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Revised parameter estimates for CACTOS growth models

by

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Abstract

Previous height growth models were developed using stem analysis (Wensel and Koehler, 1985). DBH growth models were developed using, first, stem analysis data and, then, increment core data collected at the time of the initial measurement of the Coop permanent plots (Wensel, Meerschaert, and Biging, 1987). These estimates of growth were applied to stand conditions that were back dated to the beginning of the respective growth periods.

Remeasurement of these permanent plots yielded growth estimates by difference. The previous growth models consistently underestimated the growth rates observed on these remeasurement data. Thus, new parameter estimates were constructed to agree with the remeasurement data. However, it is not clear whether the differences in the growth projections between the previous and present models represent a difference in the actual growth rates or a difference in the measurement and analytical techniques used.

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INTRODUCTION

CACTOS, the CAlifornia Conifer Timber Output Simulator, is in widespread use by federal, state, private, and industrial foresters. The simulator makes it very easy to produce estimates of timber yields for 5-year growth periods -- with or without management intervention. The operation of the CACTOS System is described by Wensel and Biging (1987) and the operation of the individual programs by a series of user's guides. The CACTOS users' guide (Wensel, Daugherty, and Meerschaert, 1986) is the principal reference for the operation of the program and the various components of the program have been described in papers by Biging (1984, 1985, and 1988), Biging and Wensel (1984, 1985, 1989), Biging and Meerschaert (1987), Meerschaert and Wensel (1988), Van Deusen and Biging (1984), and Wensel and Koehler (1985). These papers describe the modelling processes used to obtain estimates of tree volume and taper, site index, crown geometry, tree growth rates and other mensurational relationships important to the growth modelling process.

This paper presents the results of a study of the remeasurement of permanent plots maintained by the Northern California Forest Yield Cooperative. The six conifer species studied are listed in Table 1 along with the two-letter species codes used in the following tables. The objective of this study was to (1) use the current set of remeasurement data to test the validity of the growth equation coefficients and (2) to revise the coefficients if warranted. Under the assumption that the difference between two measurements of the same trees at two points in time is the best estimate of tree growth, differences between actual and predicted growth rates is referred to here as bias.

In a previous study, Wensel and Koehler (1985) presented both height and DBH growth coefficients based upon stem analysis. For DBH, these coefficients were revised based upon more extensive data, the initial measurement of over 720 permanent plots (Wensel, Meerschaert, and Biging 1987). Thus, the previous height growth coefficients were based entirely upon stem analysis but the DBH growth rates benefitted from both stem analysis data and increment cores taken on the initial measurement of the permanent plots.

The percentage bias in the growth rates given by Wensel, Meerschaert, and Biging (1987) when tested against the remeasurement data set is given in Figure 1. The apparent bias in these predicted growth rates vary with diameter growth underestimated by 38 to 76 percent and height growth underestimated from 11 to 54 percent. These underestimates certainly justify the development of revised estimates of the growth estimation coefficients. Thus this paper is devoted to the development of revised estimates of the growth coefficients.

Table 1. Definition of species codes used.

Code	Definition
PP	Ponderosa pine *Pinus ponderosa* (Laws.)
SP	Sugar pine *Pinus lambertiana* (Dougl.)
IC	Incense cedar *Libocedrus decurrens* (Torr.)
DF	Douglas-fir *Pseudotsuga menziesii* (Mirb.) Franco
WF	White fir *Abies concolor* (Gord. and Glend.) Lindl.
RF	Red fir *Abies magnifica* (A. Murr.)

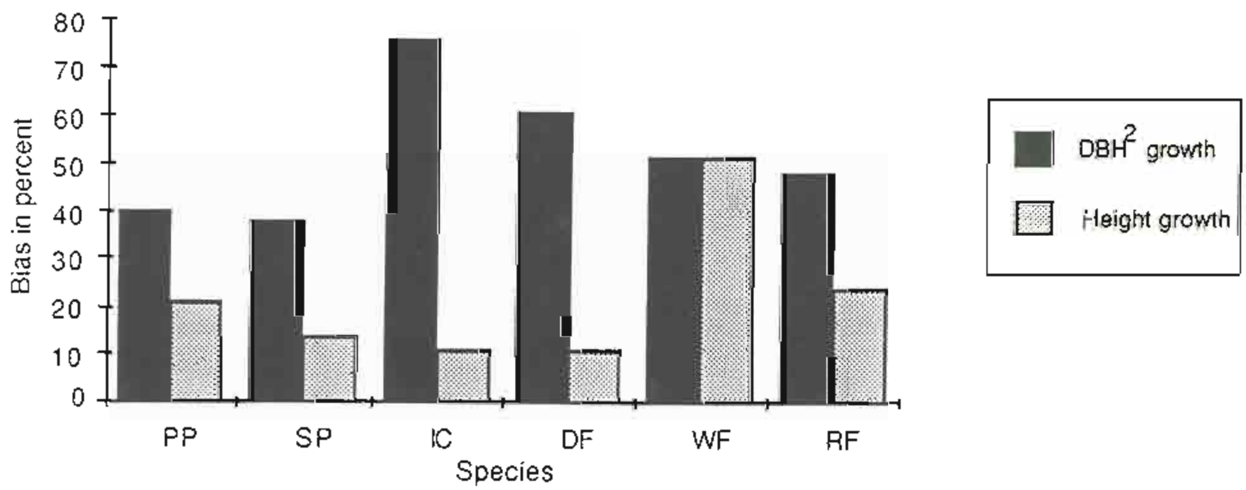

Figure 1. Average underestimate (bias) in growth rates for DBH^2 and height using growth coefficients by Wensel, Meerschaert, and Biging (1987) and data from remeasured plots.

DATA

The current paper presents revised parameter estimates for the CACTOS growth model based upon a remeasurement of the permanent growth plots maintained by the Northern California Forest Yield Cooperative. The locations of the study plots are shown in Figure 2.

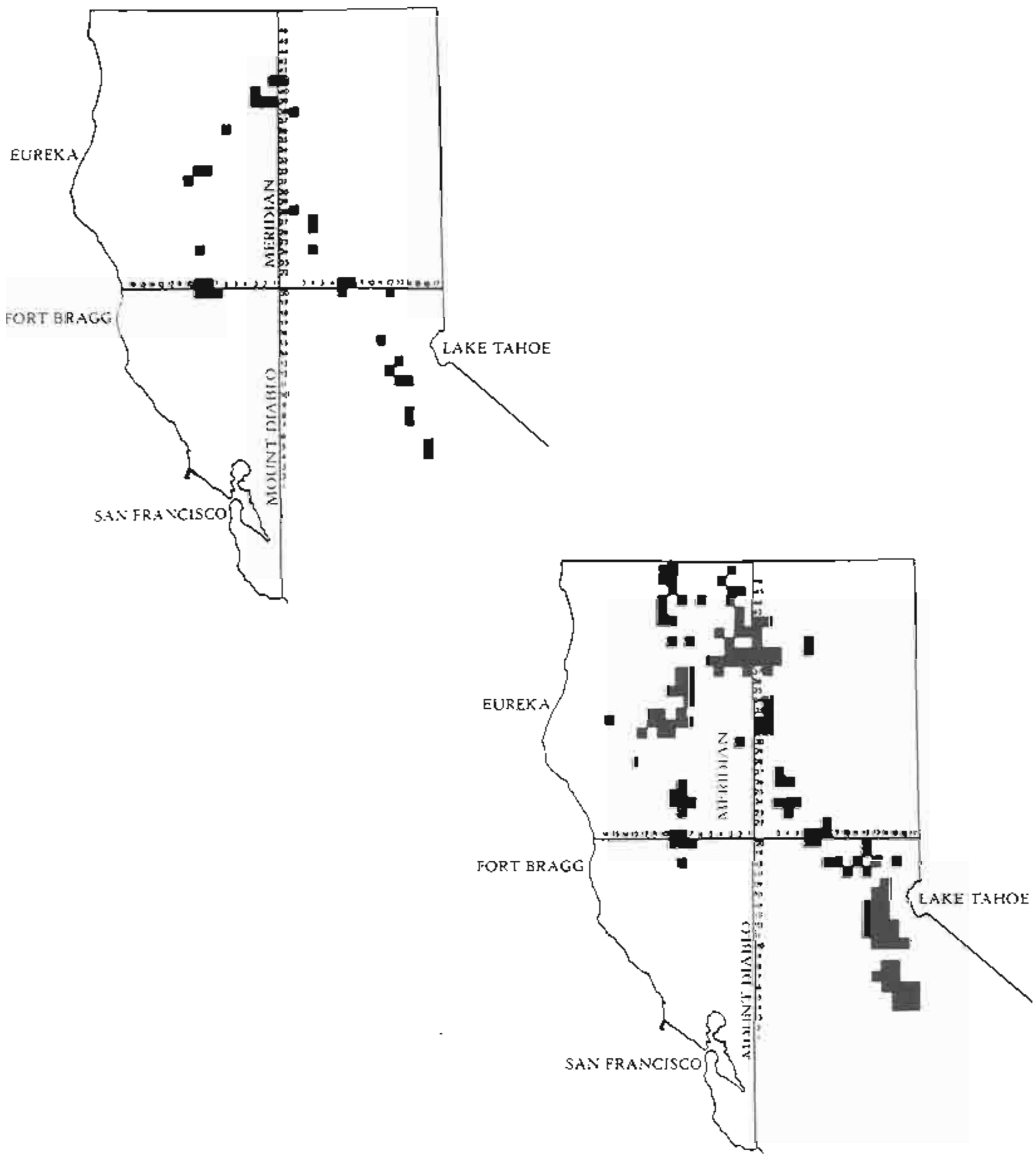

Figure 2. Distribution of sample data for growth models: (a) stem analysis plots and (b) permanent plots. Numbered to show townships and range coordinates of plot locations. (Wensel, Meerschaert, and Biging, 1987)

Two distinctly different data sets were used to obtain the previous parameter estimates. These are described by Wensel, Meerschaert, and Biging (1987) and are referred to here as STEM, the stem analysis plots and PERM, the system of permanent plots. The initial measurement of the permanent plots is designated $PERM_0$ and the 5-year remeasurement is designated $PERM_1$.

The STEM data base consists of tree data from 39 cluster plots from industrial forest lands. The initial PERM data base, $PERM_0$, consists of measurements on 29,323 trees from 710 permanent plots. Sample trees were selected from plots on lands of the industry members of the Northern California Forest Yield Cooperative (Figure 2). The remeasurement data set, $PERM_1$, consists of 569 plots with 19,363 trees. The reduction in the number of plots from $PERM_0$ to $PERM_1$ resulted from not remeasuring the plot (75 plots, some of which were clear cut or were lost due to change in ownership), plots with missing data (52 plots), and plots that were damaged (14 plots).

Four regions of northern California were recognized for the purposes of this analysis. Progressing counterclockwise around the northern end of California's central valley agricultural lands from due east of San Francisco to north of San Francisco the regions are as follows: (1) the Sierra east of San Francisco, (2) the southern Cascades in the northeast, (3) the Shasta-Trinity in the northwest, and (4) the Mendocino, north of San Francisco. Highways 32 and 36 from Chico to Susanville separate the Sierra and Southern Cascade regions, Interstate 5 separates the Southern Cascade regions and Shasta-Trinity regions, and highway 299 separates the Shasta-Trinity and Mendocino regions[1]. The PERM data not only has more plots than the STEM data but it also has a wider distribution, particularly in regions 2 and 3.

The STEM data provided estimates of the height growth coefficients as well as tree volume and taper, crown geometry, and site index coefficients estimates. The $PERM_0$ data set, divided into two random subsets $PERM_{0a}$ and $PERM_{0b}$, provided increment data for estimates of the tree diameter squared growth rates for the 6 conifer species. The data sets were split to provide a sample for model formulation and model fitting and an independent sample for testing. The STEM data were also used for initial estimates of the diameter squared growth rates but, representing a narrower range of tree sizes and conditions, these are likely to be less accurate when applied to the $PERM_0$ data. Thus they were abandoned in favor of the $PERM_0$ coefficients.

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[1] To complete the coverage of northern California, the north coast redwood and Douglas-fir forests are simulated by the CRYPTOS model by Wensel, Meerschaert and Krumland (1987).

The remeasurement of the permanent plots provided the $PERM_1$ data set which can be used to further develop the diameter and height growth parameter estimates. As with the initial measurement $PERM_0$, $PERM_1$ was divided into two subsets, putting the odd-numbered plots into $PERM_{1a}$ and the even-numbered plots into $PERM_{1b}$. The number of trees in each of the data sets is given in Table 2.

Table 2[1]. Sample sizes for initial growth parameter estimates for tree height and DBH^2 growth using the stem analysis (STEM) and permanent plot data bases ($PERM_{0a}$ and $PERM_{0b}$, for the initial measurement and $PERM_{1a}$ and $PERM_{1b}$ for the remeasurement, where the first subscript indicates the measurement sequence and the second subscript denotes the first and second halves of the data set, respectively).

		Species					
	data set	PP	SP	IC	DF	WF	RF
Height growth							
	STEM	151	47	71	145	279	37
	$PERM_{1a}$	1261	347	820	585	1464	271
	$PERM_{1b}$	1178	373	841	791	1748	†
DBH^2 growth							
	STEM	532	100	420	386	914	126
	$PERM_{0a}$	2064	905	1138	1465	3123	579
	$PERM_{0b}$	2139	†	1176	1498	3166	†
	$PERM_{1a}$	1261	743	820	215*	1464	271
	$PERM_{1b}$	1178	†	839	791	1748	†

* Only the potential was fitted as the competition components from $PERM_0$ showed no significant difference. Thus this number represents the number of trees with little or no competition.

† There were too few observations to split the SP and RF data sets to provide independent test data sets for those species.

GROWTH MODELS

The basic form of the growth models used was developed in earlier papers by Wensel and Koehler (1985) and Wensel, Meerschaert, and Biging (1987). Conceptually, they express tree growth as a product of two factors, the first reflecting the potential of the tree on the site and the

1 The data from the Mendocino region was omitted from the tabulation in Table 2 since it was not used for fitting the parameters given here.

second reflecting the inability of the tree to reach its potential growth rate. The first factor is intended to reflect the physiological capacity of the tree while the second factor is intended to reflect the competition on the site.

For tree height, the basic form of the prediction for the 5-year change in tree height, ΔH, is

$$\Delta H = P_H \times C_H \qquad [1]$$

where C_H is the competition factor which ranges between 0 and 1 and P_H is the potential growth of the tree. The equation for potential tree height growth is derived from the site index equation (Biging 1985; Wensel, Meerschaert, and Biging 1987)

$$P_H = [c_0 S^{c_1} + c_2 H^{c_3}]^{1/c_3} - H \qquad [2]$$

where S is the site index and H is the total height of the tree. Noting that trees with insufficient crown cannot reach this potential regardless of the competition and, conversely, that trees with very large crowns may grow more than the average potential, the potential growth is adjusted for live crown ratio, LCR, as follows:

$$P_H' = P_H \left\{ \frac{d_1}{1+\exp(d_0 - d_2\, LCR)} \right\} \qquad [3]$$

Thereafter, P_H' is substituted for P_H in equation [1]. (A further adjustment on the site index that was used in previous versions was dropped here.)

The height growth competition component, C_H, is given by

$$C_H = \exp(d_3\, CC_{66}^{d_4}\, PBA^{d_5}) \qquad [4]$$

where CC_{66} is the crown closure of the plot at 66% of the subject tree's height and PBA is the percent of the basal area of the plot composed of that tree's species. In order to compute CC_{66} one must model the crown shape. The procedures and coefficients used here are developed by Biging and Wensel (1989) and reported by Wensel, Meerschaert, and Biging (1987). The intuitive value of CC_{66} as a measure of competition is based upon the presumption that the crown density at two-thirds of a tree's height is a strong factor in the growth rate of the tree. Thus, root competition from other trees and/or shrubs is not included and may be a source of error in estimating competition.

The combined prediction equation is given as follows:

$$\Delta H = \left\{ [c_0 S^{c_1} + c_2 H^{c_3}]^{1/c_3} - H \right\} \left\{ \frac{d_1}{1+\exp(d_0 - d_2\, LCR)} \right\} \left\{ \exp(d_3\, CC_{66}^{d_4}\, PBA^{d_5}) \right\} \qquad [5]$$

The models used for estimating diameter growth are identical to those shown above for tree height except that DBH^2 is substituted for H in the above equations. This gives the combined equation for the 5-year change (Δ) in tree DBH^2 as

$$\Delta DBH^2 = \left\{ [c_0 S^{c_1} + c_2 DBH^{2c_3}]^{1/c_3} - DBH^2 \right\} \left\{ \frac{d_1}{1+\exp(d_0 - d_2\, LCR)} \right\} \left\{ \exp(d_3\, CC_{66}^{d_4}\, PBA^{d_5}) \right\} \qquad [6]$$

where the coefficients are computed separately for tree diameter and height growth for each species.

With 10 parameters to estimate in each equation, not all of which are independent, it is clear that the prediction equations are over-parameterized in the usual sense. That is, if we were to fit the entire equation to any of our data sets it clearly would find many of the coefficients to be redundant and therefore not significant. However, each of the coefficients must be fitted in order to maintain the structure of the model. Without this structure, the predicted growth rates that follow simulated partial harvesting or thinning would misrepresent the response of the trees.

This problem is solved by fitting the model in stages. First, the coefficients for the potential growth, the c_i's in equations 5 and 6, are estimated while fixing the competition coefficients, the d_i's, at the values reported previously. Since we are interested in fitting the potential growth of the trees (equation 2) in the absence of competition, we select a subset of the trees where there is little or no crown competition and with sufficient crown. Second, the crown adjustments (equation 3) are fitted to the entire data set to adjust the potential down for trees with small crowns and up for trees with very large crowns. Finally, the competition coefficients (equation 4) are computed from the entire data set with the potential coefficients fixed.

Under-parameterizing a model could have some serious side effects. The overall model could fit but the components could be confounded so that the model would not accurately predict the differences due to changes in competition. In that case, using CACTOS to evaluate the effects of alternative thinning trials could lead to misleading conclusions about the desirability of the cultural practices evaluated.

ANALYSIS

Previous estimates of the coefficients for estimating height and DBH growth are given for the STEM data by Wensel and Koehler (1985) and for the combined STEM and $PERM_0$ data by Wensel, Meerschaert, and Biging (1987) . As shown in Figure 1, these estimates produced underestimates of the observed growth rates or the observed difference between the two measurements of the permanent plots. This is in general agreement with other reports received by CACTOS users.

The new coefficients, developed by nonlinear regression using the previous values as starting points, are shown in Tables 3 and 4 for height and DBH^2 growth, respectively. Only the data from regions 1, 2, and 3 were used in this analysis as the model was unstable for region 4[1]. The growth relationships for region 4 will be considered in a separate study with an expanded data base.

The growth estimates derived from these revised coefficients appear to be unbiased but with more variation than that encountered when using the coefficients from the backdated initial measurement data. The new model statistics are summarized in Appendix tables A1 and A2. Regional adjustments for the growth rates computed using the revised coefficients are given in Tables 5 and 6 for height and DBH^2 growth, respectively.

[1] The growth rates for Region 4 appeared to be different enough from the other regions that the data were held aside for a separate analysis. Additional samples will be collected for this analysis.

Table 3. Revised Coefficients for Height Growth Model

Coefficient	PP	SP	IC	DF	WF	RF
c_0	0.30475	0.30475	0.20432	0.27076	0.27443	0.27443
c_1	0.28170	0.28170	0.48943	0.30046	0.31810	0.31810
c_2	0.94786	0.94786	0.88692	0.94904	0.94757	0.94757
c_3	0.54992	0.54992	0.54992	0.54992	0.54992	0.54992
d_0	0.76370	0.98431	4.0	1.53401	1.53592	4.0
d_1	3.28585	2.26250	1.0	1.0	1.0	1.0
d_2	1.27950	3.20291	20.000	9.75154	8.20475	20.000
d_3	–0.55080	–0.59041	–0.70324	0.0	–0.25402	–0.56146
d_4	0.10562	0.18682	0.16483	1.0	1.20104	1.56660
d_5	0.03335	0.0	0.0	0.0	0.0	0.0

Table 4. Revised Coefficients for Diameter-squared Growth Model.

Coefficient	PP	SP	IC	DF	WF	RF
c_0	0.0522513	0.04808	0.04831	0.07181	0.22682	0.21689
c_1	0.0300	– 0.08063	0.0300	0.07856	0.21230	0.21230
c_2	0.95	0.95	0.95	0.95	0.95	0.95
c_3	0.02027	–0.04024	0.01027	0.07793	0.27990	0.27990
d_0	1.89658	1.49303	1.83549	2.96988	1.37157	2.60000
d_1	3.48315	2.79942	1.54834	11.87146	1.13672	1.09156
d_2	1.71132	1.37713	4.04275	1.01335	6.33080	8.50000
d_3	–0.89686	–0.405455	–0.6093	–0.5770	–1.3907	–1.56166
d_4	0.60626	0.875528	0.4112	0.7961	1.0394	1.73935
d_5	1.05966	0.0000	0.0000	0.0000	0.0000	0.66029

Table 5. Regional proportional adjustments for revised height growth estimates (with numbers of trees in $PERM_1$ for each shown in Table 6).

Region no.	PP	SP	IC	DF	WF	RF
1	1.16	1.13	1.28	1.09	1.19	0.71
2	.92	.92	.64	.91	1.01	1.06
3	.87	.83	.50	1.09	0.92	1.20
4	.86	.73	.68	1.05	0.84	.82

Table 6. Regional proportional adjustments for revised diameter growth estimates (with numbers of trees in $PERM_1$ for each).

Region no.	PP	SP	IC	DF	WF	RF*
1	1.04 (375)	1.02 (125)	1.05 (448)	1.06 (96)	1.01 (530)	0.99 (97)
2	1.03 (724)	1.08 (170)	0.95 (335)	1.08 (186)	0.99 (785)	1.11 (141)
3	0.78 (162)	1.04 (52)	0.75 (37)	0.90 (303)	0.97 (149)	0.87 (33)
4	0.90 (66)	0.87 (21)	0.71 (16)	0.80 (58)	0.63 (68)	0.61 (6)

* The data for red fir was not split due to the small number of observations.

DISCUSSION

It is not particularly surprising that the previous coefficients lead to growth estimates that differ from those observed by remeasuring the permanent plots. Differences can be expected because of the different data acquisition procedures used, differences in the analysis procedures, and differences in the growth periods studied. However, the magnitudes of the differences are unexpected. Certainly they suggest that it will take another measurement of the permanent plots to more accurately estimate long-term average tree growth rates. More detailed discussion of the results follow.

Height growth

The initial models of height growth and the crown models are based upon the STEM data set as no height growth data were available from the initial measurement of the permanent plots. The initial estimates were reported by Wensel and Koehler (1985) and revised from a re-analysis with revised crown models by Wensel, Meerschaert, and Biging (1987). However, $PERM_1$ represents the first opportunity to test the previous height growth model. Even with a cursory analysis it was clear that the previous model was significantly under-estimating total height growth. As a result, new model coefficients were estimated for each of the 6 species using the previous coefficients as starting points in the nonlinear analysis. The new model provides an unbiased estimate of height growth based upon the measured height growth of a larger and more widely distributed sample of trees.

Diameter growth

The diameter-squared estimates from the $PERM_0$ data set were based upon a "back dating" of the current tree sizes on the basis of DBH increments from increment cores (Wensel and Koehler, 1985). Failure of the earlier coefficients to fit could be a result of actual differences in the growth rates for the periods or the way in which the data were developed. For $PERM_1$, no backdating was necessary because the trees were actually measured at the beginning and end of the growth period.

The $PERM_1$ data for all 4 regions were used to compute the regional proportional adjustments given above. The small sample sizes in some regions suggest that these adjustments must be used with care. In fact, we suggest that serious users of CACTOS develop adjustments for their own properties based upon a comparison of actual and predicted growth rates for each species.

IN CONCLUSION

Sampling error is inherent in any forest sampling procedure. These errors are exacerbated by the relatively short remeasurement periods (nominally 5 years but varying from 4 to 6 years). Also, we have two different techniques for estimating tree growth for the two different growth periods. It will take further study to determine which is the better indicator of long-term average growth rates.

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APPENDIX TABLE A1. Number of observations, mean squared error, standard error, mean increment, and mean residual values for height growth potential and competition model verification and model validation by species.

	Species					
	PP	SP	IC	DF	WF	RF
Verification & Fitting ($PERM_{1a}$)						
Potential						
Number of observations	174	347+	*	320	141	**
MSE	9.62	15.50	*	19.86	15.60	**
Standard error	3.10	3.94	*	4.46	3.95	**
Competition						
Number of observations	1261	347	820	585	1464	271
MSE	21.37	15.63	17.97	23.89	16.54	15.00
Standard error	4.62	3.95	4.24	4.89	4.07	3.87
Mean HT increment	5.49	5.32	3.66	5.64	5.70	4.83
Mean Residual	-0.006	.046	0.130	0.182	-0.001	1.353
Validation ($PERM_{1b}$)						
Number of observations	1178	373	841	791	1748	***
Mean HT increment	4.50	5.56	3.56	4.95	5.22	***
Mean Residual	-1.02	0.17	-0.02	-0.48	-0.30	***

* Old model coefficients used
** White fir model coefficients used
*** All RF trees are in $PERM_{1a}$ with no trees left for the validation data set.
\+ Number of observations used in SP Potential Adjustment, PP Potential model used.

APPENDIX TABLE A2. Number of observations, mean squared error, standard error, mean increment, and mean residual values for diameter growth potential and competition model verification and model validation by species.

	Species					
	PP	SP	IC	DF	WF	RF
Verification & Fitting ($PERM_{1a}$)						
Potential						
Number of observations	549	140+	820	215	582	271
MSE	424.2	1074.9	315.5	588.1	551.7	569.6
Standard error	20.6	32.8	17.8	24.3	23.5	23.9
Competition						
Number of observations	1261	743	*	*	1464	271
MSE	313.4	534.1	*	*	373.6	553.2
Standard error	17.7	23.1	*	*	19.3	23.5
Mean DBH increment	NA	NA	*	*	5.8	6.5
Mean Residual	-0.06	1.21	0.94	1.07	0.49	0.44
Validation ($PERM_{1b}$)						
Number of observations	1178	**	839	791	1748	**
Mean DBH increment	4.8	**	4.7	5.4	5.4	**
Mean Residual	-1.05	**	.54	-1.21	1.05	**

* Old model coefficients used

** All SP and RF trees are in $PERM_{1a}$

\+ Number of observations for adjustment of potential function; potential from the previous SP model was used.