_2: 0.9584	0.01668	
38	b_1: -0.6061	0.06406	0.6837
	b_2: 0.9615	0.01488	
39	b_1: -0.6244	0.05869	0.6242
	b_2: 0.9670	0.01365	
40	b_1: -0.6369	0.05517	0.5849
	b_2: 0.9711	0.01284	
41	b_1: -0.6574	0.04932	0.5206
	b_2: 0.9772	0.01150	
42	b_1: -0.6659	0.4476	0.4715
	b_2: 0.9803	0.01045	
43	b_1: -0.6719	0.04029	0.4240
	b_2: 0.9830	0.009416	
44	b_1: -0.6862	0.03465	0.3637
	b_2: 0.9877	0.008108	
45	b_1: -0.6948	0.02873	0.3015
	b_2: 0.9910	0.006732	
46	b_1: -0.7142	0.02379	0.2488
	b_2: 0.9972	0.005584	
47	b_1: -0.7249	0.02119	0.2212
	b_2: 1.001	0.004982	
48	b_1: -0.7213	0.01656	0.1732
	b_2: 1.002	0.003899	
49	b_1: -0.7262	0.01128	0.1179
	b_2: 1.004	0.002660	
50	b_1: -0.7156	0.009942	0.1042
	b_2: 1.003	0.002347	

linear way based on the criteria suggested by Ratkowsky (1983). Therefore, the reported significance level for any test that is done on the residuals is close to the actual significance level (Ratkowsky 1983). There were no apparent trends in the residuals when compared against the selected variables.

DISCUSSION

This research produced a growth intercept model for Douglas-fir in the Coastal Western Hemlock and Coastal Douglas-fir biogeoclimatic zones of British Columbia. The root mean square error, which is one measure of how well a model performs, indicates that the Douglas-fir growth intercept model provides accurate site index estimates. This model is presented in Table 3 as a series of functions, one for each breast height age between one and 50. The results are also presented as estimated site indices in Table 4. This table assumes that the height of the tree was 1.3 m (breast height) exactly midway between breast height age zero and one. Details about growth intercept models and modelling are not discussed in this report by can be obtained from Nigh (1995a, 1995b, 1996a, 1996b).

Four new features in growth intercept modelling are presented:

1. Precise annual height measurements are taken by identifying the annual nodes or by splitting the stem and identifying terminal bud scars.
2. The proportion of height growth between breast height age zero and one that is below breast height is explicitly calculated and not assumed to be 0.5.
3. The intercept parameter of the model is derived (=1.3) rather than estimated.
4. Functions are developed for breast height ages up to 50.

Precise height measurements obviate the need to interpolate heights and results in more accurate height-breast height age, and hence growth intercept, data. Explicitly calculating the proportion of height growth occurring below breast height also increases the accuracy of the model. Both of these refinements make the assumption that the regressor variables are known without error tenable. With the value of the intercept parameter based on theory rather than estimated empirically, extrapolating the model below the range of the data is less risky. The last feature,

TABLE 3 *Coastal Douglas-fir growth intercept functions for breast height ages one to 50*

A	Model	A	Model
1	$\hat{SI} = 1.3 + 3.894 \times GI_{1}^{0.5382}$	20	$\hat{SI} = 1.3 + 0.7165 \times GI_{20}^{0.8819}$
2	$\hat{SI} = 1.3 + 2.546 \times GI_{2}^{0.6330}$	21	$\hat{SI} = 1.3 + 0.7007 \times GI_{21}^{0.8872}$
3	$\hat{SI} = 1.3 + 2.449 \times GI_{3}^{0.6328}$	22	$\hat{SI} = 1.3 + 0.6814 \times GI_{22}^{0.8944}$
4	$\hat{SI} = 1.3 + 2.346 \times GI_{4}^{0.6358}$	23	$\hat{SI} = 1.3 + 0.6810 \times GI_{23}^{0.8950}$
5	$\hat{SI} = 1.3 + 2.187 \times GI_{5}^{0.6474}$	24	$\hat{SI} = 1.3 + 0.6736 \times GI_{24}^{0.8982}$
6	$\hat{SI} = 1.3 + 2.033 \times GI_{6}^{0.6593}$	25	$\hat{SI} = 1.3 + 0.6702 \times GI_{25}^{0.9003}$
7	$\hat{SI} = 1.3 + 1.768 \times GI_{7}^{0.6882}$	26	$\hat{SI} = 1.3 + 0.6579 \times GI_{26}^{0.9055}$
8	$\hat{SI} = 1.3 + 1.599 \times GI_{8}^{0.7076}$	27	$\hat{SI} = 1.3 + 0.6585 \times GI_{27}^{0.9062}$
9	$\hat{SI} = 1.3 + 1.437 \times GI_{9}^{0.7296}$	28	$\hat{SI} = 1.3 + 0.6414 \times GI_{28}^{0.9131}$
10	$\hat{SI} = 1.3 + 1.266 \times GI_{10}^{0.7570}$	29	$\hat{SI} = 1.3 + 0.6236 \times GI_{29}^{0.9204}$
11	$\hat{SI} = 1.3 + 1.155 \times GI_{11}^{0.7760}$	30	$\hat{SI} = 1.3 + 0.6177 \times GI_{30}^{0.9235}$
12	$\hat{SI} = 1.3 + 1.043 \times GI_{12}^{0.7981}$	31	$\hat{SI} = 1.3 + 0.6159 \times GI_{31}^{0.9252}$
13	$\hat{SI} = 1.3 + 0.9722 \times GI_{13}^{0.8135}$	32	$\hat{SI} = 1.3 + 0.6032 \times GI_{32}^{0.9314}$
14	$\hat{SI} = 1.3 + 0.8972 \times GI_{14}^{0.8310}$	33	$\hat{SI} = 1.3 + 0.5913 \times GI_{33}^{0.9372}$
15	$\hat{SI} = 1.3 + 0.8812 \times GI_{15}^{0.8343}$	34	$\hat{SI} = 1.3 + 0.5797 \times GI_{34}^{0.9428}$
16	$\hat{SI} = 1.3 + 0.8368 \times GI_{16}^{0.8457}$	35	$\hat{SI} = 1.3 + 0.5635 \times GI_{35}^{0.9506}$
17	$\hat{SI} = 1.3 + 0.7872 \times GI_{17}^{0.8595}$	36	$\hat{SI} = 1.3 + 0.5637 \times GI_{36}^{0.9516}$
18	$\hat{SI} = 1.3 + 0.7554 \times GI_{18}^{0.8690}$	37	$\hat{SI} = 1.3 + 0.5504 \times GI_{37}^{0.9584}$
19	$\hat{SI} = 1.3 + 0.7370 \times GI_{19}^{0.8747}$	38	$\hat{SI} = 1.3 + 0.5455 \times GI_{38}^{0.9615}$

TABLE 3 *Continued*

A	Model	A	Model
39	$\hat{SI} = 1.3 + 0.5356 \times GI_{39}^{0.9670}$	45	$\hat{SI} = 1.3 + 0.4992 \times GI_{45}^{0.9910}$
40	$\hat{SI} = 1.3 + 0.5289 \times GI_{40}^{0.9711}$	46	$\hat{SI} = 1.3 + 0.4896 \times GI_{46}^{0.9972}$
41	$\hat{SI} = 1.3 + 0.5182 \times GI_{41}^{0.9772}$	47	$\hat{SI} = 1.3 + 0.4844 \times GI_{47}^{1.001}$
42	$\hat{SI} = 1.3 + 0.5138 \times GI_{42}^{0.9803}$	48	$\hat{SI} = 1.3 + 0.4861 \times GI_{48}^{1.002}$
43	$\hat{SI} = 1.3 + 0.5107 \times GI_{43}^{0.9830}$	49	$\hat{SI} = 1.3 + 0.4837 \times GI_{49}^{1.004}$
44	$\hat{SI} = 1.3 + 0.5035 \times GI_{44}^{0.9877}$	50	$\hat{SI} = 1.3 + 0.4889 \times GI_{50}^{1.003}$

providing functions up to breast height age 50 rather than 30, smooths out the transition of site index estimates from the growth intercept model to the height-breast height age model.

Using the growth intercept method for silviculture surveys is described elsewhere (British Columbia Ministry of Forests 1995). However, the silviculture survey methodology can be refined to improve the accuracy of the estimated site index by measuring the height of the tree at breast height age zero and one and then using equation (2) to calculate the growth intercept. This will result in a more accurate growth intercept. The appropriate model would then have to be used to estimate site index instead of the table.

CONCLUSION

Douglas-fir site index can be estimated with the growth intercept method when the sample trees are between breast height age zero and 50. Four significant developments improve the growth intercept technique.

TABLE 4 *Estimated Douglas-fir site indices from the growth intercept model*

bh age (yrs)[a]	Top height (m)																								
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Site index (m at bh age 50)																								
2	30.3																								
3	21.5	36.7	48.7																						
4	17.1	29.0	38.5	46.7																					
5	14.2	24.3	32.3	39.3	45.6																				
6	12.2	20.8	27.8	33.9	39.5	44.6	49.5																		
7	10.4	18.0	24.3	29.8	34.9	39.7	44.2	48.6																	
8		15.9	21.5	26.5	31.2	35.6	39.7	43.7	47.5																
9		14.1	19.2	23.8	28.1	32.2	36.1	39.8	43.4	46.9															
10		12.5	17.3	21.6	25.6	29.4	33.0	36.6	40.0	43.3	46.5	49.7													
11		11.3	15.7	19.6	23.4	26.9	30.4	33.7	36.9	40.0	43.1	46.1	49.0												
12		10.3	14.2	18.0	21.5	24.8	28.0	31.2	34.2	37.2	40.2	43.0	45.9	48.6											
13			13.1	16.6	19.9	23.0	26.1	29.1	32.0	34.8	37.6	40.3	43.0	45.7	48.3										
14			12.1	15.4	18.4	21.4	24.3	27.1	29.9	32.6	35.3	37.9	40.5	43.0	45.5	48.0									
15			11.4	14.4	17.4	20.2	22.9	25.5	28.1	30.7	33.2	35.7	38.1	40.5	42.9	45.2	47.5	49.8							
16			10.7	13.5	16.3	18.9	21.5	24.1	26.5	29.0	31.4	33.7	36.0	38.3	40.6	42.9	45.1	47.3	49.5						
17			10.0	12.7	15.3	17.8	20.3	22.7	25.1	27.4	29.7	32.0	34.2	36.4	38.6	40.8	42.9	45.1	47.2	49.3					
18				12.0	14.5	16.9	19.2	21.5	23.8	26.0	28.2	30.4	32.6	34.7	36.8	38.9	41.0	43.0	45.1	47.1	49.1				
19				11.4	13.8	16.1	18.3	20.5	22.7	24.8	26.9	29.0	31.1	33.1	35.1	37.2	39.1	41.1	43.1	45.0	47.0	48.9			
20				10.9	13.2	15.4	17.5	19.6	21.7	23.8	25.8	27.8	29.8	31.8	33.7	35.7	37.6	39.5	41.4	43.3	45.1	47.0	48.9		
21				10.4	12.6	14.7	16.8	18.8	20.8	22.8	24.7	26.6	28.6	30.5	32.3	34.2	36.0	37.9	39.7	41.5	43.3	45.1	46.9	48.7	
22				10.0	12.1	14.1	16.1	18.0	20.0	21.9	23.7	25.6	27.5	29.3	31.1	32.9	34.7	36.5	38.3	40.0	41.8	43.5	45.3	47.0	48.7
23					11.6	13.6	15.5	17.4	19.2	21.1	22.9	24.7	26.5	28.2	30.0	31.7	33.5	35.2	36.9	38.6	40.3	42.0	43.6	45.3	46.9
24					11.2	13.1	15.0	16.8	18.6	20.3	22.1	23.8	25.6	27.3	29.0	30.6	32.3	34.0	35.6	37.3	38.9	40.5	42.2	43.8	45.4
25					10.9	12.7	14.5	16.2	18.0	19.7	21.4	23.1	24.7	26.4	28.0	29.7	31.3	32.9	34.5	36.1	37.7	39.3	40.8	42.4	44.0

TABLE 4 *Continued*

bh age (yrs)[a]	Top height (m)																								
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Site index (m at bh age 50)																								
26					10.5	12.3	14.0	15.7	17.4	19.0	20.7	22.3	23.9	25.6	27.2	28.7	30.3	31.9	33.5	35.0	36.5	38.1	39.6	41.1	42.7
27					10.2	11.9	13.6	15.2	16.9	18.5	20.1	21.7	23.3	24.8	26.4	27.9	29.4	31.0	32.5	34.0	35.5	37.0	38.5	39.9	41.4
28						11.5	13.1	14.7	16.3	17.9	19.5	21.0	22.5	24.1	25.6	27.1	28.6	30.0	31.5	33.0	34.5	35.9	37.4	38.8	40.3
29						11.1	12.7	14.3	15.8	17.3	18.8	20.3	21.8	23.3	24.8	26.3	27.7	29.2	30.6	32.1	33.5	34.9	36.4	37.8	39.2
30						10.8	12.3	13.9	15.4	16.8	18.3	19.8	21.2	22.7	24.1	25.6	27.0	28.4	29.8	31.2	32.6	34.0	35.4	36.8	38.2
31						10.5	12.0	13.5	15.0	16.4	17.9	19.3	20.7	22.1	23.5	24.9	26.3	27.7	29.1	30.4	31.8	33.2	34.5	35.9	37.2
32						10.2	11.7	13.1	14.6	16.0	17.4	18.8	20.2	21.6	22.9	24.3	25.7	27.0	28.4	29.7	31.0	32.4	33.7	35.0	36.4
33						10.0	11.4	12.8	14.2	15.6	16.9	18.3	19.7	21.0	22.4	23.7	25.0	26.4	27.7	29.0	30.3	31.6	32.9	34.2	35.5
34							11.1	12.4	13.8	15.1	16.5	17.8	19.2	20.5	21.8	23.1	24.4	25.7	27.0	28.3	29.6	30.9	32.2	33.4	34.7
35							10.8	12.1	13.4	14.7	16.0	17.4	18.7	20.0	21.2	22.5	23.8	25.1	26.4	27.6	28.9	30.2	31.4	32.7	34.0
36							10.5	11.8	13.1	14.4	15.7	17.0	18.3	19.5	20.8	22.1	23.3	24.6	25.8	27.1	28.3	29.5	30.8	32.0	33.2
37							10.3	11.5	12.8	14.1	15.3	16.6	17.8	19.1	20.3	21.5	22.8	24.0	25.2	26.5	27.7	28.9	30.1	31.3	32.6
38							10.0	11.3	12.5	13.7	15.0	16.2	17.4	18.7	19.9	21.1	22.3	23.5	24.7	25.9	27.1	28.3	29.5	30.7	31.9
39								11.0	12.2	13.4	14.6	15.8	17.0	18.2	19.4	20.6	21.8	23.0	24.2	25.4	26.5	27.7	28.9	30.1	31.3
40								10.8	12.0	13.1	14.3	15.5	16.7	17.9	19.0	20.2	21.4	22.5	23.7	24.9	26.0	27.2	28.3	29.5	30.6
41								10.5	11.7	12.8	14.0	15.2	16.3	17.5	18.6	19.8	20.9	22.1	23.2	24.4	25.5	26.7	27.8	28.9	30.1
42								10.3	11.4	12.6	13.7	14.9	16.0	17.1	18.3	19.4	20.5	21.7	22.8	23.9	25.0	26.2	27.3	28.4	29.5
43								10.1	11.2	12.4	13.5	14.6	15.7	16.8	17.9	19.0	20.2	21.3	22.4	23.5	24.6	25.7	26.8	27.9	29.0
44									11.0	12.1	13.2	14.3	15.4	16.5	17.6	18.7	19.8	20.9	22.0	23.1	24.1	25.2	26.3	27.4	28.5
45									10.8	11.9	13.0	14.0	15.1	16.2	17.3	18.4	19.4	20.5	21.6	22.7	23.7	24.8	25.9	27.0	28.0
46									10.6	11.6	12.7	13.8	14.8	15.9	17.0	18.0	19.1	20.2	21.2	22.3	23.3	24.4	25.5	26.5	27.6
47									10.4	11.4	12.5	13.5	14.6	15.6	16.7	17.7	18.8	19.8	20.9	21.9	22.9	24.0	25.0	26.1	27.1
48									10.3	11.3	12.3	13.4	14.4	15.4	16.4	17.5	18.5	19.5	20.6	21.6	22.6	23.7	24.7	25.7	26.8
49									10.1	11.1	12.1	13.1	14.1	15.1	16.2	17.2	18.2	19.2	20.2	21.2	22.3	23.3	24.3	25.3	26.3
50									10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21.0	22.0	23.0	24.0	25.0	26.0

TABLE 4 *Continued*

bh age (yrs)[a]	Top height (m)																							
	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
	Site index (m at bh age 50)																							
2																								
3																								
4																								
5																								
6																								
7																								
8																								
9																								
10																								
11																								
12																								
13																								
14																								
15																								
16																								
17																								
18																								
19																								
20																								
21																								
22																								
23	48.6																							
24	47.0	48.6																						
25	45.5	47.1	48.6																					

TABLE 4 *Concluded*

bh age (yrs)[a]	Top height (m)																							
	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
	Site index (m at bh age 50)																							
26	44.2	45.7	47.2	48.7																				
27	42.9	44.3	45.8	47.3	48.7																			
28	41.7	43.1	44.6	46.0	47.4	48.8																		
29	40.6	42.0	43.4	44.8	46.2	47.6	49.0																	
30	39.5	40.9	42.3	43.6	45.0	46.4	47.7	49.1																
31	38.5	39.9	41.2	42.6	43.9	45.2	46.5	47.8	49.2															
32	37.7	39.0	40.3	41.6	42.9	44.2	45.5	46.8	48.1	49.4														
33	36.8	38.1	39.4	40.7	42.0	43.3	44.6	45.8	47.1	48.4	49.7													
34	36.0	37.3	38.5	39.8	41.1	42.3	43.6	44.8	46.1	47.3	48.6	49.8												
35	35.2	36.5	37.7	39.0	40.2	41.5	42.7	44.0	45.2	46.4	47.7	48.9												
36	34.5	35.7	36.9	38.1	39.4	40.6	41.8	43.0	44.2	45.4	46.6	47.9	49.1											
37	33.8	35.0	36.2	37.4	38.6	39.8	41.0	42.2	43.4	44.6	45.8	47.0	48.2	49.4										
38	33.1	34.3	35.4	36.6	37.8	39.0	40.2	41.3	42.5	43.7	44.9	46.0	47.2	48.4	49.6									
39	32.4	33.6	34.8	35.9	37.1	38.3	39.4	40.6	41.7	42.9	44.1	45.2	46.4	47.5	48.7	49.8								
40	31.8	33.0	34.1	35.3	36.4	37.5	38.7	39.8	41.0	42.1	43.3	44.4	45.5	46.7	47.8	49.0								
41	31.2	32.4	33.5	34.6	35.8	36.9	38.0	39.2	40.3	41.4	42.5	43.7	44.8	45.9	47.1	48.2	49.3							
42	30.6	31.8	32.9	34.0	35.1	36.2	37.3	38.4	39.6	40.7	41.8	42.9	44.0	45.1	46.2	47.3	48.4	49.6						
43	30.1	31.2	32.3	33.4	34.5	35.6	36.7	37.8	38.9	40.0	41.1	42.2	43.3	44.4	45.5	46.6	47.7	48.7	49.8					
44	29.6	30.7	31.8	32.9	33.9	35.0	36.1	37.2	38.3	39.4	40.4	41.5	42.6	43.7	44.8	45.9	46.9	48.0	49.1					
45	29.1	30.2	31.2	32.3	33.4	34.5	35.5	36.6	37.7	38.7	39.8	40.9	41.9	43.0	44.1	45.1	46.2	47.3	48.3	49.4				
46	28.6	29.7	30.8	31.8	32.9	33.9	35.0	36.1	37.1	38.2	39.2	40.3	41.4	42.4	43.5	44.5	45.6	46.7	47.7	48.8	49.8			
47	28.2	29.2	30.3	31.3	32.4	33.4	34.5	35.5	36.6	37.6	38.7	39.7	40.7	41.8	42.8	43.9	44.9	46.0	47.0	48.1	49.1			
48	27.8	28.8	29.9	30.9	31.9	33.0	34.0	35.0	36.1	37.1	38.2	39.2	40.2	41.3	42.3	43.3	44.4	45.4	46.4	47.5	48.5	49.5		
49	27.3	28.4	29.4	30.4	31.4	32.4	33.4	34.5	35.5	36.5	37.5	38.5	39.6	40.6	41.6	42.6	43.6	44.7	45.7	46.7	47.7	48.7	49.8	
50	27.0	28.0	29.0	30.0	31.0	32.0	33.0	34.0	35.0	36.0	37.0	38.0	39.0	40.0	41.0	42.0	43.0	44.0	45.0	46.0	47.1	48.1	49.1	50.1

[a] Breast height (bh) is the number of annual growth rings at breast height

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