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Trembling Aspen Height-Age Models for British Columbia

Abstract

Trembling aspen, a common hardwood species in the interior of British Columbia, is becoming an increasingly important timber crop species, especially in the northeast corner of the province. Better growth and yield information for aspen is required to manage this species properly. We provide height-age models for estimating site height and site index. One-hundred and thirty-five stem analysis plots were established in six biogeoclimatic zones. Three trees in the 0.04 ha plots were selected and stem analyzed, and ecological data were collected at each plot. The stem analysis data were split into a model calibration and test data set. Two models were fit to the calibration data: a base model and an extended model that is calibrated for the six biogeoclimatic zones. Both models adequately estimate the height of trembling aspen in British Columbia. The base model was compared to two models for aspen in Alberta, which showed that there were no large differences in the height growth of aspen, except on lower productivity sites.

Introduction

Trembling aspen (*Populus tremuloides*) is the most widespread hardwood species throughout North America (Perala 1990). Its range extends across Canada to the northern tree line. In the United States, it is found mainly in the western mountains, and around the Great Lakes east to the Atlantic Ocean. As might be expected for a species with such a broad geographic range, it grows in a wide variety of climatic and soil conditions.

In British Columbia, aspen occurs throughout most of the interior of the province and, to a minor extent, on the southeast coast of Vancouver Island and along the mouths of the Fraser and Skeena rivers (Klinka et al. 2000). Aspen is most frequent in the Boreal White and Black Spruce (BWBS), Sub-Boreal Spruce (SBS), and Interior Douglas-fir (IDF) biogeoclimatic zones, and less frequent in the Montane Spruce (MS) and Interior Cedar-Hemlock (ICH) zones (Klinka et al. 2000). A description of the biogeoclimatic zones can be found in Meidinger and Pojar (1991).

Aspen often grows in pure, even-aged stands. It associates frequently with white spruce (*Picea glauca*), mainly in the BWBS and SBS zones, and is frequently found with lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menziesii*) (Klinka et al. 2000). It is a shade intolerant species that typically regenerates by root suckering, especially after fire or clearcutting. Aspen has become an important timber species in British Columbia. It is used for lumber, pulp, and oriented strand-board, and also provides valuable non-commercial resources such as wildlife habitat, forest biodiversity, and livestock forage areas (Peterson and Peterson 1995, Klinka et al. 2000).

As the importance of trembling aspen increases, better growth and yield information will be required for this species. The only growth and yield model available in British Columbia that is calibrated for aspen is the Variable Density Yield Prediction (VDYP) system (Ministry of Forests 1997). The Mixedwood Growth Model (MGM) (Titus 1998) is in the process of being adapted for British Columbia forests. Both MGM and VDYP use site index models developed for aspen in Alberta (Alberta Forest Service 1985). Evidence suggests that these models may be biased when estimating aspen height growth in British Columbia (Chen

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et al. 1998). Therefore, recommendations for developing MGM include new site index models for British Columbia (Harper 2000). The purpose of this project is to develop site index models for trembling aspen with data collected in the biogeoclimatic zones in which aspen is mainly found. In this project, we develop models that provide reliable estimates of height and site index for growth and yield, and for other management purposes.

Methods

Height-Age Data

The data for this project were collected as part of a study to develop the classification of aspen ecosystems in British Columbia and aspen productivity (Krestov et al. 2000). Additional information about the data can be found in Krestov et al. (2000). One-hundred and eighty-six plots were established in the BWBS (88 plots), SBS (25), Sub-Boreal Pine-Spruce (SBPS) (7), IDF (23), MS (19), and ICH (24) biogeoclimatic zones. Of these plots, 135 were available for developing site index models. Trees from the other 51 plots were either too young (they must be at least 50 yr old at breast height so that the site index is known) or were suppressed or damaged (often decayed) in some way that precluded their use. Trees with damage or suppression would bias the site index. The plots were located to cover a wide range in climate, topography, soil moisture, and nutrient conditions.

The 20 m × 20 m study plots were located in naturally established, unmanaged, fully stocked (the cover of the tree layer was >75%), even-aged stands. Each stand had a uniform canopy of trembling aspen, understory vegetation, and site. Site, vegetation, and soil were described according to Luttmerding et al. (1990). Three largest diameter dominant aspen trees were selected from each plot for stem analysis. At the time of selection, these trees had no visible signs of damage or suppression so that their height growth adequately reflected the productivity of the site. The trees were cut down and sections were taken at 0.3 m, 0.8 m, 1.3 m, and at 1-m intervals above 1.3 m. The rings on each section were counted in two directions under magnification. Suppressed growth was checked at this time and suppressed trees were deleted from further analyses.

The section height-ring count data were converted into height-breast height age data by standard methods (Carmean 1972, Dyer and Bailey 1987, Newberry 1991). Individual tree height trajectories were plotted to detect damage, errors in ring counts, and as a final check for suppression. Errors in ring counts were corrected and damaged/suppressed trees were deleted. If more than one tree in a plot was rejected, then the whole plot was excluded from the analysis. The individual tree height-breast height age data were averaged by age within plot to get site height-breast height age data. The site height at breast height age 50 is site index by definition.

Height-Age Models

The data were split into a model calibration and a model testing data set by first sorting the plots by biogeoclimatic zone. Every second plot was put into a calibration data set and the remaining plots were put into a test data set, which created balanced data sets with respect to zone. We wanted to have an approximately equal number of plots from each zone in the calibration and test data sets because we tested for differences in growth pattern between zones. The calibration and test data sets consisted of heights at 5 yr intervals starting at age 5, except the test data set excluded the height at breast height age 50 because the model is conditioned to be exact at that age.

Two models were developed: a base model and an extended model to test for differences in height growth patterns across biogeoclimatic zones.

Base Model

The functional form for the base height-age model is the logistic function (1).

(1)

$$HT = 1.3 + (SI - 1.3) \times \frac{1 + e^{a_0 + a_1 \times \ln(49.5) + a_2 \times \ln(SI - 1.3)}}{1 + e^{a_0 + a_1 \times \ln(BHA - 0.5) + a_2 \times \ln(SI - 1.3)}}$$

where HT is site height (m), SI is site index (m), BHA is breast height age (yr), e is the base for natural logarithms, ln is the natural logarithm operator, and a_0 , a_1 , and a_2 are model parameters. This function has been used successfully in other height growth modelling projects, and it seems to work quite well across a broad range of species (Thrower and Goudie 1992; Nigh 1997; Chen and Klinka 2000).

Equation (1) with an AR(1) error term was fitted to the calibration data using weighted nonlinear regression. The AR(1) model is a first-order autoregressive model that accounts for serial correlation that usually exists with stem analysis data. The AR(1) model is given in (2).

$$(2) \quad \varepsilon_{i,BHA} = \phi \times \varepsilon_{i,BHA-10} + \omega_{i,BHA}$$

where $\varepsilon_{i,BHA}$ is the error term for plot i at BHA, ϕ is the autocorrelation coefficient ($-1 < \phi < 1$), and the $\omega_{i,BHA}$'s are normally distributed independent random errors with mean zero and constant variance. The weighting was done to stabilize the variance. Both sides of the model were divided by a weight (wt) as given in (3).

$$(3) \quad wt = \begin{cases} BHA^{0.25} & \text{if } BHA < 25, \\ \text{abs}(50-BHA)^{-0.25} & \text{otherwise} \end{cases}$$

where abs is the absolute value operator.

Extended Model

The extended model was created by introducing indicator variables into the base model that allow the value of the parameters a_0 , a_1 , and a_2 to vary across zones, as shown in (4).

$$(4) \quad \begin{aligned} a_0 &= a_{00} + a_{01} \times ICH + a_{02} \times IDF + a_{03} \times MS + a_{04} \times SBPS \\ &\quad + a_{05} \times SBS \\ a_1 &= a_{10} + a_{11} \times ICH + a_{12} \times IDF + a_{13} \times MS + a_{14} \times SBPS \\ &\quad + a_{15} \times SBS \\ a_2 &= a_{20} + a_{21} \times ICH + a_{22} \times IDF + a_{23} \times MS + a_{24} \times SBPS \\ &\quad + a_{25} \times SBS \end{aligned}$$

where ICH is 1 if the plot is in the ICH zone, 0 otherwise, IDF is 1 if the plot is in the IDF zone, 0 otherwise, MS is 1 if the plot is in the MS zone, 0 otherwise, SBPS is 1 if the plot is in the SBPS zone, 0 otherwise, SBS is 1 if the plot is in the SBS zone, 0 otherwise. Parameters were deleted if they were not significantly different from 0. Terms were combined if their parameter estimates were similar, that is, if the confidence interval of one parameter enveloped the estimate of the other parameter, and vice versa. Although this method is not optimal, it is easy to implement and will lead to zones being incorrectly deemed as being different (Schenker and Gentleman 2001), which complicates the model but does not cause bias. As before, an AR(1) error term was added and

weighted regression was used to estimate the parameters, but using (5) as a weighting function.

$$(5) \quad wt = \begin{cases} BHA^{-0.30} & \text{if } BHA < 25, \\ \text{abs}(50-BHA)^{-0.30} & \text{otherwise} \end{cases}$$

It was critical to meet the regression assumptions for both the base and extended models. A violation of one or more of the Gauss-Markov conditions (the residuals are uncorrelated, have a mean of zero, and a constant variance) generally does not bias the parameter estimates, but it will bias the variances of the parameter estimates (Sen and Srivastava 1990). Biased variances will lead to biased t-tests and perhaps wrong conclusions when testing for differences between zones, although moderate heteroscedasticity does not seriously impact the results of tests on parameter estimates (Mason et al. 1989). Non-normality of the residuals may also lead to wrong conclusions because the t-test is based on normally distributed populations. However, the t-test is robust against slight deviations from normality (Mason et al. 1989). The regression assumptions were checked with the following tests:

1. expected value of the residuals is zero: a t-test;
2. normality: W test (Shapiro and Wilk 1965);
3. constant variance: plots of residuals against breast height age and site index, and the F_{kk} test (Endrenyi and Kwong 1981);
4. correlated residuals: plots of residuals against breast height age, by plot, and correlations between the residuals and their lag, by plot.

The weighting functions (3) and (5) affected all of the above tests. Much effort was expended in meeting all the regression assumptions.

The base model and the extended model were tested by using the models (and the breast height age and site index in the test data) to estimate the heights in the test data set. The errors in the height estimates were calculated by subtracting the estimated height from the actual height. The mean error and its standard error were calculated for all the observations, and for the observations for each age and within biogeoclimatic zone. We conducted t-tests on the mean errors to detect statistical bias, that is, to check whether the mean error was significantly different from zero.

Results

The distribution of the calibration and test data sets is even, with approximately equal means, minimums, and maximums for both data sets (Table 1). The balance between the two data sets means that the calibration and testing procedures equally weight the range of site indices, heights, and ages. This balance was not found across biogeoclimatic zones (Table 2). The MS and ICH zones have the highest mean and maximum site indices of all the zones (Table 2). Note, however, that the sampling was not random so that statistically-based conclusions cannot be drawn.

TABLE 1. Summary statistics for the trembling aspen stem analysis data (by data set).

	Number of plots	Minimum	Mean	Maximum
Calibration data set				
Height (m)	68	7.27	20.42	37.50
Breast height age (yr)	68	50	78	177
Site index (m)	68	6.81	16.72	29.56
Test data set				
Height (m)	67	5.74	20.61	36.00
Age (yr)	67	50	76	159
Site index (m)	67	5.60	16.61	28.73
Both data sets				
Height (m)	135	5.74	20.51	37.50
Age (yr)	135	50	77	177
Site index (m)	135	5.60	16.66	29.56

This study presents two new models for estimating the height of trembling aspen site trees in British Columbia: a base model and an extended model. The base model is a general model that could be used anywhere in British Columbia, or when the biogeoclimatic zone is unknown.

$$HT = 1.3 + (SI - 1.3) \times \frac{1 + e^{7.423 - 1.150 \times \ln(49.5) - 0.9614 \times \ln(SI - 1.3)}}{1 + e^{7.423 - 1.150 \times \ln(BH/A - 0.5) - 0.9892 \times \ln(SI - 1.3)}}$$

The parameter estimates and their standard errors, the mean error and *P*-value of the associated *t*-test for bias, the *W* statistic and *P*-value for normality, and the F_{kk} test and *P*-value for constant variance are used to evaluate the model (Table 3). These statistics show that the model is unbiased and has normally distributed, homoscedastic residuals. In addition, only five plots had statistically significant correlation in the lagged residuals. Therefore, we conclude that the

TABLE 2. Summary statistics for the trembling aspen stem analysis data by biogeoclimatic zone.

	Number of plots	Minimum	Mean	Maximum
Boreal White and Black Spruce zone				
Height (m)	56	5.74	16.65	26.25
Breast height age (yr)	56	50	79	177
Site index (m)	56	5.60	13.69	25.24
Interior Cedar-Hemlock zone				
Height (m)	16	15.33	25.73	37.50
Age (yr)	16	55	75	99
Site index (m)	16	12.46	21.15	29.56
Interior Douglas-fir zone				
Height (m)	18	9.25	21.30	29.37
Age (yr)	18	54	74	119
Site index (m)	18	8.71	17.18	23.99
Montane Spruce zone				
Height (m)	18	12.65	25.26	31.20
Age (yr)	18	53	62	74
Site index (m)	18	12.22	22.19	29.27
Sub-Boreal Pine-Spruce zone				
Height (m)	7	11.33	17.63	24.57
Age (yr)	7	50	72	114
Site index (m)	7	9.24	15.07	22.33
Sub-Boreal Spruce zone				
Height (m)	20	16.69	23.20	30.02
Age (yr)	20	53	92	153
Site index (m)	20	10.35	16.51	23.10

TABLE 3. Results of the analysis of the base model.

Statistic	Estimate	Standard error (or <i>P</i> -value)	95% confidence interval	
			Lower	Upper
Parameter a_0	7.423	0.2758	6.881	7.965
Parameter a_1	-1.150	0.02324	-1.196	-1.104
Parameter a_2	-0.9614	0.09335	-1.145	-0.7780
Parameter ϕ	0.9892	0.02151	0.9470	1.031
Mean error	0.009847	(0.8353)		
<i>W</i>	0.9805	(0.0769)		
F_{kk}	1.143	(0.2206)		

regression assumptions were adequately met. The residuals plotted against breast height age and site index demonstrate the constant variance and, to some extent, the low correlation between residuals (Figure 1). Although the variance of the residuals appears to be declining with age, a small number of data points at older ages can give the appearance of heteroscedasticity (Carroll and Ruppert 1988).

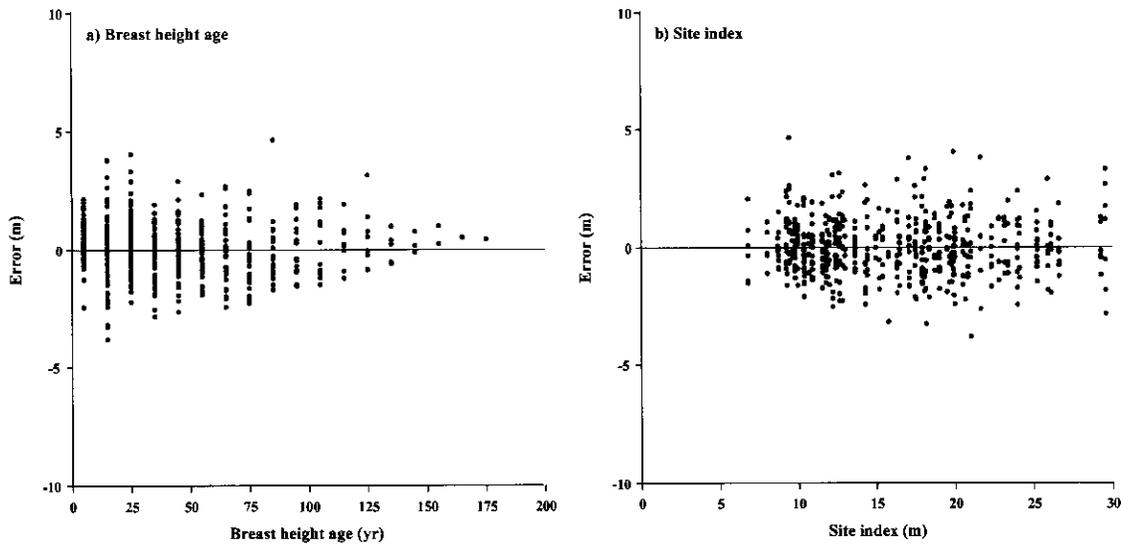


Figure 1. Residuals from the base model (1) plotted against breast height age (part a) and site index (part b). Note that the errors are weighted.

The extended model is calibrated specifically to six major biogeoclimatic zones where trembling aspen is the major species.

$$HT = 1.3 + (SI - 1.3) \times \frac{1 + e^{a_0 + a_1 \times \ln(49.5) + a_2 \times \ln(SI - 1.3)}}{1 + e^{a_0 + a_1 \times \ln(BHA - 0.5) + a_2 \times \ln(SI - 1.3)}}$$

where $a_0 = 7.314$ (for the BWBS, IDF, MS, and SBPS zones) or 8.363 (for the ICH and SBS zones), $a_1 = -1.074$ (for the BWBS, IDF, and SBS zones) or -1.446 (for the ICH zone) or -1.243 (for the MS and SBPS zones), and $a_2 = -1.011$ (for the BWBS, ICH, and IDF zones) or -0.9080 (for the MS and SBPS zones) or -1.267 (for the SBS zone). The results of the regression analysis of the extended model are in Table 4. Not all parameters in parameter set (4) are included in the extended model. The parameters in the final extended model are the result of testing many different combinations of parameters to determine which could be grouped together. The statistical tests (Table 4) show that the model is unbiased and the residuals are normally distributed and homoscedastic. Only five plots had lagged residuals that were correlated. Graphs of the residuals from the extended model plotted against breast height age and site index support our conclusion that the regression assumptions have been met (Figure 2).

The model testing shows that the both models are generally good at estimating height. Although

TABLE 4. Results of the analysis of the extended model.

Statistic	Estimate	Standard error (or <i>P</i> -value)	95% confidence interval	
			Lower	Upper
Parameter a_{00}	7.314	0.2878	6.749	7.879
Parameter a_{01}	1.049	0.1806	0.6944	1.404
Parameter a_{10}	-1.074	0.02767	-1.128	-1.020
Parameter a_{11}	-0.3723	0.06981	-0.5095	-0.2352
Parameter a_{12}	-0.1694	0.05408	-0.2757	-0.06319
Parameter a_{20}	-1.011	0.1031	-1.213	-0.8083
Parameter a_{21}	0.1030	0.04315	0.01821	0.1878
Parameter a_{22}	-0.2562	0.07059	-0.3948	-0.1175
Parameter ϕ	0.9942	0.02065	0.9536	1.035
Mean error	-0.00476	(0.9267)		
W	0.9832	(0.2683)		
F_{kk}	1.059	(0.3714)		

some biogeoclimatic zones show statistical bias, it is probably insignificant in practice (Table 5). The mean error in height across age is also small (Figure 3), except at extremely old ages, which is likely a result of only having a few plots at older ages.

We graphically compared the base model to the trembling aspen model currently used in British Columbia (Alberta Forest Service 1985) and the

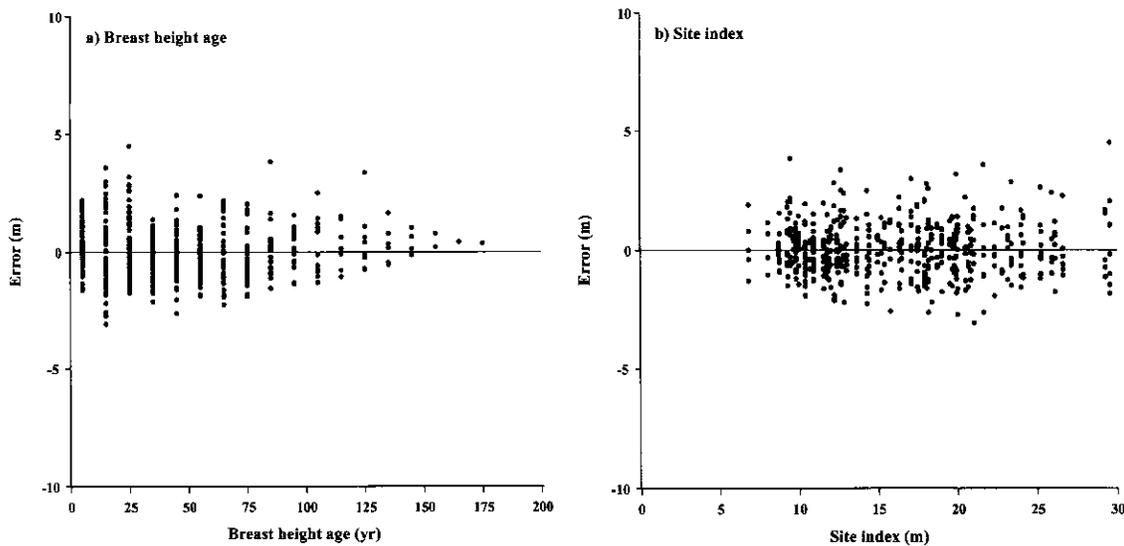


Figure 2. Residuals from the extended model plotted against breast height age (part a) and site index (part b). Note that the errors are weighted.

TABLE 5. Analysis of errors in height estimates by biogeoclimatic zone, and for all data combined for both fitted models. Mean errors that are significantly different from zero are indicated by asterisk.

Biogeoclimatic zone	Number of observations	Base model		Extended model	
		Mean error(m)	Std. dev.	Mean error (m)	Std. dev.
Boreal White and Black Spruce	384	0.1204	1.218	0.04979	1.219
Interior Cedar-Hemlock	111	0.1635	0.9260	0.6279*	1.064
Interior Douglas-fir	122	-0.1291	1.129	-0.2579*	1.174
Montane Spruce	102	0.05180	0.6127	-0.00007	0.7024
Sub-Boreal Pine-Spruce	32	0.2628*	0.6235	0.2430*	0.5309
Sub-Boreal Spruce	176	0.09701	0.6579	-0.1246*	0.6242
All	927	0.08565*	1.013	0.04659	1.061

provincial model developed by Huang et al. (1994). Because the upper range of the data for the Alberta Forest Service model was 90 yr, and the Huang et al. (1994) data did not extend much past 100 yr, we discontinued the comparison at 100 yr. The three models are plotted for site indices 10, 15, 20, and 25 m for comparison (Figure 4). We also plotted the mean error in estimated height and its 95% confidence interval by site index class (≤ 17.5 m and > 17.5 m) for the three models (Figure 5). The errors in estimated heights were calculated from the complete stem analysis data set at 5-yr age intervals from breast height age 5 to 100. There is little difference in height growth patterns to breast height age 100 for the base model

and the Alberta Forest Service model (Figures 4, 5). Although the errors are significantly different from zero at some ages, in practical terms the difference is small. The Huang et al. (1994) model underestimated height below age 50 and overestimated height above age 50 at lower site indices. All three models fit well at higher site indices.

Discussion

Two new models are now available for estimating the height of trembling aspen growing in British Columbia from site index and breast height age. One model is a generic base model and the other is extended to be specifically calibrated for six biogeoclimatic zones.

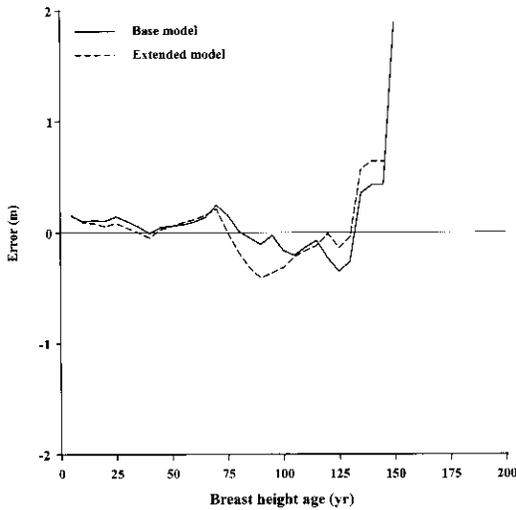


Figure 3. Mean error in the test data set plotted against breast height age for the two fitted models.

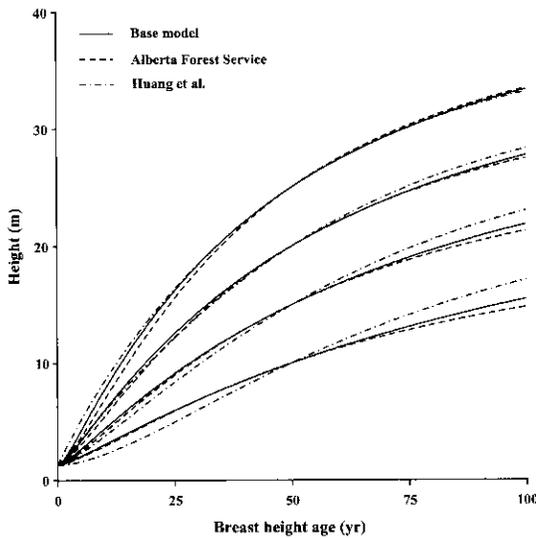
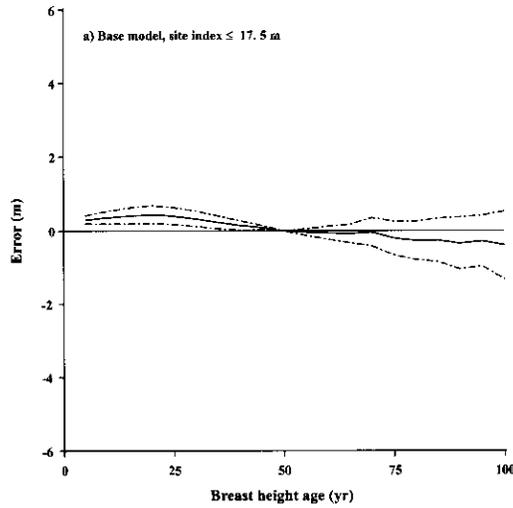


Figure 4. Graphical comparison of the base model, the current model for British Columbia (Alberta Forest Service 1985), and the provincial model by Huang et al. (1994). Curves for site indices 10, 15, 20, and 25 m are shown.

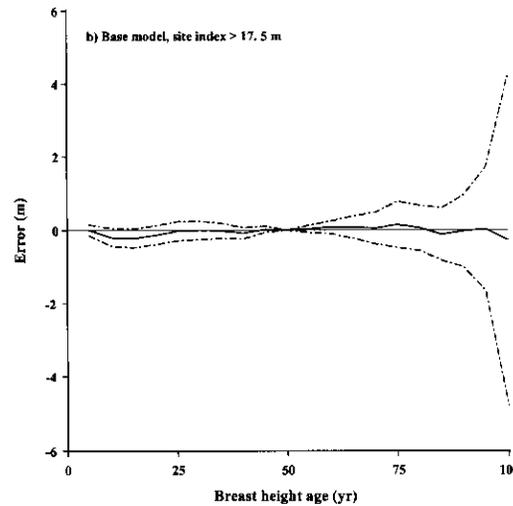
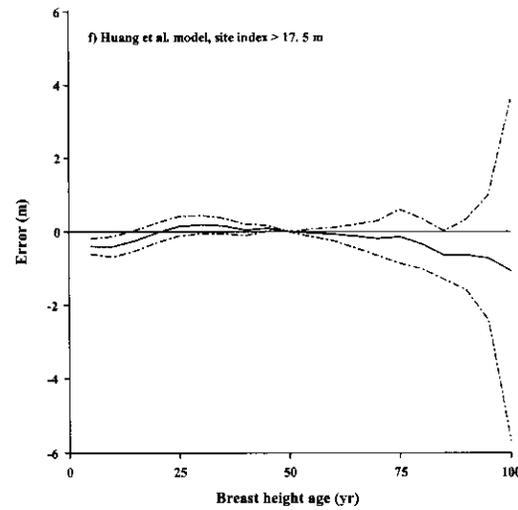
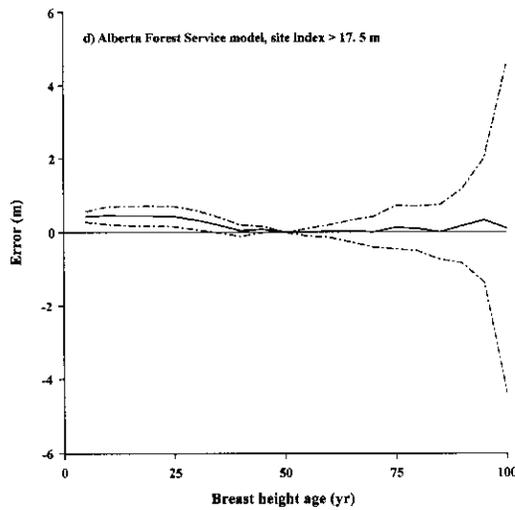
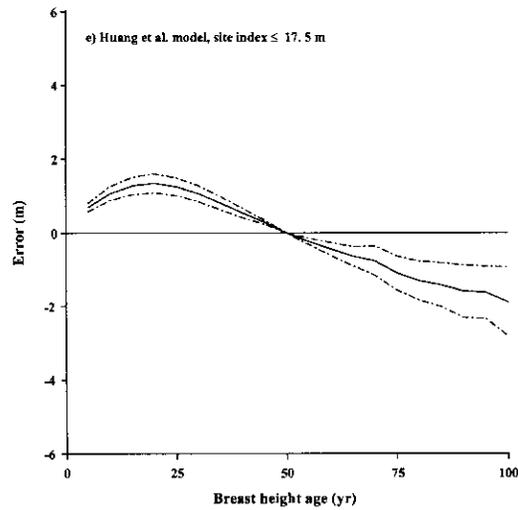
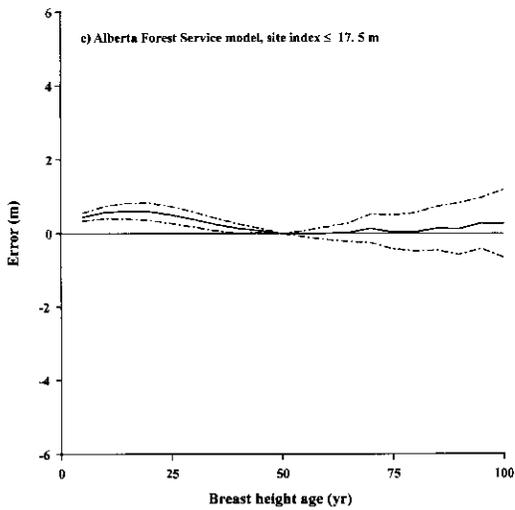


Figure 5(a-f). Mean errors and their 95% confidence intervals for

The trends in the site indices for the six biogeoclimatic zones (Table 2) sampled in this study correspond to the trends in their climate (Table 6). The ICH zone is the second-most productive zone in Canada (Meidinger and Pojar 1991), so that the high site indices are not surprising for that zone. In fact, the maximum height

of 37.5 m recorded in one study stand in the ICH zone (Table 2) is greater than the 36.5 m previously observed on the best sites (Perala 1990). Compared to the other study zones, the ICH zone is influenced by the warmest and wettest cool temperate climate. Aspen site index gradually increased from 13.7 m in the BWBS zone to 15.1 m in the SBPS zone to 16.5 m in the SBS zone to 17.2 m in the IDF zone and to 22.2 m in the MS zone (Table 2). This trend is reflected in the tem-



the base model, the Alberta Forest Service model, and the Huang et al. (1994) model, by site class (≤ 17.5 m, > 17.5 m).

perature and growing season duration (increasing potential evapotranspiration), i.e., the number of months with the mean temperature $> 10^{\circ}\text{C}$, which increases from the BWBS zone to the SBPS zone to the SBS zone to the IDF zone. The MS zone, however, has a lower mean annual temperature and more months with a mean temperature $> 10^{\circ}\text{C}$ than the IDF zone, but has higher mean annual precipitation, which could compensate for lower temperature and result in higher actual

evapotranspiration. Although the MS zone has a lower mean annual precipitation, it has a higher mean annual temperature and slightly longer growing season than the SBS zone.

The base and extended models are graphed for site indices at 10, 15, 20, and 25 m (Figure 6). There were only 13 plots older than 120 yr breast height age, so the curves in Figure 6 are not well supported above this age. For some biogeoclimatic zones, the data are exhausted well below this age

TABLE 6. Environmental characteristics of the six biogeoclimatic zones.

Zone	Environmental characteristics		
	MAP (cm) ¹	MAT (°C) ²	T>10 (mo) ³
Boreal White and Black Spruce	45	-1.4	3
Interior Cedar-Hemlock	80	6.9	5
Interior Douglas-fir	44	4.3	5
Montane Spruce	60	3.2	4
Sub-Boreal Pine-Spruce	48	0.4	3
Sub-Boreal Spruce	65	3.3	3

¹MAP – mean annual precipitation

²MAT – mean annual temperature

³T>10 – number of months with mean temperature > 10°C

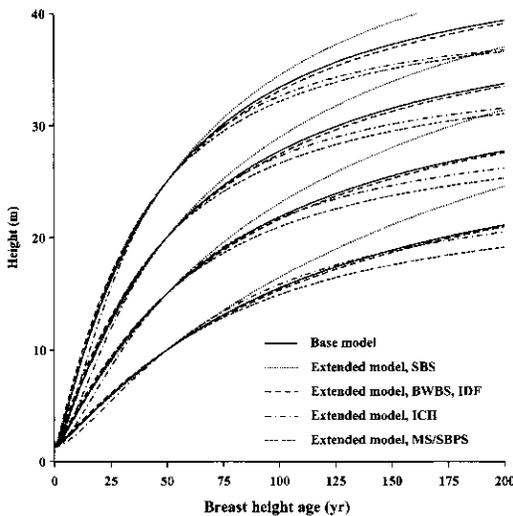


Figure 6. Height estimates from the base and extended models plotted against breast height age for site indices 10, 15, 20, and 25 m.

(Table 2), which must be considered when comparing and using the models. The largest difference in the height estimates between the models are above age 120. The base model, therefore, is adequate for all the zones, but the extended model would be preferred if the situation allows for its use. The adequacy of the base model is also borne out by the error analysis, where it performed about the same as the extended model (Table 5). The base model had a smaller mean error than the extended model in four of the six zones. The overall error for the base model was slightly larger than

that for the extended model, but the difference was a matter of a few centimetres. Both models have about the same error across the range of breast height ages (Figure 3). In fact, the base model appears to have a smaller mean error in the 50-100 yr age range, which may be the most important ages because the rotation age for aspen can be between 60 and 90 yr total age (Peterson and Peterson 1995).

The SBS curves are conspicuous by their continued height growth at older ages, which could be attributed to a combination of climatic and edaphic factors. First, most of the aspen stands sampled in the SBS zone were associated with fine-textured, base-rich Luvisols (Krestov et al. 2000), which support productive aspen growth across its range (Perala 1990). Second, decay in relatively short-lived aspen is generally slower in cooler (boreal) climates, such as in the SBS zone, than warmer (temperate) climates (Perala 1990). More data are required to confirm whether the height growth pattern in the SBS zone is indeed different from the other zones. One plot in the SBS was older than 120 yr breast height age, so that the model is not well-supported at ages above 120 yr for this zone. However, the difference in the height growth trend starts before age 120 where the model is supported by more data. There is no evidence of bias in the model below age 120, indicating that the trend is not necessarily an artifact of one plot causing bias in the model.

In contrast, the plots from the ICH and the MS zones were the most productive, that is, they had the highest site indices. The plots from these two zones, however, had the lowest height trajectories, which could be due to perhumid (water surplus) and warm climate, especially in the ICH zone (Perala 1990), or perhaps to the low age range of the data from these zones or to some unknown biological factor. In the early growth stages and in closed-canopy stands, aspen develops a relatively narrow, short, pyramidal crown with a distinct apical dominance. In the late growth stages, crowns become domed. We hypothesize that the development of a flat, domed crown is associated with the onset of decline in height growth that may be environmentally or genetically triggered.

Four groups of biogeoclimatic zones had similar height growth patterns: SBS, BWBS/IDF, ICH, and MS/SBPS. It appears that, to some extent, these patterns could be related to climate, such

as for the SBS and ICH zones, but not the patterns of BWBS/IDF and MS/SBPS zone groups, which are climatically dissimilar. Given the unbalanced nature of the data set with respect to age, the similarity of all the curves (except for the SBS zone), and the inconclusive nature of the model testing, we are hesitant to conclude that we detected real differences in growth patterns, even though they were detected statistically in the model calibration.

The extended height-age model specific to the six biogeoclimatic zones should be used for sites in those zones. If the zone is unknown, or the site is in another zone, then the base model should be used. The differences between the zones when using the extended model can be significant, depending on the application, even though the curves look quite similar (Figure 6). As an example, we compare the models for the ICH and the BWBS zones with the following three scenarios.

1. At breast height age 15 and site index 10 m, the estimated heights are 3.43 m (ICH) and 4.23 m (BWBS). At site index 20 m, these estimates are 9.55 m and 11.53 m. Therefore, with the extended model, the difference in heights can be between 1 and 2 m.
2. In British Columbia, a harvested stand usually has to reach green-up height (often 3 m) before an adjacent stand can be harvested. For site index 10 m, the green-up age for aspen in the ICH zone is 13 yr and the green-up age in the BWBS is 9 yr. At site index 25 m, the

green-up ages are 12 and 9.5 yr. Since green-up constraints are modelled in timber supply analyses, these differences could be significant for management units where the constraints are tying up timber.

3. Assuming a site has a height of 4 m at age 15 yr, the site index for sites in the ICH will be 12 m and the site index for sites in the BWBS will be 9.5 m. This 2.5 m difference in site index could translate into a significant amount of volume at rotation age.

Further to these examples, as one reviewer pointed out to us, height is critical in growth and yield modelling and small changes at young ages may result in significant changes in stand development in the model.

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