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DOMINANT-HEIGHT-GROWTH AND SITE-INDEX EQUATIONS FOR DOUGLAS-FIR AND PONDEROSA PINE IN SOUTHWEST OREGON

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INTRODUCTION

Equations or graphs for predicting the height growth of dominant trees and the site index of a stand have long been useful to forest managers. The average height growth of dominant trees is a major component of volume growth in even-aged stands. Equations for dominant height growth have also been used to assess potential height-growth rate in growth-and-yield models projecting development of a representative sample of individual trees in a stand (Mitchell 1975, Krumland and Wensel 1981, Arney 1985, Wensel and Koehler 1985, Ritchie and Hann 1986).

The height growth of dominant trees is relatively independent of stand density and therefore can be used as a measure of site productivity. Site index, defined as the average height of the dominant trees in an even-aged stand at a selected base age, is the common expression for such a productivity measure.

Early efforts at developing height-growth equations for dominant trees (e.g. Bruce 1926, Osborne and Schumacher 1935) used observations of heights and ages from many stands at one point in time. Such cross-sectional data were used to fit a general "guide curve": an estimate of the general height-growth pattern over time, which can be scaled up or down to reflect differences in site index. The resulting anamorphic curves exhibited the same shape for all site indices. Site index was estimated by solving the guide-curve equation to express site index as a function of dominant height and age. Examples of anamorphic dominant-height-growth curves for western trees are McArdle's and Meyer's (1930) graphs for Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) and Meyer's (1938) graphs for ponderosa pine (Pinus ponderosa Dougl. ex Laws.).

Most recent dominant-height-growth and site-index estimates have utilized stem analysis that provides real growth-series data: multiple observations over time of height and age from individual dominant trees. Curtis (1964) presents the many advantages of using stem-analysis data, the primary one being a greater ability to model polymorphic height-growth patterns. The resulting predictions of dominant height growth follow different patterns for different site indices, an attribute thought more representative of true dominant height growth. Monserud (1985) showed that very different dominant-height-growth forms resulted from using anamorphic and polymorphic equations for Douglas-fir. He too concluded that the polymorphic approach was more appropriate for developing dominant-height-growth and site-index equations. Examples of polymorphic dominant-height-growth curves for western trees are the equations of King (1966) and Bruce (1981) for Douglas-fir and the equations of Barrett (1978) for ponderosa pine.

A single-tree/distance-independent (Munro 1974) growth-and-yield model is currently being developed for the mixed conifer zone (Franklin and Dyrness 1973) of southwest Oregon by the Growth-and-Yield Project of the FIR (Forestry Intensified Research) Program. A map of the study area is shown in Figure 1. Because Douglas-fir and ponderosa pine are major components of most stands in this area and will continue to be favored in future stands, equations for predicting dominant height growth for each species are critical elements of the growth-and-yield model. Unfortunately, none of the existing polymorphic equations for dominant height growth were developed using data from southwest Oregon. This study, therefore, had two objectives: (1) to develop equations for dominant height growth and site index (base age 50 years) for both Douglas-fir and ponderosa pine and (2) to develop equations to interconvert site indices for Douglas-fir and ponderosa pine.

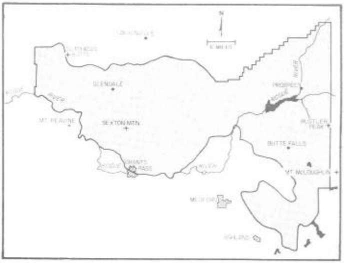

FIGURE 1.

MAP OF THE STUDY AREA.

DATA DESCRIPTION

All trees used in this study were of site quality, meeting the following criteria.

(1) They came from the dominant crown class; predominant and open-grown trees[1] were not used.
(2) The increment cores from breast height showed no irregular radial growth patterns caused by suppression or damage.
(3) The crowns appeared healthy.
(4) No disease, insect, or other damage to the bole or top that would affect height was observable.

One or two dominant trees were felled in each of 351 sample stands. Stem analysis was conducted on each potential site-index tree, with sectioning at stump height (1.0 foot)[2], breast height (4.5 feet), and 8.4-foot intervals thereafter up the stem. Age of each section was determined by ring counts, providing an observation of age and cumulative tree height for each section. The height-age profile for each tree was then plotted and checked for evidence of top damage or height suppression. This procedure identified 89 undamaged site-quality trees for Douglas-fir and 41 for ponderosa pine. Descriptive statistics for these data sets are given in Table 1.

TABLE 1.

DESCRIPTIVE STATISTICS FOR THE DOMINANT-HEIGHT-GROWTH DATA FROM 89 DOUGLAS-FIR AND 41 PONDEROSA PINE TREES.

	Douglas-fir		Ponderosa pine	
Statistics	Breast-height age (yr.)	Site index (ft.)	Breast-height age (yr.)	Site index (ft.)
Mean	73.1	99.9	82.7	84.0
Standard deviation	19.4	14.5	22.3	12.8
Minimum	48.0	65.9	50.0	61.7
Maximum	136.0	139.5	148.0	112.8

[1] Dominants are trees with crowns that extend above the crown cover, receiving full sunlight from above and partial sunlight from the side; they are larger than the average trees in the stand, with crowns well-developed but possibly somewhat crowded on the sides. Predominants are overstory trees remaining from an earlier stand, with crowns well above the dominant crowns of the newer stand.

[2] One foot (ft.) = 0.305 meter (m)

Data for each of the site-quality trees were fitted to a Weibull dominant-height-growth model (Scrivani 1986). These fits were used to estimate each tree's height above breast height at age 5 years and at every 5 years thereafter, to the age of the tree or age 100, whichever was less. The height above breast height at age 50 determined the site index of the tree. The estimated heights above breast height for each 5-year period were used in constructing the site-index equations.

Thirty-two stands were used to develop conversion equations for Douglas-fir and ponderosa pine site indices. Each stand had enough dominant Douglas-fir and ponderosa pine trees to compute a site index for each species. Descriptive statistics for these data are provided in Table 2.

TABLE 2.

DESCRIPTIVE STATISTICS FOR 32 STANDS WITH SITE INDICES FOR BOTH DOUGLAS-FIR AND PONDEROSA PINE.

	Site index (ft.)	
Statistics	Douglas-fir	Ponderosa pine
Mean	86.7	81.5
Standard deviation	15.5	16.7
Minimum	54.8	46.3
Maximum	121.1	111.1

DATA ANALYSIS

The equation forms and estimation procedures used to develop the dominant-height-growth and site-index equations for Douglas-fir are described in detail in Scrivani (1986). Similar procedures were used to develop the ponderosa pine equations. Briefly, Scrivani (1986) compared the fit of nine alternative dominant-height-growth equation forms to the data from each tree in the following data sets: (1) the 89 Douglas-fir and 41 ponderosa pine site-quality trees in southwest Oregon; (2) six dominant Douglas-fir trees from a high-elevation old-growth site in the Oregon Cascades; and (3) one spruce tree from Austria. He concluded that the Weibull model provided excellent characterization of the height growth of each individual tree and exhibited the best nonlinear statistical properties.

To develop an equation for predicting dominant height growth of Douglas-fir in southwest Oregon, Scrivani (1986) used the combined data from all 89 site-quality trees to examine five parameterizations of the Weibull equation and six procedures for estimating parameter values. This analysis resulted in selection of the following equation:

$$H - 4.5 = (S - 4.5)\left(\frac{1.0 - EXP(-EXP[a_0 + a_1 \ln(S - 4.5) + a_2 \ln(A)])}{1.0 - EXP(-EXP[a_0 + a_1 \ln(S - 4.5) + a_2 \ln(50)])}\right) \quad [1]$$

where

H = total height (feet) at age A,
S = 50-year site index of the tree (feet),
$EXP(a) = e^a$, where e is the base of the natural logarithm (ln),
A = age at breast height,
a_0, a_1, a_2 = regression coefficients.

The best approach to parameter estimation combined all observations into one nonlinear least-squares problem, in which the errors about the model were assumed to be independently and identically distributed, with zero mean and the variance changing from tree to tree.

Early site-index studies, such as King (1966), developed one equation that predicted dominant height growth as a function of site index and age. The dominant-height-growth equation was manipulated to give site index as a function of dominant height and age. However, Curtis et al. (1974) showed that site-index equations derived this way differed substantially from equations that used regression techniques to fit site index to dominant height and age. As a result, most recent studies have fitted and presented both dominant-height-growth and site-index equations (e.g., Barrett 1978, Monserud 1985).

To develop a separate site-index equation, Scrivani (1986) used simple least-squares regression procedures to fit the equation

$$\ln[(S - 4.5)/(H - 4.5)] = b_1^* + b_2^* \ln(H - 4.5)$$

to the heights of each of the predicted 5-year age classes. Plots of the regression coefficients b_1^* and b_2^* over age showed that each had a curvilinear trend with age, with both curves passing near or through zero at age 50. This finding suggested that both parameters should be modeled by a linear and quadratic expression of age, giving the following equation:

$$\ln[(S - 4.5)/(H - 4.5)] = b_1(A - 50) + b_2(A - 50)^2 + b_3[\ln(H - 4.5)](A - 50) + b_4[\ln(H - 4.5)](A - 50)^2$$

This equation has the desirable property of predicting S = H at age 50. It was fitted to actual height and age observations, rather than predicted 5-year-interval heights, to avoid possible bias from poor fit of the Weibull height-growth model to each tree. Once the regression coefficients have been estimated, site index can be predicted by

$$S = 4.5 + (H - 4.5)\ EXP(X) \qquad [2]$$

where

$X = b_1(A - 50) + b_2(A - 50)^2 + b_3(A - 50)\,[\ln(H - 4.5)] + b_4(A - 50)^2[\ln(H - 4.5)]$, and

b_1, b_2, b_3, b_4 = regression coefficients.

The following equation was used to predict ponderosa pine site index from Douglas-fir site index:

$$S_P = c_o + c_1\ S_D \qquad [3]$$

where

S_P = ponderosa pine site index with a 50-year base age at breast height, and

S_D = Douglas-fir site index with a 50-year base age at breast height.

Equation [3] was fitted to the 32 Douglas-fir: ponderosa pine site-index observations, using simple linear regression techniques. The intercept term, c_o, was tested for significant difference ($p = 0.01$) from zero and the slope term, c_1, was tested for significant difference ($p = 0.01$) from one by the t-test. Once c_o and c_1 have been estimated, Equation [3] can be inverted (Draper and Smith 1981) to obtain an estimator of Douglas-fir site index, given a ponderosa pine site index:

$$S_D = d_o + d_1\ S_P \qquad [4]$$

where

$d_o = -c_o/c_1$ and

$d_1 = 1.0/c_1$.

RESULTS AND DISCUSSION

The regression coefficients for Equations [1] and [2] are given for both species in Table 3 (p. 6). Graphs of Equation [1] for breast-height ages from 20 to 120 years and site indices from 40 to 140 feet are presented in Appendix 1 (Figures 2 and 3). Figures 4 and 5 (Appendix 1) show graphs of equation [2] for site index of Douglas-fir and ponderosa pine, with total heights from 10 to 240 feet and breast height ages from 20 to 120 years.

The dominant-height-growth equations developed by Bruce (1981) predict almost identical heights to those predicted by King (1966) for Douglas-fir growing in western Washington. For a given site index, our equation predicts lower dominant heights than Bruce's (1981) for ages less than 50 and higher dominant heights for ages greater than 50 years (Figure 6A). Monserud (1985) and Biging and Wensel (1985) reported similar trends when comparing their dominant-height-growth equations to that of King (1966). Therefore, estimating site index in southwest Oregon using the equations developed by King (1966) or Bruce (1981) would underestimate the site index for stands younger than 50 and overestimate it for stands older than 50 years.

Our ponderosa pine dominant-height-growth equation is compared in Figure 6B to that of Barrett (1978) for trees in eastern Oregon and Washington, with Barrett's curves transformed to base age 50. Again, our equations predict a lower dominant height below 50 and a higher dominant height above 50 years.

The intercept of the site-index conversion (Equation [3]) for Douglas-fir and ponderosa pine did not differ significantly from zero ($p = 0.01$). However, the slope term did differ significantly from one ($p = 0.01$), producing the following equation:

$$S_P = 0.940792\ S_D \qquad [5]$$

The adjusted coefficient of determination was 0.8016 and the mean squared error was 55.4267.

The corresponding reduced version of Equation [4] is

$$S_D = 1.062934\ S_P \qquad [6]$$

These equations predict that, at a breast height age of 50 years, a dominant ponderosa pine will be approximately 6 percent shorter than a dominant Douglas-fir growing in the same stand.

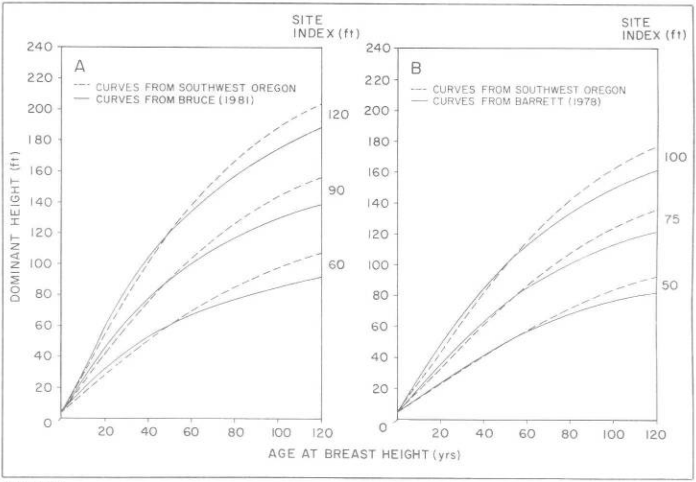

FIGURE 6.
(A) COMPARISON OF DOMINANT-HEIGHT-GROWTH CURVES FOR DOUGLAS-FIR IN SOUTHWEST OREGON TO THOSE DERIVED BY BRUCE (1981) FOR THE SAME SPECIES. (B) COMPARISON OF DOMINANT-HEIGHT-GROWTH CURVES FOR PONDEROSA PINE IN SOUTHWEST OREGON TO THOSE DERIVED BY BARRETT (1978) FOR THE SAME SPECIES, WITH BARRETT'S CURVES TRANSFORMED TO BASE AGE 50.

APPLICATIONS

Estimating Site Index of a Stand

The data used to develop these equations came from natural, even- and uneven-aged, second-growth stands or portions of stands that were uniform in species composition, density, land form, soils, bedrock, slope (± 20 percent of mean slope was acceptable), and aspect (± 15 degrees of mean aspect was acceptable). Most dominant trees were under 120 years old. We therefore recommend use of these same criteria in defining a "stand" for site-index estimation. This may require dividing operational stands into smaller components to estimate site index. An average site index for the operational stand can then be estimated by the following weighted mean of the component site indices:

$$\bar{S} = \sum_{i=1}^{m} (A_i/TA)S_i$$

where

$\bar{S}$ = average site index for the operational stand,
m = number of uniform components in the operational stand,
A_i = area of the i^{th} uniform component of the operational stand,
TA = total area of the stand,
S_i = site index for the i^{th} uniform component of the operational stand.

For each uniform stand or stand component, we recommend that six site-quality trees per acre be selected for measurement of total tree height and breast height age. These trees need not be limited to those on standard inventory plots, but should represent the best site-quality trees that can be found in the stand. Criteria for selecting site-quality trees are described on p. 2.

Site index should be estimated for each tree using either Figure 4 or 5 (Appendix 1) or, preferably, Equation [2] and the appropriate regression coefficients from Table 3. Because of extrapolation problems, the Douglas-fir site-index equation should not be used for stands over 110 years old at breast height with site indices under 55 feet. Our experience also suggests that application of both the Douglas-fir and the ponderosa pine equations to stands under 15 to 20 years old at breast height will produce imprecise estimates of site index. The site index of the uniform stand or stand component is the arithmetic average of the individual-tree site indices from that component.

Applying these site-index equations to an independent data set, we found that the following iterative procedure provides site-index estimates which further reduce the error in predicting future height-growth rate of dominant trees.

(1) Estimate site index ($\hat{S}_o$) from either Figure 4 or 5 or, preferably, Equation [2].

(2) Using the regression coefficients from Table 3, obtain a new prediction of site index from

$$\hat{S}_1 = 4.5 + (H - 4.5)\left(\frac{1.0 - EXP(-EXP[a_o + a_1 \ln(\hat{S}_o - 4.5) + a_2 \ln(50)])}{1.0 - EXP(-EXP[a_o + a_1 \ln(\hat{S}_o - 4.5) + a_2 \ln(A)])}\right).$$

(3) Compute the difference:

$$diff = \hat{S}_1 - \hat{S}_o .$$

(4a) If diff $\leq$ 0.1, stop; the site index for the tree is the one computed in the last iteration of Step 2.

(4b) If diff $\geq$ 0.1, repeat Steps 2, 3 and 4, replacing $\hat{S}_o$ with $\hat{S}_1$ and computing $\hat{S}_2$. Repeat this process until diff $\leq$ 0.1; five iterations usually suffice. These calculations are best done on a programmable calculator or microcomputer; BASIC programs for both species therefore are in Appendix 2.

This iterative procedure solves dominant-height-growth Equation [1] for site index in a manner analogous to the approach taken by earlier site-index modelers such as King (1966).

TABLE 3.

REGRESSION COEFFICIENTS FOR THE DOMINANT-HEIGHT-GROWTH EQUATION [1] AND THE SITE-INDEX EQUATION [2].

Regression coefficient	Douglas-fir	Ponderosa pine
	Equation [1]	
a_o	-6.21693	-6.54707
a_1	0.281176	0.288169
a_2	1.14354	1.21297
	Equation [2]	
b_1	-0.0521778	-0.0699340
b_2	0.000715141	0.000359644
b_3	0.00797252	0.0120483
b_4	-0.000133377	-0.0000718058

An iterative solution is required because Equation [1] cannot be solved mathematically for site index.

In a mixed stand of Douglas-fir and ponderosa pine, it would be best to measure enough trees of both species to estimate the site indices directly. When this is not feasible, Equation [5] can be used to convert an estimate of Douglas-fir site index to an estimate of ponderosa pine site index. Equation [6] can be used for the opposite conversion.

Estimating Future Heights of Dominant Trees in Existing Stands

We have found the following approach provides the most accurate estimates of future dominant heights:

$$H_j = 4.5 + (H_o - 4.5)\left(\frac{1.0 - EXP(-\ EXP[a_o + a_1 \ln(\bar{S} - 4.5) + a_2 \ln(SA + j)]}{1.0 - EXP(-\ EXP[a_o + a_1 \ln(\bar{S} - 4.5) + a_2 \ln(SA)]}\right)$$

where

H_j = height of the dominant tree "j" years in the future,

H_o = current height of the dominant tree,

$\bar{S}$ = average site index for the stand,

SA = breast height age, current stand,

a_o, a_1, a_2 = regression coefficients from Table 3.

Estimating Future Heights of Dominant Trees in Hypothetical Stands

The following approach should be used to estimate dominant height in hypothetical stands:

$$H_K = 4.5 + (\bar{S} - 4.5)\left(\frac{1.0 - EXP(-\ EXP[a_o + a_1 \ln(\bar{S} - 4.5) + a_2 \ln(K)]}{1.0 - EXP(-\ EXP[a_o + a_1 \ln(\bar{S} - 4.5) + a_2 \ln(50)])}\right)$$

where

H_K = height of dominant trees at breast height for the stand at age K,

$\bar{S}$ = average site index for the stand,

K = stand age at breast height,

a_o, a_1, a_2 = regression coefficients from Table 3.

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APPENDIX 1: Dominant-height-growth and Site-index Curves for Douglas-fir and Ponderosa Pine (Figures 2, 3, 4, 5)

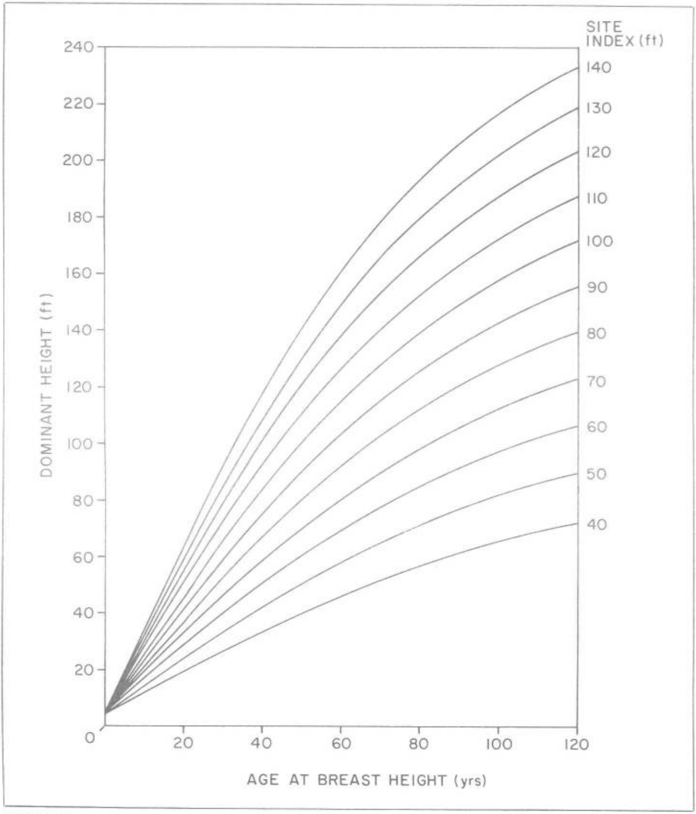

FIGURE 2.

DOMINANT-HEIGHT-GROWTH CURVES (EQUATION [1]) FOR DOUGLAS-FIR IN SOUTHWEST OREGON

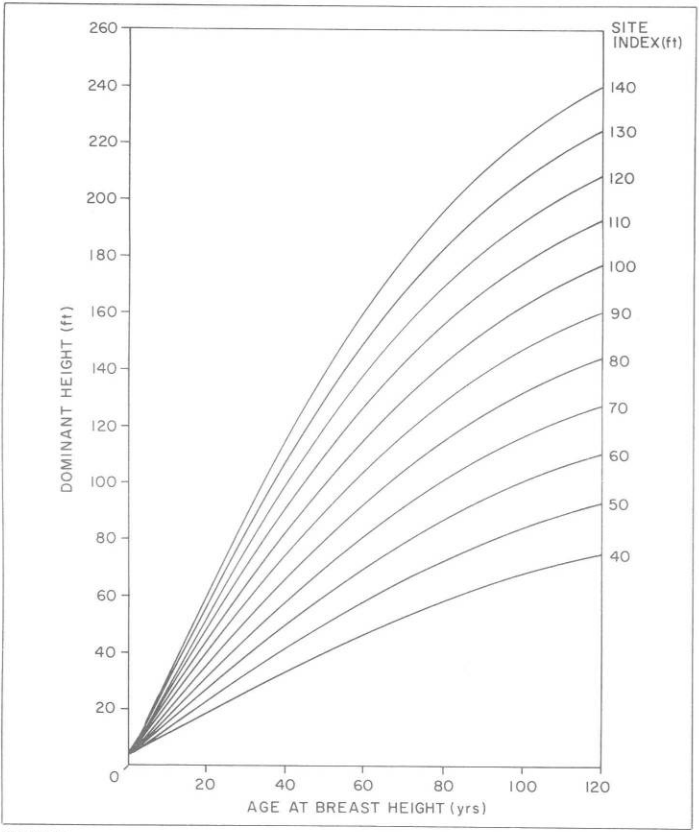

FIGURE 3.

DOMINANT-HEIGHT-GROWTH CURVES (EQUATION [1]) FOR PONDEROSA PINE IN SOUTHWEST OREGON

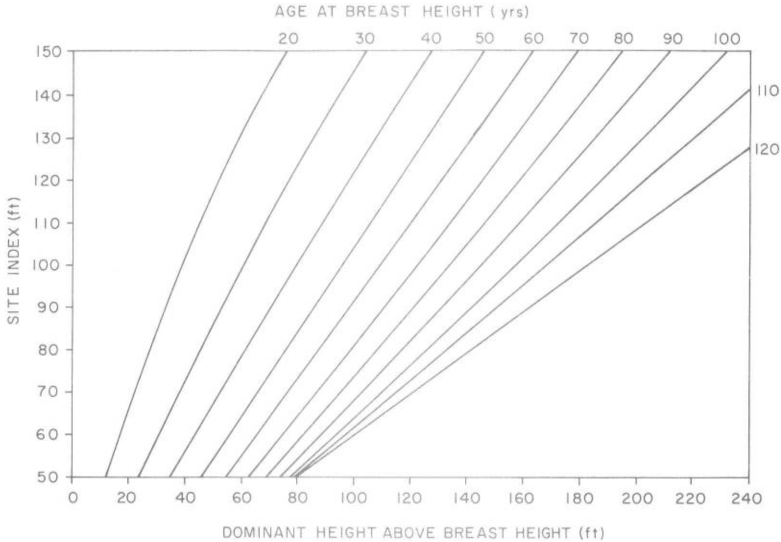

FIGURE 4.

SITE-INDEX CURVES (EQUATION [2]) FOR DOUGLAS-FIR IN SOUTHWEST OREGON.

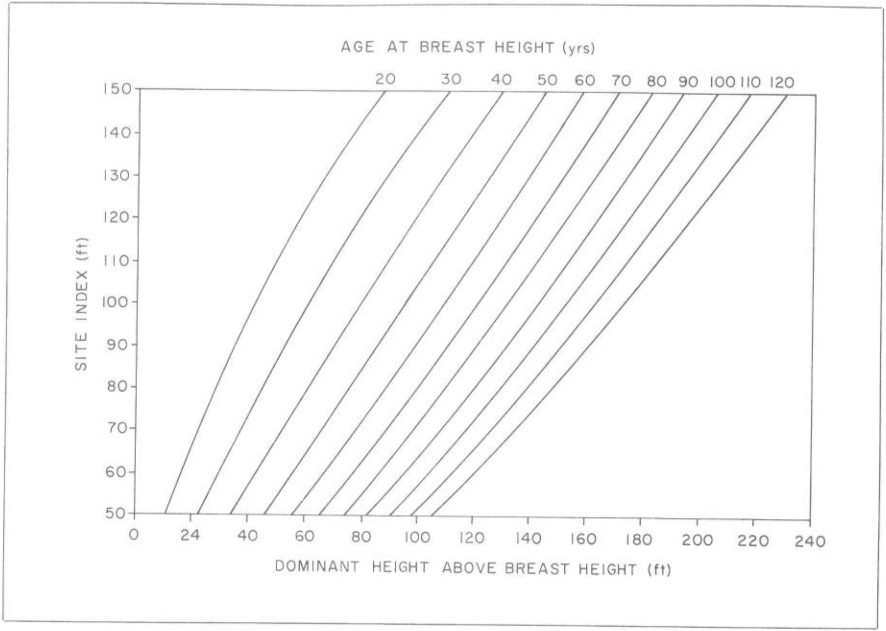

FIGURE 5.

SITE-INDEX CURVES (EQUATION [2]) FOR PONDEROSA PINE IN SOUTHWEST OREGON.

APPENDIX 2: BASIC Computer Programs

The following BASIC computer programs numerically solve dominant-height-growth Equation [1] for site index.

BASIC PROGRAM FOR DOUGLAS-FIR

```
5   B1=-.0521778 : B2=7.15141E-04 : B3=7.97252E-03 : B4=1.33377E-04
6   A0=-6.21693 : A1=.281176 : A2=1.14354
10  CLS
15  INPUT "Height ";H
20  INPUT "Age    ";A
25  TEMP=B1*(A-50)+B2*(A-50)^2+B3*LOG(H-4.5)*(A-50)+B4*LOG(H-4.5)*(A-50)^2
30  SI=4.5+(H-4.5)*EXP(TEMP)
35  PRINT SI
40  TEST=0
45  WHILE TEST<.999
50    TEMP=SI
55    B=1-EXP(-EXP(A0+A1*LOG(SI-4.5)+A2*3.912023))
60    B=B/(1-EXP(-EXP(A0+A1*LOG(SI-4.5)+A2*LOG(A))))
65    SI=4.5+(H-4.5)*B
70    TEST=1-ABS((SI-TEMP)/TEMP)
75  WEND
80  PRINT USING "###.#"; SI
```

BASIC PROGRAM FOR PONDEROSA PINE

```
5   B1=-.0699340 : B2=3.59644E-04 : B3=1.20483E-02 : B4=-7.18058E-05
6   A0=-6.54707 : A1=.288169 : A2=1.21297
10  CLS
15  INPUT "Height ";H
20  INPUT "Age    ";A
25  TEMP=B1*(A-50)+B2*(A-50)^2+B3*LOG(H-4.5)*(A-50)+B4*LOG(H-4.5)*(A-50)^2
30  SI=4.5+(H-4.5)*EXP(TEMP)
35  PRINT SI
40  TEST=0
45  WHILE TEST<.999
50    TEMP=SI
55    B=1-EXP(-EXP(A0+A1*LOG(SI-4.5)+A2*3.912023))
60    B=B/(1-EXP(A0+A1*LOG(SI-4.5)+A2*LOG(A))))
65    SI=4.5+(H-4.5)*B
70    TEST=1-ABS((SI-TEMP)/TEMP)
75  WEND
80  PRINT USING "###.#"; SI
```

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Equations and graphs for dominant height growth and site index (base age 50 years) are presented for Douglas-fir and ponderosa pine in the mixed conifer zone of southwest Oregon. Additional equations are provided to interconvert Douglas-fir and ponderosa pine site indices for stands supporting or capable of supporting both species. The height-growth equation for dominant Douglas-firs exhibits a different pattern than that found with Douglas-fir with the same site index in western Washington. Similarly, the dominant-height-growth equation for ponderosa pine differs from that developed for ponderosa pine with the same site index in eastern Oregon and eastern Washington. Our equations for both species in southwest Oregon predict lower dominant heights for ages less than 50 years and higher dominant heights for ages greater than 50 years for a given site index.

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