RESEARCH PAPER 46 OCTOBER 1982

MAXIMUM CROWN-WIDTH EQUATIONS FOR SOUTHWESTERN OREGON TREE SPECIES

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CONTENTS

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Acknowledgment

This research was partially funded by the Pacific Northwest Forest and Range Experiment Station under a cooperative agreement with the Renewable Resources Evaluation Project (Agreement Number PNW-80-275).

ABBREVIATIONS:

CCF	crown competition factor
MCA	maximum crown area
MCW	maximum crown width
D	diameter breast height
MS	miles south
ME	miles east

INTRODUCTION

Density is a stand characteristic of considerable concern to forest managers and silviculturists because it is directly related to crowding or competition. Stands of high-level density (i.e., over-crowded stands) have reduced diameter growth and thus produce smaller, less valuable trees. However, stands of low-level density may not fully occupy the land; therefore total wood production is reduced.

One measure of stand density that has been applied successfully to predict growth of several tree species is the crown competition factor (CCF) (Krajieck et al. 1961; Vezina 1962, 1963; Alexander 1966, 1971; Dahms 1966; Smith 1966; Arney 1973). CCF was developed by Krajieck et al. (1961) to estimate the area utilized by all trees in a stand in relation to the maximum crown area (MCA) they would use if they were open grown. Thus CCF is defined as the sum of the MCA values for all trees in a stand, divided by the area in acres.

Because a stand-grown tree never reaches maximum crown development, maximum crown width (MCW) of a completely open-grown tree is predicted indirectly by regression, using diameter breast height (D) and perhaps other characteristics. Maximum crown area can then be expressed as a percentage of an acre:

$$MCA_i = 100 \frac{0.7854 \ (MCW_i)^2}{43,560} = 0.001803(MCW_i)^2,$$

where

MCA_i = maximum crown area for the *ith* tree,

MCW_i = maximum crown width for the *ith* tree,

and CCF is computed by

$$CCF = \frac{1}{A} \sum_{i=1}^{n} MCA_i,$$

where

A = area in acres,
n = number of trees on the area.

A CCF value of 100 indicates full occupancy of a site by tree crowns without crowding--provided that the spacing is uniform. A CCF below 100 indicates less than full occupancy, and a value above 100 indicates crowding.

In a careful examination of various measures of density, CCF was found to be the best in the most recent tree diameter-growth models of PROGNOSIS.[1] PROGNOSIS was created to predict the development of the even- and uneven-aged stands of mixed conifer species in Idaho and Montana (Stage 1973, Monserud 1978). It is currently being adapted to stands of mixed conifer species in southwest Oregon; therefore, the objective of this study was to develop MCW equations for computing CCF for the tree species in mixed conifer stands of that area.

[1]Albert R. Stage, Symposium on Growth and Yield Models, May 12, 1980, Bend, Oregon.

PREVIOUS STUDIES

Smith (1966) studied the relationship of MCW to D of open-grown Douglas-fir and found that the ratio decreased rapidly toward the upper altitudinal limit of the species in the Cascade Mountains of British Columbia. He observed (p. 2311), "Major variations which are likely to be genetic in origin can be seen easily in open grown trees. In Douglas fir, especially, the variation from tree to tree within provenances is very great. Among 154 open-grown Douglas fir near Haney, B.C., there is as much variation in CW/D [i.e. MCW/D] of individual trees as between extremes of lowland and mountain provenances."

The most common form used to model MCW has been

$$MCW = a_0 + a_1D.$$

However, Arney (1973) found that the model

$$MCW = a_0 + a_1D + a_2D^2 \qquad [1]$$

was a significantly better predictor for Douglas-fir in both northwest Oregon and southwest British Columbia[2]. Arney, finding no significant differences between the two data sources, combined them into one set. He included age, height, and site index in his original model, but none of these variables were found to be significant. Combining the two data sets is questionable. First, the residuals were not checked for normality or homogeneity before testing for significant differences in the parameter estimates. Smith (1966, p. 2310) states that, "Variance increases with DBH [D] but percentage differences will remain relatively constant for the regression of CW on D [MCW/D]." A close examination of the scatter diagrams of MCW on D of others (Krajicek et al. 1961; Vezina 1962, 1963) further substantiates this statement. Second, site index values for stands

[2]Smith (1966) also reported findings indicating a curvilinear trend over D for several species. However, all MCW equations he presented used the simple linear relationship.

under 20-30 years old may be in considerable error (Curtis et al. 1974); thus differences may have been nonsignificant due to problems of obtaining accurate data (B.C. stands averaged 12.3 years at breast height; Oregon stands 16.7 years).

None of the research on CCF reviewed here indicates that residuals were checked for normality or homogeneity of variance. Because variance increases with an increase in D, appropriate transformations or weighted regression must be used.

DATA COLLECTION

Data were collected on 1,056 open-grown trees representing 16 species found from the North Umpqua River Basin south to the California border between the crests of the Cascade Mountains and the Coast Range (Table 1). D was measured to the nearest 0.1 inch with a diameter tape, and crown diameters were measured to the nearest 0.5 foot with a logger's tape. The widest crown diameter and that at a 90-degree angle to the widest diameter were recorded for each tree. For out-of-round crowns, the geometric mean was used to develop the MCW equations. Criteria for selecting individual trees were:

A crown presently free of surrounding crown competition; no indication of past competition (stumps, etc.).

Limbs extending to the ground or nearly to the ground.

Lowest limbs as long or longer than limbs above.

No forking in the lower 75 percent of the bole.

No evidence of pruning, disease, or other damage.

TABLE I.

NUMBER OF OBSERVATIONS OF SPECIES BY RANGE IN D AND GEOGRAPHIC RANGE FROM A REFERENCE POINT 60 MILES WEST OF THE WILLAMETTE MERIDIAN ON THE WILLAMETTE BASE.

Species	Number of observations	Range: D (in.)	Range: Miles south	Range: Miles east
California black oak	42	1.1 - 59.9	149 - 223	12 - 72
Chinkapin	57	0.5 - 19.5	191 - 228	14 - 83
Douglas-fir	206	0.2 - 56.7	148 - 238	11 - 80
Incense-cedar	111	0.5 - 44.8	148 - 238	14 - 83
Jeffrey pine	16	1.3 - 30.1	191 - 224	25 - 42
Madrone	49	1.2 - 38.2	149 - 237	15 - 57
Noble fir	34	0.3 - 37.0	147 - 149	77 - 78
Oregon white oak	75	0.6 - 37.3	149 - 229	16 - 72
Ponderosa pine	155	0.3 - 48.2	149 - 237	16 - 80
Red fir	9	1.4 - 19.8	238	58
Sugar pine	33	1.7 - 54.8	191 - 227	11 - 80
Tanoak	38	0.5 - 17.6	194 - 230	15 - 35
Western hemlock	62	0.6 - 23.8	147 - 198	36 - 81
Western white pine	51	0.6 - 36.8	149 - 219	15 - 80
White and grand fir[a]	118	0.2 - 33.2	148 - 238	15 - 82
Total	1,056			

[a]Because white fir and grand fir hybridize in southwestern Oregon, these species were combined in the analysis.

Because open-grown trees meeting these criteria were hard to find, they were not selected through a sampling design. Instead, all qualifying trees were located by surveying the vegetation from roads within the boundaries of the study area. Each measured tree was located on a map, and the Section, Township, and Range were recorded to ensure that the trees were well distributed throughout the study area and that the same tree was not measured twice by different crews. Not all species were found over the entire study area.

As the data were collected from north to south, the ratio of MCW to D appeared to decrease for some species; therefore miles south (MS) and miles east (ME) from a reference point were added to the data for each tree for later analysis.

The reference point was established 60 miles west of the Willamette Meridian on the Willamette Base to avoid negative numbers for trees in the western ranges. Perfect Townships were assumed. Each tree location was recorded as MS and ME from the northwest corner of the section with the following algorithms:

Miles south

If in Sections 1- 6, then MS = 6(TS#-1) + 0
If in Sections 7-12, then MS = 6(TS#-1) + 1
If in Sections 13-18, then MS = 6(TS#-1) + 2
If in Sections 19-24, then MS = 6(TS#-1) + 3
If in Sections 25-30, then MS = 6(TS#-1) + 4
If in Sections 31-36, then MS = 6(TS#-1) + 5

Miles east

Ranges east of primary meridian
If in Sections 6, 7,18,19,30,31, then ME = 60 + 6(RE#-1) + 0
If in Sections 5, 8,17,20,29,32, then ME = 60 + 6(RE#-1) + 1
If in Sections 4, 9,16,21,28,33, then ME = 60 + 6(RE#-1) + 2
If in Sections 3,10,15,22,27,34, then ME = 60 + 6(RE#-1) + 3
If in Sections 2,11,14,23,26,35, then ME = 60 + 6(RE#-1) + 4
If in Sections 1,12,13,24,25,36, then ME = 60 + 6(RE#-1) + 5

Ranges west of primary meridian
If in Sections 1,12,13,24,25,36, then ME = 60 - 6(RW#-1) + 1
If in Sections 2,11,14,23,26,35, then ME = 60 - 6(RW#-1) + 2
If in Sections 3,10,15,22,27,34, then ME = 60 - 6(RW#-1) + 3
If in Sections 4, 9,16,21,28,33, then ME = 60 - 6(RW#-1) + 4
If in Sections 5, 8,17,20,29,32, then ME = 60 - 6(RW#-1) + 5
If in Sections 6, 7,18,19,30,31, then ME = 60 - 6(RW#-1) + 6

where

MS = Miles south
ME = Miles east
TS# = Township south number
RE# = Range east number
RW# = Range west number

DATA ANALYSIS

The first step of the analysis was to plot MCW over D for each species. An examination of the plots indicated either a linear or slight curvilinear trend over D, reconfirming the earlier findings of Krajicek et al. (1961), Vezina (1962, 1963), Smith (1966), and Arney (1973). Therefore, Model [1] was used as the basic model form to characterize crown width as a function of D. To test whether geographic position was significantly correlated to MCW, each parameter in Model [1] was related to MS and ME:

$$a_i = b_{1,i} + b_{2,i}\,MS + b_{3,i}\,MS^2 + b_{4,i}\,ME + b_{5,i}\,ME^2; \quad i = 0,1,2. \qquad [2]$$

The resultant "full" model consists of 15 parameters. If geographic position is not correlated to MCW, only $b_{1,0}$, $b_{1,1}$ and, possibly, $b_{1,2}$ should be significantly different from zero.

The plots of MCW over D also indicated that the residuals of each data set would probably not be homogeneous across D.

It was therefore necessary to use weighted regression to develop efficient estimators of the parameters and their variances. The general form of the weight used in this analysis was

$$\text{Weight} = D^{-w} \qquad [3]$$

Because earlier studies had not determined an appropriate value for w, it was estimated for each species.

All combinations from each data set were screened to pick the combination of independent variables that minimized the mean square residual. For the first screening, initial values for w were surmised from plots of the data. The number of independent variables in each of the initial equations represented the maximum number to be included in the final equations. All combinations resulting in fewer independent variables were then examined, and the most promising combinations (i.e., those with the smallest mean square residual for each number of independent variables) were selected for further study. Of promising equations, the one with the lowest mean square residual was used in sequential procedures described by Hann and McKinney (1975) to determine the exact value for w. If the final value of w differed markedly from the initial value, then a second all-combinations screening was made, and promising combinations were again selected for analysis.

The most promising combinations were examined for possible erratic equation behavior over the full range of the independent variables to which the final equations would be applied. The objective was to find, for each species, the equations that both minimized the mean square residual and behaved in a rational manner. After these equations were identified, residuals were examined for normality with standard skewness and kurtosis statistics (Snedecor and Cochran 1980). If normality could be confirmed, the significance of each parameter was tested with Student's t-test (Snedecor and Cochran 1980). Only parameters that were significant at approximately the 5 percent level were included in the final equations.

RESULTS

Specific parameter estimates for the equations of Model [1] that predict MCW as a function of D alone are given in Table 2 with the adjusted coefficient of determination ($\overline{R^2}$) (Draper and Smith 1981), the mean square weighted residual, and, if applicable, the value of D where MCW peaks. The Model [1] equations should not be applied to D values larger than the quantities given in Table 2. Six of the equations are curvilinear and nine are linear. Both Douglas-fir and ponderosa pine are curvilinear, confirming earlier findings of Smith (1966) and Arney (1973).

TABLE 2.
PARAMETER ESTIMATES AND CORRESPONDING STATISTICS FOR MODEL [1].

Species	a_0	a_1	a_2
California black oak	3.3625	2.0303	-7.3307E-3
Chinkapin	2.9794	1.5512	-1.4161E-2
Douglas-fir	4.6366	1.6078	-9.6250E-3
Incense-cedar	3.2837	1.2031	-7.1858E-3
Jeffrey pine	5.3030	0.9293	0.0
Madrone	3.4299	1.3532	0.0
Noble fir	3.6883	0.8627	0.0
Oregon white oak	3.0786	1.9242	0.0
Ponderosa pine	3.4835	1.3430	-8.2544E-3
Red fir	3.0884	0.7871	0.0
Sugar pine	4.6601	1.0702	0.0
Tanoak	4.4443	1.7040	0.0
Western hemlock	4.5652	1.4147	0.0
Western white pine	3.2095	1.2633	-8.2873E-3
White and grand fir	6.1880	1.0069	0.0

In 11 of the 15 data sets analyzed, the mean square weighted residual was significantly reduced when geographic variables MS and ME were introduced. Parameter estimates for the equations of Model [2] for these species are in Table 3. Table 4 contains the adjusted coefficient of determination, the mean square weighted residual for each equation, and the recommended maximum range for each independent variable. The equations of Model [2] should be applied only to data sets falling entirely within these ranges, otherwise the parameters for Model [1] shown in Table 2 should be used for an entire data set.

$\overline{R}^2$	Mean square residual	D where MCW peaks (in.)
0.9683	4.2900	138.5
.9549	1.4359	54.8
.9557	2.3407	83.5
.9532	1.0772	83.7
.9529	0.4824	-
.9276	7.2380	-
.9460	0.8119	-
.9633	1.4082	-
.9325	2.8634	81.3
.9498	0.7451	-
.9668	1.2014	-
.9014	0.7272	-
.9730	0.9878	-
.9475	4.6245	76.2
.9016	5.3353	-

TABLE 3.
PARAMETER ESTIMATES FOR a_0, a_1, AND a_2 IN MODEL [2], WHICH INCLUDES GEOGRAPHIC VARIABLES

	California black oak	Chinkapin	Douglas-fir	Incense-cedar	Madrone
$b_{1,0}$	-0.1609	-5.7185	4.6198	3.2522	3.3445
$b_{2,0}$	0.0	0.0	0.0	0.0	0.0
$b_{3,0}$	0.0	1.3626E-04	0.0	0.0	0.0
$b_{4,0}$	1.9356E-01	1.7348E-01	0.0	0.0	0.0
$b_{5,0}$	-2.6597E-03	-1.6957E-03	0.0	0.0	0.0
$b_{1,1}$	2.1872	1.5389	5.5125	0.6925	1.7963
$b_{2,1}$	0.0	0.0	-3.9303E-02	2.5772E-03	0.0
$b_{3,1}$	0.0	0.0	9.8015E-05	0.0	-1.1347E-05
$b_{4,1}$	0.0	0.0	0.0	0.0	0.0
$b_{5,1}$	0.0	0.0	0.0	0.0	0.0
$b_{1,2}$	0.0	0.0	-1.1311E-02	0.0	0.0
$b_{2,2}$	0.0	-1.1375E-04	0.0	0.0	0.0
$b_{3,2}$	-4.6702E-07	0.0	0.0	-1.8147E-07	0.0
$b_{4,2}$	0.0	2.1891E-04	0.0	0.0	0.0
$b_{5,2}$	0.0	0.0	0.0	0.0	0.0

Oregon white oak	Ponderosa pine	Sugar pine	Tanoak	Western hemlock	White and grand fir
.2676	5.4596	0.2838	-2.0270	4.5207	3.0701
.0	0.0	0.0	1.2356E-04	0.0	2.2726E-02
.5104E-05	0.0	1.0404E-04	0.0	0.0	0.0
.0	0.0	0.0	0.0	0.0	0.0
.0	-3.6578E-04	0.0	0.0	0.0	-3.7834E-04
.1672	4.1307	1.0738	1.8660	1.7023	4.5993
.9041E-03	-2.8296E-02	0.0	0.0	0.0	-3.3843E-02
.0	6.8306E-05	0.0	0.0	0.0	7.8739E-05
.0	0.0	0.0	0.0	-4.0268E-03	0.0
.0	0.0	0.0	0.0	0.0	0.0
.0	-5.9502E-03	0.0	0.0	0.0	0.0
.0	0.0	0.0	0.0	0.0	0.0
.0	0.0	0.0	0.0	0.0	0.0
.0	0.0	0.0	0.0	0.0	0.0
.0	0.0	0.0	0.0	0.0	0.0

TABLE 4.

ADJUSTED COEFFICIENT OF DETERMINATION, MEAN SQUARE RESIDUAL, AND MAXIMUM RANGE FOR MODEL [2].

Species	$\overline{R}^2$	Mean square residual	Maximum range D(in.)	Maximum range Miles south	Maximum range Miles east
California black oak	0.9706	3.9751	0-37.5	140-250	10-70
Chinkapin	.9670	1.0489	0-30.0	180-250	10-90
Douglas-fir	.9608	2.0739	0-69.5	140-250	0-90
Incense-cedar	.9546	1.0459	0-58.9	140-250	0-90
Madrone	.9387	6.1265	0-100.0	140-250	0-90
Oregon white oak	.9712	1.1045	0-100.0	140-250	0-90
Ponderosa pine	.9499	2.1256	0-100.0	140-250	0-90
Sugar pine	.9715	1.0287	0-100.0	140-250	0-90
Tanoak	.9250	0.5532	0-100.0	140-250	0-90
Western hemlock	.9749	0.9180	0-100.0	140-250	0-90
White and grand fir	.9228	4.1858	0-100.0	140-250	0-90

Table 5 gives weighting parameters for the equations of Model [3] and the skewness and kurtosis statistics for each final equation. When species have two MCW equations, skewness and kurtosis statistics apply to the equation with variables for geographic position. The statistics were tested for conformance to normality with the Bowman and Shenton (1975) and Shenton and Bowman (1977) tests. With the exception of data for chinkapin, all data sets failed to show a significant difference from normality at the 5 percent level. Because weighted residuals for chinkapin were leptokurtic, and thus might cause the associated t-tests to be conservative (i.e., to indicate nonsignificant difference when the difference was significant), the significance level for chinkapin t-tests were set at 10 percent rather than 5

TABLE 5.

WEIGHTING PARAMETER ESTIMATES FOR MODEL [3] AND SKEWNESS AND KURTOSIS STATISTICS FOR THE FINAL MCW EQUATIONS OF MODEL [3].

Species	w	Skewness[a]	Kurtosis[a]
California black oak	1.2718	0.2177	-0.0242
Chinkapin	1.1520	.6021	3.6747
Douglas-fir	1.0443	.3575	0.1608
Incense cedar	1.2470	.2240	0.0299
Jeffrey pine	1.1602	.1333	-0.1835
Madrone	0.9498	.5056	0.3016
Noble fir	1.0676	.7047	0.0388
Oregon white oak	1.9934	.0671	-0.1063
Ponderosa pine	0.7995	.1356	0.6374
Red fir	1.0	.3576	-1.1131
Sugar pine	1.4077	.0372	1.0053
Tanoak	2.2158	.6244	0.9119
Western hemlock	1.2440	.4811	0.1085
Western white pine	0.2362	.2383	0.7890
White and grand fir	0.4147	.3698	0.4037

[a]Skewness = $k_3/k_2^{3/2}$

Kurtosis = k_4/k_2^2

where
k_i = the ith cumulant.

percent. However, the only parameter in the chinkapin equation that was significantly different at the 10 percent level was a_2 of Model [1].

DISCUSSION

The change in MCW with geographic position ranges widely. As MS increases, MCW increases for incense cedar, sugar pine, tanoak, chinkapin with D $\leq$20.8 inches, Oregon white oak with D<2.6 inches, and white and grand fir with D$\leq$1.9 inches; but decreases for California black oak, madrone, chinkapin with D $\geq$24.5 inches, and Oregon white oak with D $\geq$4.7 inches. MCW first decreases, then increases for Douglas-fir, ponderosa pine, chinkapin with D between 20.8 and 24.5 inches, Oregon white oak with D between 2.7 and 4.7 inches, and white and grand fir with D>1.9 inches.

As ME increases, MCW increases for chinkapin with D$\geq$24.5 inches, but decreases for ponderosa pine, western hemlock, and white and grand fir. MCW first increases, then decreases for California black oak and chinkapin with D<24.5 inches.

Why is geographic position significant in predicting MCW? We suspect that the geographic variables are indicators or integrators of more basic factors such as elevation, latitude, and genetic variability (Smith 1966). The minimum value of MCW along MS for Douglas-fir and ponderosa pine occurs in the area dividing the Cow Creek and Umpqua River drainages from the Rogue River drainage; the maximum value of MCW along ME for California black oak and chinkapin with D < 24.5 inches occurs in the valley between the Coast Range and the Cascade Mountains. This suggests that the geographic variables may be surrogates for elevation, but this study was not designed to examine such a factor. We strongly recommend that future studies of MCW collect information on such factors for more thorough analysis.

Although the models incorporating MS and ME may be complex, we believe that equations that include these variables are more completely specified (and therefore potentially less biased) than the general equations resulting from Model [1], and we recommend their use if a stand falls within the range

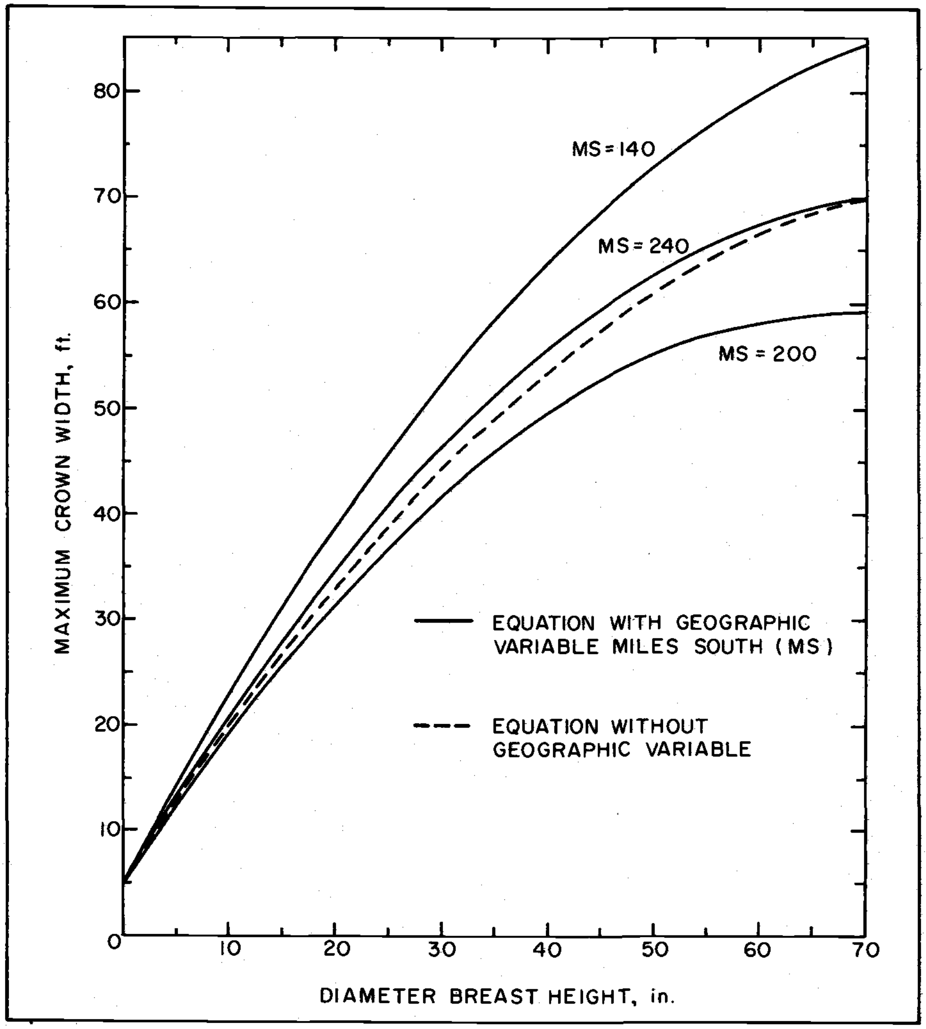

FIGURE 1.
MAXIMUM CROWN WIDTH OF DOUGLAS-FIR PLOTTED FOR TWO MODELS.

of conditions specified in Table 4. A plot of alternative equations for Douglas-fir (Fig. 1) shows that MCW curves for the model incorporating geographic variables change considerably as MS changes, indicating that position has a substantial impact.

Our results also show that weighted regression is required to produce efficient parameter estimates and that, in all species except one, the weighted (or transformed) residuals are normally distributed. The resulting parameter estimators are therefore uniformly minimum variance unbiased estimators, and standard testing procedures are appropriate.

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Key words: Crown competition factor, maximum crown width, mixed conifer stands, prognosis, stand density.

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