Research Paper 50 March 1987

EQUATIONS FOR PREDICTING HEIGHT TO CROWN BASE FOR FOURTEEN TREE SPECIES IN SOUTHWEST OREGON

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Acknowledgments

This study was conducted as part of the Forestry Intensified Research (FIR) Program, a cooperative effort of Oregon State University, the USDA Forest Service, and the USDI Bureau of Land Management. We thank Boise Cascade Corporation and Medford Corporation for their special assistance.

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CONTENTS

ABSTRACT

Equations are presented for predicting height to crown base (or bole ratio) for fourteen species of trees common to the mixed-conifer zone of southwest Oregon. Nonlinear regression was used to fit a weighted logistic function for each species. The independent variables include height, crown competition factor in larger trees, stand basal area, site index, and diameter divided by height. Although a number of alternative model forms were considered, the logistic function was found to fit the data best. Validation of the model indicated possible difficulties with ponderosa pine and golden chinkapin, but these problems are probably due to inconsistencies in the validation data rather than shortcomings in the individual models.

INTRODUCTION

A tree's capacity for growth is largely determined by the quantity of its foliage. This quantity can be characterized by leaf area or foliage weight; but, because these variables are difficult to measure, live absolute crown length or relative crown length (crown ratio) are often used as surrogates in individual-tree growth equations (Stage 1973, Daniels and Burkhart 1975, Krumland 1982, Ritchie and Hann 1985, Wensel and Koehler 1985). In that context, a crown ratio of 1.0 indicates the maximum leaf area or foliage weight attainable for a tree of a given height; a value approaching zero indicates a restricted crown and implies that growth is constrained by the relative lack of foliage. More recently, crown ratio estimates have been used as predictor variables in taper equations (Walters and Hann 1986).

In growth simulations, where projections for a given period are based on stand and tree variables at the beginning of that period, the crown-ratio term in component growth equations must be updated for each successive projection period. If crown change cannot be predicted directly (e.g., Maguire 1986), static equations for predicting height to crown base can be used to simulate this change (Stage 1973, Daniels and Burkhart 1975, Van Deusen and Biging 1985). Change in crown ratio can then be predicted by

$$\Delta CR = [CR \cdot H + \Delta H - \Delta HCB]/[H + \Delta H] - CR$$

where

ΔCR = change in crown ratio
H = total tree height at start of growth period
CR = crown ratio at start of growth period
ΔH = change in tree height
ΔHCB = change in height to crown base (calculated with static crown equations)

Static crown equations can also replace missing crown measurements so that growth simulations can be made from data that lack values for either crown ratio or height to crown base.

The goal of this study was to develop species-specific static equations for predicting height to crown base. These equations are part of an individual-tree, distance-independent (Munro 1974) stand simulator currently being developed for the mixed-conifer region of southwest Oregon. The fourteen species considered in the present analysis are:

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco)
Grand fir (*Abies grandis* [Dougl.] Lindl.)
White fir (*Abies concolor* [Gord. and Glend.] Lindl.)
Ponderosa pine (*Pinus ponderosa* Laws.)
Sugar pine (*Pinus lambertiana* Dougl.)
Incense-cedar (*Calocedrus decurrens* [Torr.] Florin.)
Western hemlock (*Tsuga heterophylla* [Raf.] Sarg.)
Golden chinkapin (*Castanopsis chrysophylla* [Dougl.] A.DC.)
Tanoak (*Lithocarpus densiflorus* [Hook and Arn.] Rehd.)
Pacific madrone (*Arbutus menziesii* Pursh.)
Canyon live oak (*Quercus chrysolepis* Liebm.)
California black oak (*Quercus kelloggii* Newb.)
Oregon white oak (*Quercus garryana* Dougl.)
Bigleaf maple (*Acer macrophyllum* Pursh.)

DATA

The study area (Figure 1) extends from near the California border (42°00'N) on the south to Cow Creek (43°00'N) on the north and from the Cascade crest (122°15'W) on the east to approximately 15 miles west of Glendale (123°50'W). Elevations range from 900 to 5,100 feet, January mean minimum temperatures from 23 to 32°F, and July mean maximum temperatures from 79 to 90°F. Annual precipitation varies from 29 to 83 inches, less than ten percent of which falls during June, July, and August.

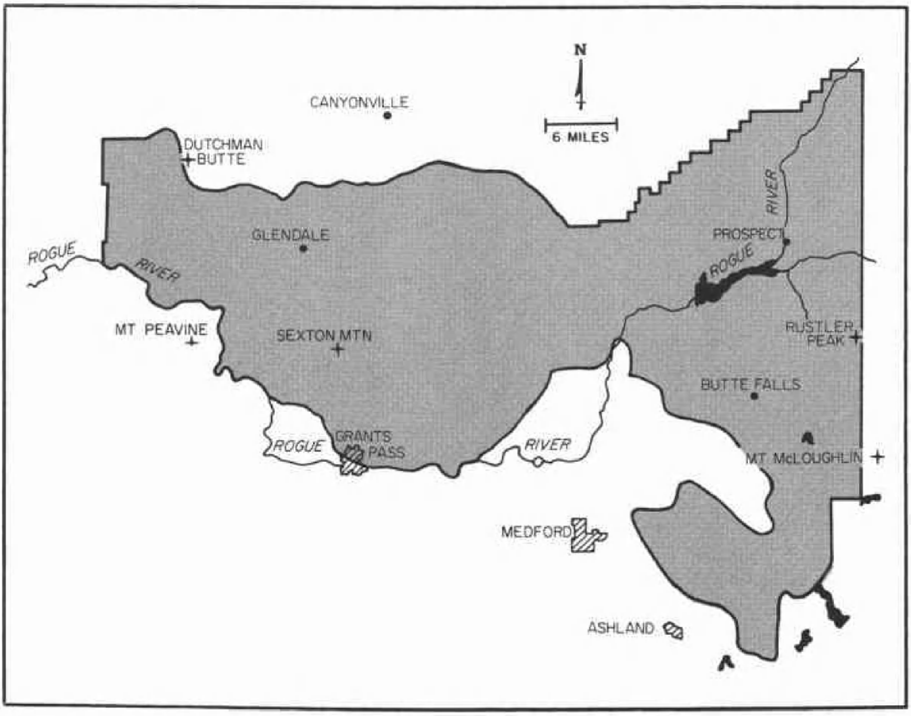

FIGURE 1.

THE STUDY AREA.

Data were collected from 391 stands as part of the Growth and Yield Project conducted by the FIR (Forestry Intensified Research) Program. In each stand, trees were measured on a cluster of variable-radius plots (BAF 20) and nested, fixed-area subplots. Measurements included breast-height diameter (D), total tree height (H), and height to live-crown base (HCB). Height measurements were taken by the tangent method (Curtis and Bruce 1968). Calculations for each plot included site index (SI) (from Hann and Scrivani 1987), crown competition factor (CCF) (from Krajicek *et al.* 1961), and stand basal area (SBA) in square feet per acre. Maximum crown-width values for CCF were estimated from equations by Paine and Hann (1982).

In preparation for analysis, each plot was designated for either modeling or validation. Validation plots were selected to cover a broad range of stand ages, densities (basal area), and site indices. To ensure that crowns had stabilized, 126 of the 391 sampled stands were eliminated from the analysis because they had been thinned within the last 20 years. Of the remaining plots, 237 were used for modeling and 28 for validation.

In the modeling data, breast-height stand age ranged from 13 to 138 years and averaged 56 years; stand basal area ranged from 16 to 400 ft^2/acre and averaged 200 ft^2/acre; and site index ranged from 50 to 140 feet and averaged 90 feet.

In the validation data, breast-height stand age ranged from 18 to 83 years and averaged 57 years; stand basal area ranged from 42 to 300 ft^2/acre and averaged 190 ft^2/acre; and site index ranged from 59 to 130 feet and averaged 90 feet.

A summary, by species, of data for trees taller than breast height (i.e., $H > 4.5$ ft) is presented in Table 1. Only eight species are represented in the validation data; data for the remaining species were insufficient for validation, and were therefore combined with the modeling data to strengthen the data base for those species.

TABLE 1.

SUMMARY, BY SPECIES, OF DATA USED IN DEVELOPING AND VALIDATING A MODEL FOR HEIGHT TO CROWN BASE.

Species	Number of observations	Height (ft) Range	Height (ft) Mean	Diameter (in) Range	Diameter (in) Mean	Crown ratio Range	Crown ratio Mean
				Modeling data			
Douglas-fir	9778	4.5–210.3	74.4	0.1–84.0	12.8	0.006–0.996	0.467
Grand/white fir	1354	4.5–193.3	68.8	0.1–53.2	11.8	0.009–0.997	0.503
Ponderosa pine	959	4.5–192.2	76.1	0.1–55.8	15.2	0.031–0.949	0.441
Sugar pine	223	4.5–170.5	80.1	0.1–60.8	18.7	0.095–0.928	0.474
Incense-cedar	1008	4.5–165.0	30.2	0.1–67.1	7.0	0.024–0.977	0.482
Western hemlock	53	4.6–117.9	42.5	0.1–23.4	7.0	0.016–0.943	0.604
Golden chinkapin	766	4.5–89.2	19.1	0.1–27.6	3.1	0.031–0.957	0.433
Tanoak	337	4.5–65.0	13.5	0.1–13.0	1.6	0.057–0.875	0.450
Pacific madrone	713	4.6–107.5	40.7	0.1–42.1	7.8	0.005–0.958	0.398
Canyon live oak	205	4.7–57.9	17.7	0.1–10.3	3.1	0.071–0.989	0.518
California black oak	250	4.5–111.1	41.3	0.1–43.7	10.7	0.053–0.942	0.377
Oregon white oak	37	5.5–55.8	26.6	0.2–24.5	6.3	0.063–0.655	0.377
Bigleaf maple	47	4.9–91.3	46.8	0.2–20.0	6.9	0.114–0.714	0.356
				Validation data			
Douglas-fir	1084	4.6–198.5	74.6	0.1–70.4	12.4	0.080–0.950	0.478
Grand/white fir	186	4.7–156.8	65.2	0.1–39.6	10.7	0.061–0.977	0.483
Ponderosa pine	142	5.4–181.3	101.6	0.3–59.8	20.1	0.018–0.895	0.451
Sugar pine	33	7.3–118.1	68.1	0.8–30.7	14.3	0.118–0.906	0.511
Incense-cedar	108	4.7–111.8	32.8	0.1–52.6	7.4	0.160–0.896	0.562
Golden chinkapin	105	4.5–70.5	14.9	0.1–14.6	2.1	0.067–0.775	0.355
Tanoak	38	4.5–38.7	12.1	0.1–6.2	1.3	0.115–0.852	0.500
Pacific madrone	96	4.7–95.2	38.3	0.1–25.0	7.3	0.051–0.941	0.366

ANALYSIS AND RESULTS

Equation Selection

For this analysis, the first height-to-crown-base equation to be considered was the general equation presented by Wykoff *et al.* (1982), which is a logarithmic equation for crown ratio, fit through ordinary least squares.

$$\ln(CR) = \sum_{i=1}^{k} b_i X_i$$

where

b_i = parameter estimate
X_i = predictor variable
k = maximum number of parameters in the equation.

If this equation is expressed in the nonlinear form

$$HCB = H\,[1.0 - \exp\,(\sum_{i=1}^{k} b_i X_i)], \qquad [1]$$

values of HCB are constrained to be less than H but not necessarily greater than zero. Preliminary analysis with Douglas-fir data indicated that, in the extremes of the data range, this equation may predict HCB to be less than zero.

A similar equation was presented by Van Deusen and Biging (1985):

$$HCB = H\,[1.0 - \exp\text{-}(\sum_{i=1}^{k} b_i X_i)^2] \qquad [2]$$

The following logistic equation (Walters and Hann 1986) also provides the desired constraints on predicted HCB:

$$HCB = H/[1.0 + \exp(\sum_{i=1}^{k} b_i X_i)] \qquad [3]$$

Hatch (1980) found little difference between equations similar to [1] and [3]. We found that [1] and [3] perform comparably, but [3] has several advantages over both [1] and [2]. First, it is better constrained than either, and thus should be a more reliable expression of the true relationships between crown length and the predictor variables; second, preliminary analyses indicated that [3] provided slightly better fits than [2] for five of the seven conifer species; and third, [3] is more easily interpreted than [2] because squaring the expression

$$\sum_{i=1}^{k} b_i X_i$$

in [2] causes difficulty in interpreting the signs on the parameter estimates. For these reasons, equation [3] was selected for the present analysis.

Variable Selection and Weighting

Variables were screened by ordinary least-squares regression applied to a linearization of the weighted equation [3]. These linear regressions also provided starting values for subsequent nonlinear analyses. The variables selected were tree height, crown competition in larger trees (CCFL), natural log of stand basal area, diameter divided by height, and site index.

Plots of residuals about equation [3] indicated that variance in HCB increases as height increases. A weight of $(1.0/H)^2$ was chosen to homogenize this variance. Because applying this weight is equivalent to dividing both sides of equation [3] by H (Neter *et al.* 1983, p. 171–172), all subsequent fits were made using bole ratio (HCB/H) as the dependent variable.

Because analysis of covariance showed no significant difference between the grand-fir and white-fir models, data for these species were combined into a true-fir data set for the final analysis.

Parameter Estimates

The final equations were fitted separately for each species by the use of nonlinear regression:

$$\frac{HCB}{H} = \frac{1.0}{[1.0 + \exp(b_0 + b_1 \cdot H + b_2 \cdot CCFL + b_3 \cdot \ln(SBA) + b_4 \cdot D/H + b_5 \cdot SI]} \quad [4]$$

where
- HCB/H = predicted bole ratio = (1.0 − CR)
- H = total tree height (feet)
- CCFL = stand crown competition factor for trees whose diameter is greater than that of the subject tree (percent)
- ln(SBA) = natural log of stand basal area (ft^2/acre)
- D/H = breast height diameter (inches) divided by height (feet)
- SI = base age 50 site index minus 4.5 (feet).

Parameter estimates and mean squared error (weighted residuals) for all species are presented in Table 2. (Nonsignificant coefficients were set to zero and appear as dashes.) Height to crown base can be determined by multiplying the predicted bole ratio (equation [4]) by the height of the subject tree.

DISCUSSION

Evaluating the Equations

Adjusted R^2 values range from 0.04 for tanoak to 0.63 for Oregon white oak (Table 2). When calculated for height to crown base instead of bole ratio, adjusted R^2 values are much higher (about 0.80 to 0.90 for major conifer species).

Equation [4], with the coefficients presented in Table 2, was applied to the validation data; mean residual bole ratio and standard deviation for eight major species are shown in Table 3. A t–test was used to test for significance of mean residuals. The t–test in model validation is often suspect because a significant score may reflect low variance associated with the model rather than actual significance of the bias (Freese 1960). For this reason, a high level of significance ($\alpha = 0.01$) was chosen for these tests.

Mean bias for Douglas–fir, ponderosa pine, and golden chinkapin was significant at the 99% confidence level, but we feel that this

TABLE 2.

REGRESSION COEFFICIENTS, WEIGHTED MEAN SQUARED ERRORS (MSE), AND ADJUSTED COEFFICIENTS OF DETERMINATION ($\bar{R}^2$) FOR HEIGHT-TO-CROWN-BASE MODELS, BY SPECIES.

Species	b_0	b_1	b_2	b_3	b_4	b_5	MSE	$\bar{R}^2$
Douglas-fir	2.59959	-0.00725950	-0.00458228	-0.441557	1.61311	0.00467539	0.0181	0.4761
Grand/white fir	2.71071	-0.00366952	-0.00455308	-0.505344	1.72963	0.00472740	0.0239	0.4506
Ponderosa pine	2.34665	-0.00206403	-0.00260411	-0.622085	3.09805	0.00426037	0.0134	0.5897
Sugar pine	3.33895	-0.00430671	-0.00334020	-0.550645	—	—	0.0190	0.3045
Incense-cedar	4.40376	—	-0.00267306	-0.844515	1.08515	—	0.0247	0.5409
Western hemlock	0.791433	—	-0.00255926	—	—	—	0.0415	0.0656
Golden chinkapin	1.65623	—	-0.00240594	-0.355275	1.24983	—	0.0202	0.3558
Tanoak	—	—	-0.00088567	—	—	—	0.0278	0.0359
Pacific madrone	1.98835	-0.00594721	-0.00352276	-0.342935	—	—	0.0169	0.4116
Canyon live oak	2.22352	—	—	-0.426931	—	—	0.0292	0.1104
California black oak	2.65524	—	—	-0.646829	0.728396	—	0.0278	0.1313
Oregon white oak	0.361630	—	-0.00647642	—	—	—	0.0083	0.6290
Bigleaf maple	0.919152	-0.00768402	-0.00618461	—	—	—	0.0133	0.5303

TABLE 3.

VALIDATION OF MODELS FOR HEIGHT TO CROWN BASE OF MAJOR SPECIES.[1]

Species	$\bar{B}$	s	N
Douglas-fir	0.0112 **	0.1280	1084
Grand/white fir	0.0192	0.1757	186
Ponderosa pine	-0.0530 **	0.0969	142
Sugar pine	0.0038	0.1464	33
Incense-cedar	-0.0334	0.1447	108
Golden chinkapin	0.0831 **	0.1774	105
Tanoak	-0.0506	0.1588	38
Pacific madrone	0.0244	0.1939	96

** Significant at $\alpha = 0.01$.

[1] $\bar{B}$ = mean residual bole ratio (observed minus predicted), s = standard deviation of residuals, N = number of observations in the validation data set.

may be misleading. Mean bias and standard deviation for Douglas-fir are not appreciably different from those for other species; the residual is statistically significant mainly because of the large sample size. In the golden chinkapin validation data, almost all trees were less than 10 feet tall, and more than one-third were on one plot whose high elevation and low basal area placed it at the extremes of the data range. Similarly, a high percentage of the trees in the ponderosa pine validation data were on two atypically dense, high-elevation plots. When these questionable plots were removed from the data, mean residuals for ponderosa pine and golden chinkapin were not significant. From these results we conclude that significant mean residuals may be due to abnormalities in the validation data, and that behavior of the model is suspect at the extremes of the modeling data.

For all species except golden chinkapin and tanoak, at least 40% of the bole-ratio predictions were within 0.10 of the true bole ratio, and accuracy was much higher for Douglas-fir and ponderosa pine (Table 4). Furthermore, removal of the questionable plot from the golden chinkapin data substantially increased the accuracy of predictions for that species.

TABLE 4.

PERCENT OF OBSERVATIONS IN THE VALIDATION DATA WITHIN FOUR RANGES OF ABSOLUTE VALUE OF BIAS (|B|).

Species	|B| <0.05	|B| <0.1	|B| <0.2	|B| <0.3
Douglas-fir	33	59	87	97
Grand/white fir	18	44	75	89
Ponderosa pine	33	65	93	99
Sugar pine	27	48	82	94
Incense-cedar	20	47	86	96
Golden chinkapin	21	33	66	83
Tanoak	13	34	79	89
Pacific madrone	27	46	69	82

Projecting Crown Change

Although static equations are not ideal for predicting changes in height to crown base, they offer the only available method because data for developing crown-change equations are lacking. A major problem with this use of static equations is that, in some cases, predicted HCB may decrease in response to stand-density reductions from thinning and mortality. To ensure that HCB will either remain constant or increase over time, we can constrain its value at the end of the growth period to be greater than or equal to HCB at the beginning of the period. This procedure may result in predictions of zero crown recession after thinning until stand density and tree height have increased enough to offset the effects of thinning.

SUMMARY

The signs on the coefficients in equation [4] indicate how bole ratio will respond to changes in the predictor variables. Thus, predicted bole ratios decrease with increasing values of D/H (higher D/H values indicate greater stem taper) and increase with increasing density (CCFL and SBA) and tree height. Of those species for which the site-index coefficient is not zero (*e.g.*, Douglas-fir and ponderosa pine), trees on high sites will tend to have a smaller bole ratio than those on lower sites.

If these equations are used to simulate crown recession, they will be most reliable in stands which are more than 20 years old and which have not been thinned in the past 20 years. With these static equations, crown response to thinning is assumed to be immediate and will be affected not by thinning intensity but rather by residual density of the stand. However, in stands that have been thinned, we can constrain our predictions such that height to crown base is monotonically increasing over time.

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