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Height Growth and Site Index Curves for Douglas-Fir on Dry Sites in the Willamette National Forest

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Abstract

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Equations and curves are presented for estimating height and site index of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on hot, dry sites in the Willamette National Forest in western Oregon. The equations are based on the dissected stems of 27 trees. The curves differ from those previously published for Douglas-fir. Instructions are presented for their use.

Keywords: Increment (height), site index, Douglas-fir, Oregon (Willamette National Forest).

Research Summary

This study provides height growth and site index curves for Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) on hot, dry sites in the Willamette National Forest in western Oregon. Stems of 40 trees were dissected; 27 of the trees were suitable for construction of height growth and site index curves, and they provided 505 observations of height, site, and age.

Smoothed height growth curves developed from these data were compared with published Douglas-fir height growth curves. Because the published curves could not adequately describe height growth patterns of these trees, new height growth and site index curves were constructed.

Four estimating equations for height growth and three for site index were fitted by use of weighted least squares regression, and site index and height were constrained to be equal at index age, 100 years. The equations with the best fit to the data across the ranges of age and site index were chosen as the final models. The resulting curves differ from those previously published for Douglas-fir.

Instructions for using the equations are presented.

Introduction

In the western Cascade Range of Oregon and Washington, height growth and site index curves are available for Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) on mesic, midelevation sites (McArdle and others 1961, King 1966), and on upper slopes near the cool extreme of its range (Curtis and others 1974b). No height growth or site index curves have been available, however, for Douglas-fir near the relatively hot, dry extreme of its range in the western Cascades. Height growth of Douglas-fir is slower initially but is more prolonged on such dry sites than on moister sites (Means 1980), and as a result volume growth follows a similar trend. Thus, available site index curves (for example, McArdle and others 1961, King 1966), yield tables (for example, McArdle and others 1961, Curtis and others 1982), and height growth curves in stand growth simulators (for example, DFSIM by Curtis and others 1981) are not applicable. The objective of this study was to construct height growth and site index equations for Douglas-fir on hot, dry sites in the Willamette National Forest in Oregon.

Curves that reach well beyond 200 years are needed for estimating site index for old stands and for estimating height at advanced ages to evaluate the effects of management of stands for old-growth characteristics.

Several methods have been used in constructing Douglas-fir height growth and site index curves. McArdle and others (1961) built height growth curves from many one-time observations of height and age, fitting a mean guide curve, then making other curves proportional to the guide curve. This technique, however, includes several sources of significant error that can be eliminated by using stem dissection data (Curtis 1964). King (1966) used stem dissection data to construct height growth curves for Douglas-fir with height as the dependent variable and then used these curves to estimate site index. Site index estimating equations, however, should be fit with site index as the dependent variable, and height growth estimating equations should be fit with height as the dependent variable (Curtis and others 1974a). Curtis and others (1974b) built upper-slope Douglas-fir height growth and site index curves in this way. Dahms (1975) built on this basic idea by first fitting, for decadal ages, linear regressions to estimate site index (SI = a0 + a1 HT) and height (HT = b0 + b1 SI), then building age back into the models by defining the slopes of these regressions and the mean height curves in terms of age; Dahms worked with lodgepole pine (*Pinus contorta* Dougl. ex Loud.). Cochran (1979) used Dahms' technique to build curves for Douglas-fir in eastern Oregon and Washington. Monserud (1984) found Dahms' technique suitable as a first step in deriving a site index estimating equation, but inferior to a logistic equation for describing height growth of Douglas-fir in the northern Rocky Mountains. As a final step, Monserud (1984) eliminated highly correlated terms from the site index equation without degrading model fit. The equation forms used for Douglas-fir by the above investigators were examined in this study.

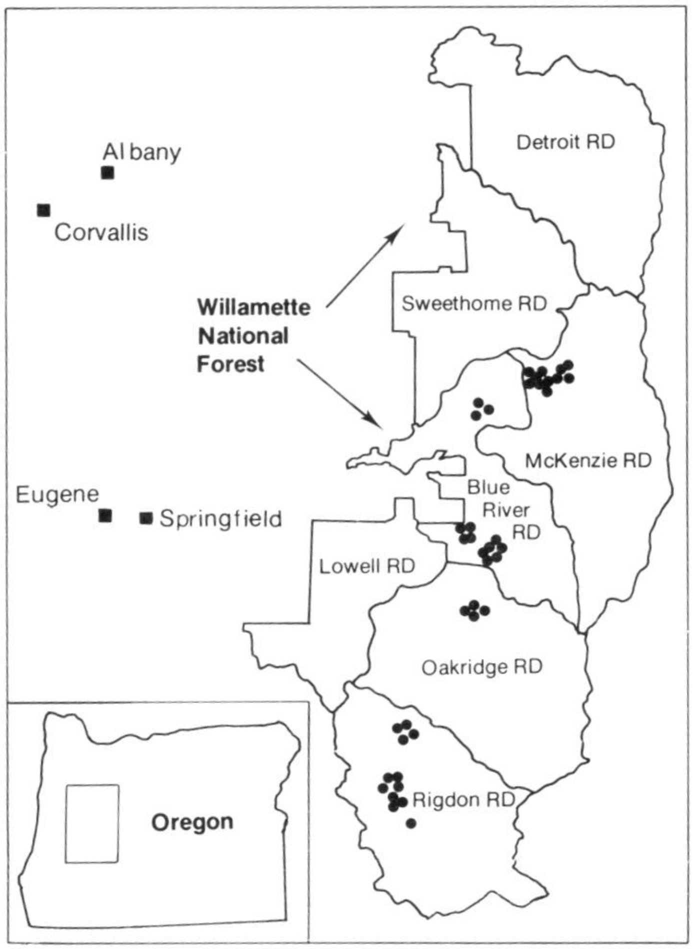

Figure 1.—Locations of sample trees (•) in the Willamette National Forest (RD is Ranger District).

Data Cleaning and Screening

Height versus age was then plotted for each tree. Anomalies such as abrupt changes in height growth rate were often corrected by recounts or counts of new radii on whole sections. A program written in FORTRAN 77, STEM, was used to plot height over age and height growth rate for each tree and to calculate (by linear interpolation) heights at decadal ages for fitting height growth and site index models.

Ten trees showed suppressed height growth early in life or had isolated periods of relatively slow height growth, indicating significant top breakage or suppression. These were excluded from further analysis. Two trees with breast-height age less than 100 were too young to be used for constructing site curves with an index age of 100 and were also excluded. After these trees were rejected, only one 0.1-ha plot remained with two trees. Height growth curves for these trees did not cross, so their decadal heights were averaged and treated as one tree. The height growth curves of two trees were truncated to eliminate height growth anomalies at advanced ages. The analyses thus were based on 27 trees and 505 observations of: height above breast height, site index (height above breast height at 100 years breast-height age), and decadal breast-height age. These trees are summarized by site index class, breast-height age, and topographic position in table 1, and by dry-site plant community in table 2.

Table 2—Distribution of the 27 Douglas-fir trees used in analyses, by plant community for ranges of site index

Plant community 1/	Range of site index (meters above breast height, index age 100)						
	26-30	30.1-34	34.1-38	38.1-42	42.1-46	46.1-50	All site indices
	- - - - - - Number of trees - - - - - -						
Psme/Hodi/grass:							
Asde phase	1						1
Cohe phase	2		1	1			4
Psme/Hodi-Acci	1		1	2	1	2	7
Psme/Beaq/Dispo	1	2	1	1			5
Lide/Whmo				2			2
Lide/Chum		2	1	3	2		8

1/ Plant communities are described by Means (1980). The species codes are: Acci = *Acer circinatum*, Asde = *Aspidotis densa*, Beaq = *Berberis aquifolium*, Chum = *Chimaphila umbellata*, Cohe = *Collomia heterophylla*, Dispo = *Disporum* spp., Hodi = *Holodiscus discolor*, Lide = *Libocedrus decurrens*, Psme = *Pseudotsuga menziesii*, Whmo = *Whipplea modesta*.

Analysis

Examination of Available Curves

Because our data set is small (27 trees) it was important to determine as a first step whether new curves were really needed or whether existing Douglas-fir curves would suffice. Toward this end, we compared our height growth curves, smoothed using Heger's (1968) data summarization method (at site indices of 28, 32, 36, 40, and 44 m), with the height growth curves published by Curtis and others (1974b), Monserud (1984), King (1966), and Cochran (1979). Site indices for these curves were chosen so they would cross our curves at their index ages.

The height growth curves of King (1966), Cochran (1979), and Monserud (1984) were consistently biased compared with ours; they had higher values for height before their index age (50 yr) and lower values past this age. At age 120, discrepancies were 2.5 to 3.5 m for Cochran's, 4 to 6.5 m for King's, and 3 to 7.5 m for Monserud's. These discrepancies consistently increased past age 120, especially for Cochran's (1979) height curves which declined past age 180–an extrapolation past his data that extended to 130 years.

Curtis and others' (1979b) upper-slope Douglas-fir height growth curves are closer to ours in a narrow range of moderate site indices (32-36 m), where errors are all less than 2 m (within the range of our data). At low sites indices, however, our dry-site trees grow more slowly initially and more rapidly at advanced ages than do upper-slope Douglas-firs. At high site indices, conversely, our trees grow more rapidly initially, and more slowly later than do upper-slope Douglas-firs. Errors range from -1.5 to 2.2 m for trees less than 100 years old and from -2.7 to 3.0 m for trees older than 100 years. The dry-site Douglas-fir height growth curves are more polymorphic than the curves for upper-slope Douglas-fir.

Figure 2.—Height growth curves based on Heger's (1968) family of regressions, equation (1)—solid and dashed curves (dashes indicate points beyond the data); and the final height growth model, equation (6)—dotted curves.

Choosing the height growth model.—Four height growth models were examined. The model used by Curtis and others (1974b), rewritten to express height as a function of site and age, is

$$HT = SI/(a + bA^n + cA^n/SI); \quad (2)$$

where a, b, c, n = regression coefficients and A = breast-height age. The model King (1966) used was examined,

$$HT = A^2/(a + bA + cA^2); \quad (3)$$

where a, b, c = functions of SI. The equation used by Beck (1971) is

$$HT = a\,(1 - \exp(bA))^c; \quad (4)$$

where a, b, c = functions of SI and exp(bA) is the base of the natural logarithm to the power bA. The model form used by Monserud (1984) was also fit,

$$HT = a\,SI^b/(1 + \exp(c + d\ \ln A + e\ \ln SI); \quad (5)$$

where a, b, c, d, e = regression coefficients.

When fitting equation (11), we wished to maintain MHT at the same mean site index (MSI = 37.312 m) for all decadal ages. Therefore, when trees dropped out at advanced ages, we estimated MHT from Heger's regressions, equation (7), at SI = MSI. Then MHT was substituted for HT, and MSI (MSI can be considered constant with age since older MHT's were adjusted to it) was substituted for SI in equation (8), which was solved to provide an equation for a:

$$a = MSI - b\ MHT. \tag{12}$$

Substituting equation (11) for MHT in equation (12), then substituting equation (10) for b and the modified equation (12) for a in equation (8), and simplifying, gave a smoothed site index estimating equation of the type used by Dahms (1975):

$$SI = MSI + f_b(A)\ (HT - f_{mht}(A)). \tag{13}$$

This equation was constrained to pass through HT = SI at index age, which eliminated the constant MSI; and new parameters were estimated by least squares to improve its fit.

Height over age curves for each site index model were compared with Heger's curves from equation (7), and plots of the "residuals" (difference) between each model and Heger's curves were examined. Plots of site (predicted, actual, and Heger's) over height and their residuals for alternate decadal ages were also examined. Problems with bias became readily apparent, which facilitated rejection of some models and simplified selection of equation (13) as the final model.

Attempts to reduce the number of coefficients of equation (13), as Monserud (1984) did, markedly reduced the fit, so all fitted coefficients (b-g) were retained. After equation (13) was constrained and simplified it became

$$SI = (b + c\ A + d\ A^{-0.5})\ (HT - 1/(e + f\ A^{g})) + k\ HT + j; \tag{14}$$

where SI, HT, and A are defined as for equations (1) and (2), b = 0.94622, c = -0.00175322, d = 3.6660, e = 0.0168601, f = 2.7676, g = -1.19554, k = -0.137502, and j = 40.470. Site index curves based on this equation are presented in figure 3 and are compared with those based on Heger's regressions, equation (7), in the more familiar inverted form in figure 4.

The final height growth and site index curves are compared in figure 5.

Figure 5.—Comparison of final height growth (solid curves) and site index curves (dashed curves).

Discussion

Comparison With Other Height Growth Curves

The final height growth curves, equation (6), are compared with other height growth curves for Douglas-fir in figure 6. The curves of McArdle and others (1961) for western Washington and Oregon, King (1966) for Washington, Cochran (1979) for eastern Washington and Oregon, and Monserud (1984) for the northern Rocky Mountains all show more rapid height growth at early ages and slower height growth later than do the curves for dry-site Douglas-fir. One important implication is that volume growth in dry-site Douglas-fir stands is initially slower but is more prolonged and maximum mean annual increment occurs later than in the other forest types studied (Means 1980).

Height growth of upper-slope Douglas-fir in the Washington and Oregon Cascade Range (Curtis and others 1974b) is similar to that on dry sites at midsite indices (fig. 6a). At higher site indices, however, height growth on dry sites is initially faster but is slower later in life, whereas at lower site indices it is initially slower but is faster later in life.

Reliability

The reliability of all predicting equations is strongly influenced by the unexplained variation in the data used to build the equations. The variation the final models cannot explain is expressed as the standard error of the estimate (SEE) in figures 7 and 8. Estimates are less reliable when the SEE is greater.

Figure 7.—Standard error of the estimate (uncorrected for the degrees of freedom in the models) for height growth models by decadal age. The solid line is for the final height growth model, equation (6), and the dashed line is for the regressions produced by Heger's (1968) method, equation (1).

Figure 8.—Standard error of the estimate (uncorrected for the degrees of freedom in the models) for site index models by decadal age. The solid line is for the final site index model, equation (14), and the dashed line is for the regressions produced by Heger's (1968) method, equation (7).

How To Use the Equations

The height growth and site index curves differ in form (fig. 5) and recommended use. The height growth equation was fit with height as the dependent variable. It describes the height growth of trees that attain a specified site index at index age and is appropriate for prediction of height and height growth for stands of given site index, as in construction of yield tables and in stand simulators. The site index equation was fit with site index as the dependent variable. It is a more efficient estimator of site index than is the height growth equation (Curtis and others 1974a) and should be used for estimating site index when age and height are known.

Stand Selection

These equations should be applied to stands in the Willamette National Forest in the Ranger Districts sampled (fig. 1). These equations may be more appropriate than other available equations for use in other Ranger Districts or in adjacent areas (for example, southwestern Oregon); this, however, is not certain. The error associated with this sort of extrapolation probably increases with distance from the areas sampled (fig. 1) and cannot be estimated from data at hand.

Stands should be in dry-site Douglas-fir, defined as Douglas-fir or incense-cedar climax and should lack a significant cover (0.1 percent) of western hemlock in any size class. The above comparisons with other curves indicate that the dry-site Douglas-fir curves are not appropriate for other communities.

Tree Selection

Site index estimates should be based on one or two (when possible) healthy dominants or strong codominants on each 0.1-ha (0.25-acre) plot. Boles should be straight and there must be no signs of past top damage. Candidate trees must be increment bored at breast height, and trees showing suppressed radial growth must be rejected. The desired precision of the site index estimate will determine the number of plots to be taken in a stand.

Top breakage and periods of suppression are likely to be common problems on dry sites where understory trees can eventually reach the canopy. When two acceptable trees occur on a plot, their site index estimates should be averaged. Acceptable site index trees are rare in stands with many trees older than about 200 years, so estimating the site index for these stands may be difficult.

Equations for Total Height in Feet

The following equations are in a form probably most useful to most people. The height growth equation, equation (6), in units of feet is,

$$HT = 4.5 + (SI-4.5) / (d + bA^{n} + e/(SI-4.5) + cA^{n}/(SI-4.5)); \qquad (15)$$

where HT = total height in feet, A = age at breast height (4.5 ft), SI = total height in feet at 100 yr, d = 0.90031, b = 36.932, e = -39.258, c = 14544.39, and n = -1.28438.

The site index estimating equation, equation (14), in units of feet is;

$$SI = 4.5 + 3.28084((b + cA + d/A^{0.5})(0.3048(HT-4.5) - 1/(e+fA^{g})) + k(HT-4.5) + j); \qquad (16)$$

where SI, HT, and A are defined as for equation (15), b = 0.94622, c = -0.00175322, d = 3.6660, e = 0.0168601, f = 2.7676, g = -1.19554, k = -0.041911, and j = 40.470.

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