Tree Height Estimation in Redwood/Douglas-fir Stands in Mendocino County

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Abstract

In this study, height-diameter equations were developed for managed stands of coastal redwood/Douglas-fir stands in Mendocino County. Equations were developed by species to predict tree height as a function of diameter as well as other factors that are known to potentially explain tree height, including site class and live crown ratio. Two equation forms were compared and evaluated. Forest inventory data from Jackson Demonstration State Forest were used to fit the equations. These height-diameter equations will be useful in explaining height-diameter relationships in largely uneven-aged coastal redwood/Douglas-fir stands, and for predicting missing heights in forest inventories.

Key words: generalized height-diameter equations, live crown ratio, site class

Introduction

The objective of this study was to develop height-diameter equations for major tree species in largely uneven-aged managed stands in western Mendocino County. Height was estimated from diameter at breast height (DBH) alone and from DBH in combination with live crown ratio and site class.

Height-diameter equations are used to predict heights from measured diameters. These equations avoid the need for expensive and time-consuming height measurements in forest inventories. In addition to DBH and other variables, height is measured on a sub-sample of trees. These data are used to fit regression equations that predict heights from DBH and potentially other tree and stand variables. These equations are then used to predict the heights of the remaining trees.

Height-diameter equations are often fitted to regional data sets of tree heights and diameters. Such equations provide reasonable predictions in local applications as long as the local data are similar to the larger regional data set used to fit the equations. This study developed height-diameter equations specifically for western Mendocino County. All the data used to fit the equations came from Jackson Demonstration State Forest, a research and demonstration forest managed by the California Department of Forestry and Fire Protection on behalf of the public.

Height-diameter models commonly use only DBH as a predictor variable. Several authors however, have explored the use of additional variables that might influence the height-diameter relationship. Curtis (1967) developed equations including age in addition to DBH. Larsen and Hann (1987) reported that including site index as a predictor variable improved height estimation. Temesgen and von

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Gadow (2004) used measures of stand density and relative tree position. The average height and diameter of the largest trees in the stand, a measure of top height, has been used by Hanus et al. (1999) and Krumland and Wensel (1988).

Methods

Data

Because the objective of this study was to characterize the height-diameter relationship in managed stands, no stands were excluded from the analysis due to management activity. The majority of the data used in this study (*table 1*) were collected on Jackson Demonstration State Forest (JDSF) in western Mendocino County during the 2005 field season. The data include a temporary plot inventory consisting of 4,920 plots located on a 5 chain (330 ft) by 20 chain (1,320 ft) grid across the Forest, and 143 permanent plots located on a 60 chains by 60 chains grid across the Forest. Only the 2005 remeasurement data were used from the permanent plot data set. Data used to fit madrone and western hemlock equations also included additional data from a 1991 JDSF temporary plot inventory, which had the same design as the 2005 temporary plot inventory.

Table 1—*Description of the data used to fit height-diameter equations.*

Species	Trees	Mean DBH (inches)	Std. Dev.	Min	Max	Mean Height (feet)	Std. Dev.	Min	Max
Redwood	2,235	24.0	10.6	5.1	76.3	107.4	36.8	19.0	244.0
Douglas-fir	1,567	23.8	10.5	5.1	61.3	126.8	43.6	24.0	241.0
Grand fir	225	22.1	10.1	5.2	50.2	121.2	42.2	28.0	217.0
Western hemlock	234	14.7	6.2	5.2	39.7	89.6	27.4	32.0	168.0
Tanoak	819	13.3	5.9	5.0	43.3	60.4	18.5	18.0	122.0
Madrone	527	13.4	5.5	5.8	36.2	58.7	15.4	15.0	107.0

The 1991 and 2005 temporary plot inventory consisted of variable radius plots with a concentric 1/100th ac fixed area regeneration plot on the same plot center. The variable radius plots included trees 5.0 in DBH and greater. The continuous forest inventory permanent plots, first installed in 1959, were one-fifth acre circular plots. The minimum DBH measured was 7.0 in. The most common tree species on JDSF include coast redwood, Douglas-fir, grand fir, western hemlock, tanoak and madrone.

Analysis

Two sets of height-diameter equations were developed. The first set of equations estimated height using DBH as the only predictor variable. The second set of equations estimated height as a function of DBH in combination with other tree or stand variables. In addition, two model forms were used. This produced four model forms to be evaluated for each species. The model form that provided the best fit was selected for each height-diameter equation for each species.

The following equations were fitted to the data:

1. $\text{Height} = 4.5 + \exp(a + b\text{DBH}^c)$

2. $\text{Height} = 4.5 + a(1 - \exp(b\text{DBH}^c))$

3. $\text{Height} = 4.5 + \exp(a_0 + a_1\text{ASC} + b\text{DBH}^c)$

4. $\text{Height} = 4.5 + \exp(a_0 + a_1\text{ASC} + a_2\text{LCR} + b\text{DBH}^c)$

Other predictor variables used in addition to DBH included:

Aggregated site class (ASC). ASC was a binary variable in which the value 1 denoted site class II or better, and the value 0 denoted site class III or less productive.

Live crown ratio (LCR). LCR is the percent of the bole of a tree that contains live crown. This measurement consisted of a visual estimate by cruisers. Two sides were averaged in the case of non-uniform crown length.

Temesgen et al. (2007) found equation 1 to be the best equation when using DBH as the only predictor variable. The equation 1 model form was also used by Hanus et al. (1999) and Larsen and Hann (1987). Unlike equation 1, equation 2 is downward concave, with no inflection point. Huang et al. (1992) found equation 2 to give the best results.

Equation parameters were estimated using a nonlinear least squares estimation procedure with the Gauss-Newton estimation method. The STATISTICA software (StatSoft 2011) was used to fit all equations.

Results

Table 2 shows the coefficients and their standard error of estimate in parentheses, root mean squared error (MSE) and coefficient of determination (R^2) for equations 1 and 2. MSE is the square root of the division of the sum of squared residuals by the degrees of freedom. R^2 is the proportion of the variation explained by the regression (regression sum of squares divided by the total sum of squares).

Equations were evaluated for predictive ability using the MSE, R^2, the t-statistic of the coefficients and their confidence intervals. Plots of residuals versus predicted heights indicated no lack of fit.

Table 2—*Regression coefficients and standard errors for equations 1 and 2, by species. The best fit is shown for each species. All parameter estimates were significantly different from zero ($p<0.05$).*

Species	Eq.	Coefficients			MSE	R^2
		a	b	c		
Redwood	1	5.6911	-7.3644	-0.6294	20.1	0.969
		(0.087)	(0.582)	(0.052)		
Douglas-fir	1	5.9429	-6.2041	-0.5531	22.6	0.972
		(0.125)	(0.450)	(0.059)		
Grand fir	1	5.8095	-6.3265	-0.6015	20.9	0.974
		(0.281)	(1.290)	(0.159)		
Western hemlock	2	162.7225	-0.05723	0.9763	16.9	0.968
		(30.625)	(0.010)	(0.152)		
Tanoak	1	4.5343	-6.4926	-1.0345	14.7	0.946
		(0.090)	(1.942)	(0.195)		
Madrone	2	68.9322	-0.1767	0.8723	13.9	0.948
		(5.383)	(0.065)	(0.220)		

Table 3 shows the coefficients and fit statistics for equation 3. Adding aggregated site class as a predictor variable in addition to DBH improved the accuracy of height prediction, for the species shown in *table 3*.

Table 3—*Regression coefficients and standard errors for equation 3, by species. The best fit is shown for each species. All parameter estimates were significantly different from zero ($p<0.05$).*

Species	Coefficients				MSE	R^2
	a_0	a_1	b	c		
Redwood	5.5535	0.0775	-7.7612	-0.6782	19.8	0.970
	(0.075)	(0.008)	(0.657)	(0.053)		
Douglas-fir	5.6268	0.1138	-6.6508	-0.6601	21.6	0.974
	(0.087)	(0.01)	(0.591)	(0.061)		
Grand fir	5.7813	0.0686	-6.1524	-0.5855	20.6	0.975
	(0.294)	(0.026)	(1.203)	(0.158)		
Tanoak	4.597	0.1162	-5.3565	-0.8725	14.3	0.949
	(0.121)	(0.018)	(1.366)	(0.184)		

Table 4 shows the coefficients and fit statistics for equation 4. Adding aggregated site class and live crown ratio as predictor variables in combination with DBH improved the accuracy of height prediction, for the species shown in *table 4*.

Table 4—*Regression coefficients and standard errors for equation 4, by species. The best fit is shown for each species. All parameter estimates were significantly different from zero ($p<0.05$).*

	Coefficients						
Species	a_0	a_1	a_2	**b**	**c**	**MSE**	R^2
Redwood	5.9093	0.0753	-0.0036	-6.812	-0.5656	19.3	0.971
	(0.110)	(0.008)	(0.000)	(0.457)	(0.050)		
Douglas-fir	5.8146	0.111	-0.0027	-6.2817	-0.6101	21.2	0.975
	(0.103)	(0.009)	(0.000)	(0.507)	(0.060)		
Tanoak	4.756	0.0996	-0.0019	-5.0244	-0.7834	13.8	0.951
	(0.153)	(0.019)	(0.001)	(1.124)	(0.174)		

Conclusions

Equations one through four were all found to adequately predict height from DBH alone or in combination with other predictor variables, for the species indicated. Adding aggregated site class and live crown ratio as predictor variables incrementally improved the height predictions. In practice, the choice of which equation to use will depend primarily on ease of use and availability of data for the additional predictor variables.

Additional tree and stand characteristics in combination with DBH can improve height prediction, but the repeated harvest entries that are typical of uneven-aged managed stands have the potential to confound their effect. Some of these additional variables proved to be relatively unaffected by management activity and were therefore useful additional predictor variables in the height-diameter equations. Other variables provided no additional information, presumably because management activity had confounded any possible correlation with height.

Stand characteristics such as basal area and stand density are directly manipulated in harvest entries and were therefore not investigated further. Aggregated site class, a stand characteristic that is arguably relatively unaffected by management activity, proved to be a significant contributor to estimating heights in some species in this study.

Some tree characteristics such as live crown ratio also appeared to be relatively unaffected by harvest activity. Live crown ratio proved to be a useful estimator in addition to DBH for estimating height in some species. Other tree characteristics such as crown class, which can be changed instantly by a harvest entry in a stand, were not significantly correlated with height for any of the species investigated in this study.

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