1115

Height Growth and Site Index Curves for Douglas-Fir in the Siuslaw National Forest, Oregon

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ABSTRACT. On the Siuslaw National Forest in the central Oregon Coast Range we performed stem analysis of 55 trees selected with the criteria used by the forest. Height growth patterns of these trees were significantly different ($\alpha = 0.05$) from commonly used regional height growth curves. Height growth patterns also differed significantly among groups of floristically similar plant associations in the Siuslaw National Forest. We constructed height growth and site index curves for two classes of plant associations having different height growth curve forms and for the combined data. Forest managers should consider building local height-growth and site-index curves if these are important in estimating stand yield or site productivity.

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Appropriate height growth and site index estimation equations are crucial for forest management. Monserud (1984) and Daubenmire (1961) show that height growth patterns change significantly among different environments within a region. The height growth curves of King (1966) and Bruce (1981) are the primary ones used for height and site index prediction for lowland Douglas-fir (*Pseudotsuga menziesii*) in western Oregon and Washington. Hann and Scrivani (1987) show Douglas-fir height growth patterns in southwest Oregon differ from these, and we surmised height

[1] Staff of the Siuslaw National Forest, Sheila Logan and Miles Hemstrom, USDA Forest Service, contributed significantly through funding the analysis, conducting the field work, and helpful discussions.

growth patterns in the Oregon Coast Range may also differ.

The objectives of this study in the Siuslaw National Forest were (1) to determine if tree height growth patterns differed significantly from King's (1966) and Bruce's (1981) curves (given that Siuslaw personnel select site trees differently than King and Bruce did) and, if so, (2) to build appropriate site index and height growth curves.

FIELD METHODS, RING COUNTING, AND DATA CLEANING

The Siuslaw National Forest occupies 253,000 ha (625,000 ac) in the immediate coastal and mountainous portions of the central Oregon Coast Range. Environments include the wet and often foggy and relatively cool coastal margin, the higher interior ridges receiving up to 500 cm (200 in.) of annual precipitation, and the drier east side of the range and southern end of the forest (Hemstrom and Logan 1986).

Sixty trees cut in 1984 and 1986 were chosen to span the range of environments in the forest (Figure 1). Trees chosen were dominants and codominants with no signs of top breakage and no narrow rings that might indicate suppression in increment cores. The tallest tree meeting these selection criteria on each plot (0.1 ha) was selected. These criteria for selecting site trees were chosen to be very similar to those used on the Siuslaw so that estimates from height and site curves we developed would not be potentially biased by differences in such criteria.

Stem cross sections were cut every 3.05 m (10 ft) up to a 12.7-cm-diameter (5 in) top, and every 1.52 m (5 ft) above that. After the disks were sanded, rings were counted in the laboratory using magnification when necessary. Two counts were made along opposing radii on each disk. Decadal heights and ages were calculated by linear interpolation and were used in fitting equations as others have done (e.g., Curtis et al. 1974).

Examination of height-over-age curves for obvious height growth suppression caused us to reject four whole trees and portions of four other trees. We rejected a fifth tree because it was an obvious outlier from an initial set of Heger regressions (described below) at ages 70 through 110, indicating that the shape of its height growth curve was qualitatively different from the remaining 55 trees; thus it probably had been suppressed.

The remaining 55 trees, comprising 591 decadal heights and ages, were used in the analyses. Each observation consisted of height above breast height (1.37 m) (*HT*), age at breast height (*A*), and site index (*SI*) (*HT* at *A* = 50). Site index ranged from 29.1 to 49.5 m (mean, 39.8 m) and age ranged from 70 to 120 yr (mean, 107 yr) (Figure 2).

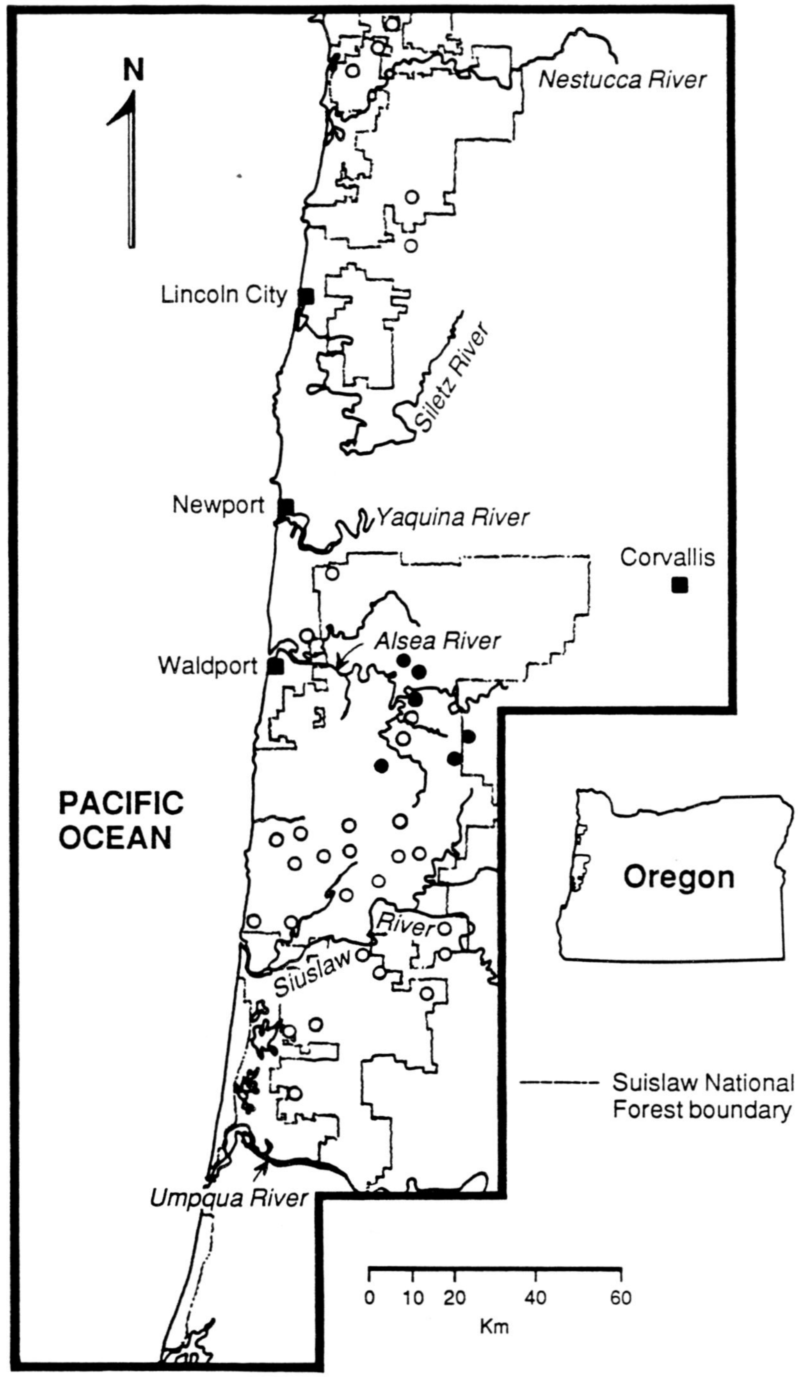

Fig. 1. Map of the Siuslaw National Forest, Oregon, showing the locations of trees cut for this study. Five trees were cut near (1–2 km) each of the filled circles.

COMPARISON WITH EXISTING CURVES

The height-growth curves of King (1966) and Bruce (1981) are the most commonly used in the Oregon Coast Range. We wanted to determine if these curves adequately describe height growth of Douglas-fir on the Siuslaw National Forest, or if new height growth and site index curves were needed. Comparisons between these curves showed their predicted heights to be very similar within the range of ages and site indices sampled by both. Most differences were less than 0.2 m and the maximum difference was 0.8 m. For this reason, and because King's curves extend to 120 years (40 years beyond Bruce's), as do our data, we compared our data only with King's curves.

We compared the actual tree heights with the King height curve estimates by using linear regression.

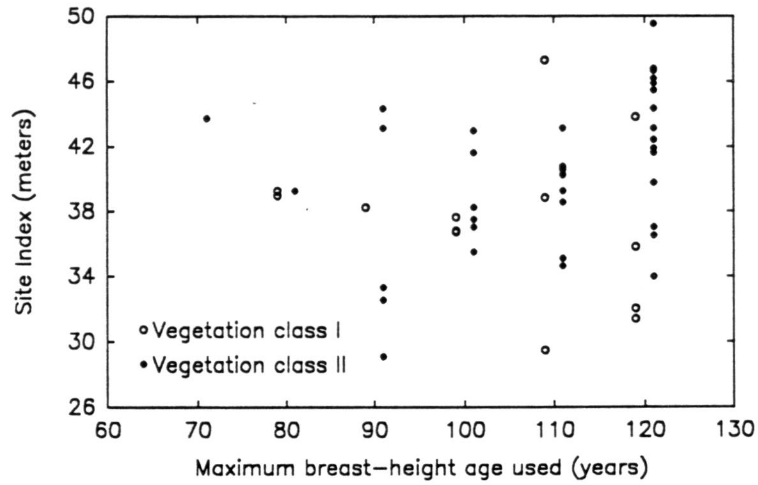

Fig. 2. Distribution of the data by age, site index, and vegetation class.

Table 1. Coefficients and their significances for the linear regressions comparing actual tree heights with King (1966) height curve estimates.

Age	Intercept (p-value)	Slope (p-value)
60	2.206 (0.052)	0.957 (0.044)
70	5.187 (0.013)	0.897 (0.008)
80	9.574 (0.001)	0.814 (0.001)
90	13.198 (<0.001)	0.750 (<0.001)
100	17.667 (<0.001)	0.672 (<0.001)
110	20.098 (<0.001)	0.628 (<0.001)
120	21.428 (<0.001)	0.602 (<0.001)

The regression between these two values was performed separately by age (10, 20, 30, 40, 60, 70, 80, 90, 100, 110, and 120) to avoid nonindependence due to measurements at different ages being from the same tree.

We found significant differences between the observed heights and King's height curve estimates for ages 60 through 120, though not for ages 10 through 40. The parameter estimates for the intercepts and slopes, and their associated p-values are shown in Table 1. Note that the p-values in Table 1 are the probability of rejecting the hypotheses that the intercept is equal to zero and that the slope is equal to one. These two tests indicated that King's curves underestimate the height of small trees and overestimate the height of large trees. We concluded that King's curves [and Bruce's (1981) curves since the two are quite similar] can be improved upon for the ages 60 to 120 on the Siuslaw National Forest.

GROUPING BY PLANT ASSOCIATION

We thought height growth curve form might differ among plant associations because the Siuslaw covers a broad range of environments (Hemstrom and Logan 1986), so we tested for an effect of plant association. The 55 trees occurred in 13 plant associations (Hemstrom and Logan 1986) that we combined into 5 plant groups (shown in Table 2) based on similarities in floristic composition and inferred environment. Then height data for each tree was multiplied by the mean site index of all trees and divided by its own site index so all trees had site index equal to the mean. Using these reproportioned height data we calculated an analysis of variance for each decadal age (except 50) with plant group as the class variable.

Fisher's protected LSD

We chose to test for differences among pairs of plant associations because it has been found to have the highest correct-decision rate (Carmer and Swanson 1973).

The ANOVAs for ages 60, 70, and 80 showed significant differences (α = 0.05) in height pattern; those for other ages did not. The plant groups were further combined into the two vegetation classes in Table 2, so that all pairs of groups shown to be significantly different by Fisher's LSD (α = 0.05) were separated. Analysis of variance on the reproportioned height data then showed the height patterns of trees in the two classes to be highly significantly different at ages 60 (P = 0.0003), 70 (P = 0.0001), 80 (P = 0.0009) and 90 (P = 0.0125). The relatively few trees in class I (Table 2) reflected the relatively small area of these plant associations in the forest. We then built different height and site index estimating equations for these two classes and for the combined data.

PRELIMINARY ANALYSES AND MODEL BUILDING CONVENTIONS

The first step in building each height equation was to fit, for each decadal age, a family of height estimating equations of the form,

$$HT = a + b\ SI \tag{1}$$

called Heger (1968) height equations, where HT = total height − 1.37 m (height above breast height), a and b are regression coefficients, and SI is HT at 100 years breast-height age. The first step in building each site equation was to fit a family of site index estimating equations of the form,

$$SI = c + d\ HT \tag{2}$$

called Heger site equations, where c and d are regression coefficients. Residuals from all these equations showed uniform variance and no nonlinear trends.

All models were fitted by weighted least squares regression because variance was not uniform across the range of age. The weight at each decadal age was the inverse of the mean squared error from equation (1) for height models and from equation (2) for site models.

HEIGHT GROWTH MODELS

Height Model for Combined Data

Initially we examined height growth models previously used for Douglas-fir, including those of Curtis et al. (1974), King (1966), and Monserud (1984), but rejected them because of their biased fit to the data. Fit of height models was examined on plots of residuals over age for six site index

Table 2. Vegetation classes and groups of plant associations, with number of trees in each in parentheses.

Class	Group	Plant association (Hemstrom and Logan 1986)	
I (13)	Pisi (5)	Sitka spruce/fool's huckleberry-red huckleberry	(4)
		Sitka spruce/salmonberry	(1)
	Rhma (8)	Western hemlock/rhododendron-salal	(3)
		Western hemlock/rhododendron-evergreen huckleberry	(3)
		Western hemlock/evergreen huckleberry	(2)
II (42)	Rusp (15)	Western hemlock/salmonberry	(5)
		Western hemlock/salmonberry-vine maple	(5)
		Western hemlock/salmonberry-salal	(5)
	Pomu (14)	Western hemlock/vine maple/swordfern	(10)
		Western hemlock/oxalis	(1)
		Western hemlock/swordfern	(3)
	Gash (13)	Western hemlock/vine maple-salal	(9)
		Western hemlock/salal	(4)

classes spanning the range in the data, and on plots of residuals over site index for ages 10, 20, 40, 50, 60, 80, 100, 110, and 120. These plots also included the differences between values predicted by the candidate model and values from the Heger equations (1). Since the Heger equations provide the best possible fit (lowest m.s.e.) when *SI* and age are the only predictors, these differences provided a helpful assessment of bias.

A Richards (1959) function of the form,

$$HT = a\,[1 - \exp(b\,AGE)]^{c} \quad (3)$$

was also examined where a, b, and c are functions of *SI*. The first step was to fit Richards functions (with a, b, and c as simple parameters) individually to the five smoothed Heger height growth curves obtained from equation (1), using *SI* values of 30, 34, 38, 42, and 46 to provide an estimate of each parameter for each value of *SI*. These *SI* values spanned the range in the data. The a, b, and c parameters in (3) were then made functions of *SI* by using stepwise regression with *SI* and a wide range of transformations of *SI* as candidate predictors.

Trials using several of these functions substituted into (3) led to a 5-parameter height growth model that fit the actual decadal heights and ages well:

$$HT = (b_0 + b_1\,SI)\,[1 - \exp(b_2\,SI\,AGE)]^{(b_3 + b_4\,SI)} \quad (4)$$

where $b_0 = 37.57$, $b_1 = 0.71698$, $b_2 = -0.00055019$, $b_3 = 0.95516$ and $b_4 = 0.0072776$. We judged this model fit well because differences between its predictions and those of the Heger height equations (1) were no more than 1.0 m for the full range of SI within each decadal age. Figure 3 shows these height growth curves, and Table 3 gives the statistics on model fit.

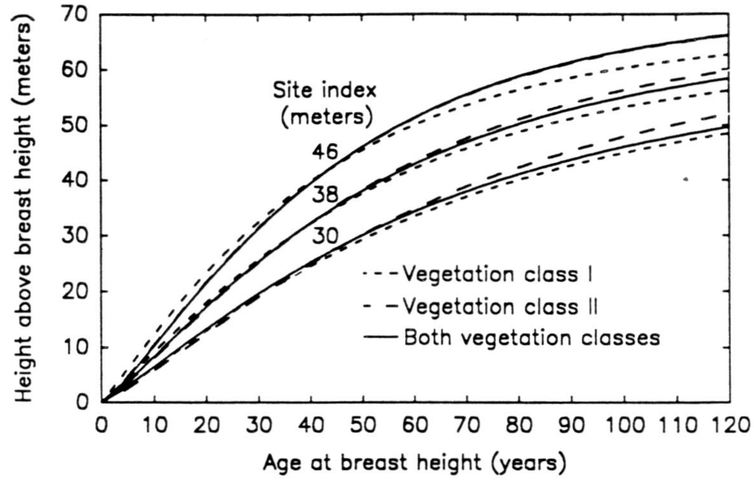

Fig. 3. Height growth curves for all data combined and for vegetation classes I and II.

Height Model for Vegetation Classes

Regressions with the form of equation (4) were fitted separately to both vegetation classes. This full (10-parameter) model improved the fit to the classes and reduced the weighted mean square error and the unweighted standard error of the estimate (standard deviation of the difference between observed and estimated values) (Table 3). Steps to share parameters between vegetation classes were guided by asymptotic correlations between parameters and resulted in the final height growth model,

$$HT = (c_0 + c_1\,SI)\,[1 - \exp(b_2\,SI\,AGE)]^{(b_3 + c_4\,SI)} \quad (5)$$

where $c_0 = 42.34$, $c_1 = 0.52223$ and $c_4 = -0.0032083$ for vegetation class I; $c_0 = 49.29$, $c_1 = 0.46223$ and $c_4 = 0.0$ for class II; and $b_2 = -0.00054132$ and $b_3 = 1.2625$ for both classes. Of the difference in explained variation between the 10-parameter and 5-parameter models, 78% is explained by this 7-parameter model. In addition, standard errors of the estimate for class II are not materially increased from the full 10-parameter model and are only slightly increased for class I (Table 3). Figure 3 shows height growth curves based on this equation (5). This equation and equation (4) behave realistically beyond the range of the data, flattening out from ages 170 to 250 for site indices 46 to 30, respectively.

We tested the null hypothesis that incorporating vegetation class does not improve model fit with an F-ratio, and found it to be highly significant ($F = 40$, $df = 2$ & 48, $P < 0.0001$, weighted ANOVA). Thus fitting the height equations separately by vegetation class significantly improves the model.

Table 3. Number of parameters, weighted mean square error for all 55 trees (m.s.e.), and unweighted standard error of the estimate (s.e.e.), for height growth and site index models that do or do not distinguish vegetation classes.

Dependent variable	Type of model (equation number)	Number of parameters	Weighted m.s.e.	Unweighted s.e.e. — Vegetation Class I	Vegetation Class II	All trees combined
				.... (m)		
Height	Classes not distinguished (4)	5	0.899	2.12	1.84	1.90
	Classes completely distinguished	10	0.764	1.50	1.78	1.72
	Classes partially distinguished (5)	7	0.794	1.64	1.77	1.74
Site index	Classes not distinguished (6)	5	0.901	2.46	2.00	2.11
	Classes completely distinguished	10	0.814	2.06	2.00	2.01
	Classes partially distinguished (7)	7	0.813	2.03	2.00	2.00

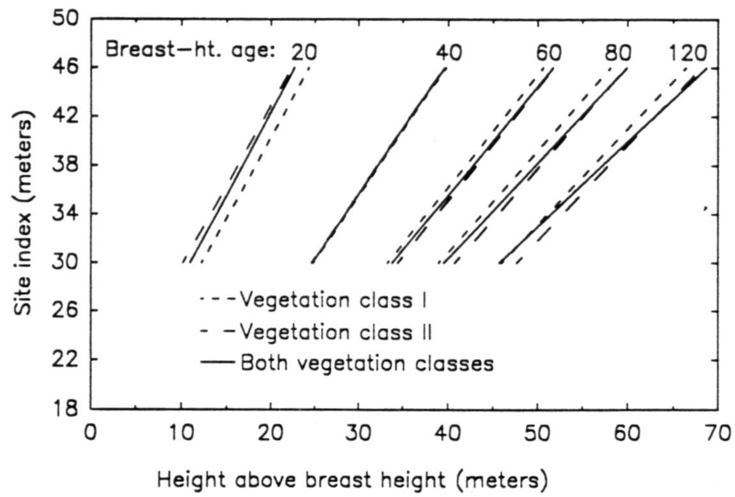

Fig. 4. Site index curves for all data combined and for vegetation classes I and II.

SITE INDEX MODELS

Site Model for Combined Data

As with the height models, the first site index models examined—those of Monserud (1984) and Cochran (1979)—had been used previously for Douglas-fir. The site index model of Ek (1971) and many models of the form $SI = a + b\ HT$, where a and b were functions of age, were also examined. All these models provided biased fits to site index and were rejected. Fit of candidate site index models were examined on plots of residuals over height for ages 10, 20, 40, 50, 60, 80, 100, 110, and 120; the plots also included the differences between values predicted by the candidate model and values from the Heger equations (2).

A model was also constructed using Dahms' (1975) technique. After trying several different forms for the slope and mean height functions in this model, we found the following model fit the combined data from both classes well:

$$SI = 39.77 + [b_0/\exp(AGE/50) + b_1 \exp(AGE/300)] \{HT - b_2[1 - \exp(b_3\ \mathrm{AGE})]^{b_4}\} \quad (6)$$

where $b_0 = 1.42956$, $b_1 = 0.37900$, $b_2 = 65.11$, $b_3 = -0.022733$, $b_4 = 1.27157$, and 39.77 is the mean SI for the 55 trees. We judged this model fit well because differences between its predictions and those of the Heger site equations (2) were no more than 1.0 m for the full range of SI within each decadal age except ages 10 (−1.4 m) and 120 (1.2 m). Figure 4 shows plots of these site index curves and Table 3 gives fit statistics for the model.

Site Model for Vegetation Classes

A model with the form of equation (6) was fitted separately to both vegetation classes. This full (10-parameter) model improved the fit to the classes and reduced the weighted mean square error and the unweighted standard error of the estimate (Table 3). Attempts to share parameters between classes were guided by asymptotic correlations between parameters and resulted in the final site index model,

$$SI = 39.77 + [b_0/\exp(AGE/50) + b_1 \exp(AGE/300)] \{HT - b_2[1 - \exp(c_3\ AGE)]^{c_4}\} \quad (7)$$

where $b_0 = 1.2508$, $b_1 = 0.44688$ and $b_2 = 65.13$ for both vegetation classes; $c_3 = -0.19440$ and $c_4 = 1.0596$ for class I; and $c_3 = -0.023795$ and $c_4 = 1.3470$ for class II. This 7-parameter model explained all the additional variation explained by fitting separate site models to each class, and the standard errors of the estimate are not materially changed (Table 3). Figure 4 shows site index curves based on this equation. This equation and equation (6) behave realistically beyond the range of the data.

We tested the null hypothesis that incorporating vegetation class does not improve model fit with an F-ratio, and found it to be highly significant ($F = 35$, $df = 2$ & 48, $P < 0.0001$, weighted ANOVA). Thus fitting the site equations separately by vegetation class significantly improves the model.

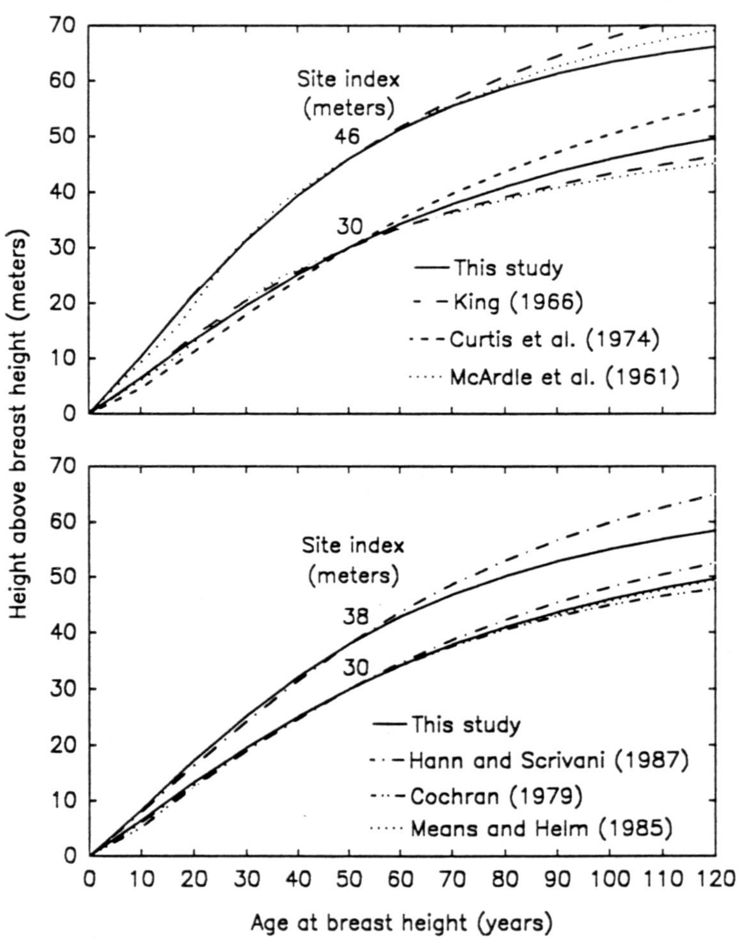

Fig. 5. Comparison of our height growth curves (equation 4) with the Douglas-fir height growth curves of King (1966), Curtis et al. (1974), McArdle et al. (1961), Cochran (1979), Hann and Scrivani (1987), and Means and Helm (1985). No curves are shown for site indices not sampled in other studies.

DISCUSSION

Comparison wiith King's Curves

We found statistically significant differences in height-growth-curve form between our Siuslaw Douglas-fir and King's (1966) curves developed with data from Washington. These may be caused by differences between the geographic areas sampled (e.g., environment, genetics), by differences between the tree selection criteria we used and those of King, or both. We cannot distinguish between these two causes. King (1966), for example, selected the 10 trees in 50 with the largest dbh as site trees, while we selected the tallest tree on a 0.1 ha plot. Clearly, however, since our selection criteria closely match the Siuslaw's, new curves developed from our data will benefit the Siuslaw, regardless of the cause.

Effects of Plant Association

We present equations for vegetation class I that contains only 13 trees, fewer than others have used. We chose to present models for both vegetation classes for two reasons. First, the distinction is significant, as shown by statistical tests on tree data of the two classes and on the improvement in fit of the expanded model. Second, the height and site models for class I (and II) are based in part on all 55 trees; in effect, they tap the strength of this larger dataset. This occurs because the models share coefficients and the models for both classes were fit as one simultaneously to the whole dataset. The height models share 2 of 5 parameters and the site models share 3 of 5 parameters.

Compared to the majority of the forest, the coastal margin sites of the Pisi group (see Table 2 for group definitions) are cooler, foggier, and receive winds straight off the ocean; the southern end of the forest where the Rhma group occurs is warmer and drier (Hemstrom and Logan 1986). Yet the 13 trees in these two groups have height growth patterns that are similar and differ from those of trees on the majority of the forest. These disparate environments apparently act through different mechanisms to produce similar height growth patterns.

Comparison with other Douglas-Fir Height Curves

Height growth of Siuslaw Douglas-fir on high-quality sites ($SI \geq 38$ m) is as fast or faster when young, and slower when older, than that of Douglas-fir from all other places in Oregon and Washington where height growth curves exist (Figure 5). At lower sites, these height growth curves are intermediate in form compared to those from other areas. Bruce's (1981) curves are not shown because they are quite similar to King's (1966).

It is perhaps surprising that our height growth curves for site index 46 m flatten out more than those of McArdle et al. (1961), because the biased sample that the McArdle curves are based on makes them flatter at advanced ages (Curtis 1964). Examination of height growth trends of the nine trees we sampled with site index 44 to 50 m indicate this difference exists in our data and is not the result of model bias.

Reliability

Mean error or bias (difference between observed and estimated values) for all site indices combined is less than 25 cm for height and site estimates for trees in our sample except at the smallest (10, 20) and largest (110, 120) ages (Figure 6). This bias increases at advanced ages where younger trees fall out of the sample, but is less than 1.0 m for all ages and site indices in the data.

The variation not explained by the final equations for combined vegetation classes is expressed as the standard error of the estimate in Figure 6. Estimates of height and site are most reliable near the index age of 50 years and least reliable far from it. When these curves are applied, sampling error will further reduce accuracy and precision because predictions will be for trees not in our sample.

Implementation

If these height growth and site index equations are used in a forest yield prediction system, both must be incorporated at the same time. Incorporation of only one set of equations will produce biased estimates of yield. Use of these height growth equations instead of King's (1966) in yield models will cause a decrease in predicted yield (at a rotation age greater than 50) for high sites (e.g., site index 46) and an increase for low sites (e.g., site index 30), due to their different shapes. Use of the new site index equations will give site estimates that range from 4 m higher to 2 m lower, depending on age and site quality, within the range of our data. The changes in productivity estimated by a yield model from these two sources may be in the same or opposite directions depending on age of site trees, selected rotation age, and site quality.

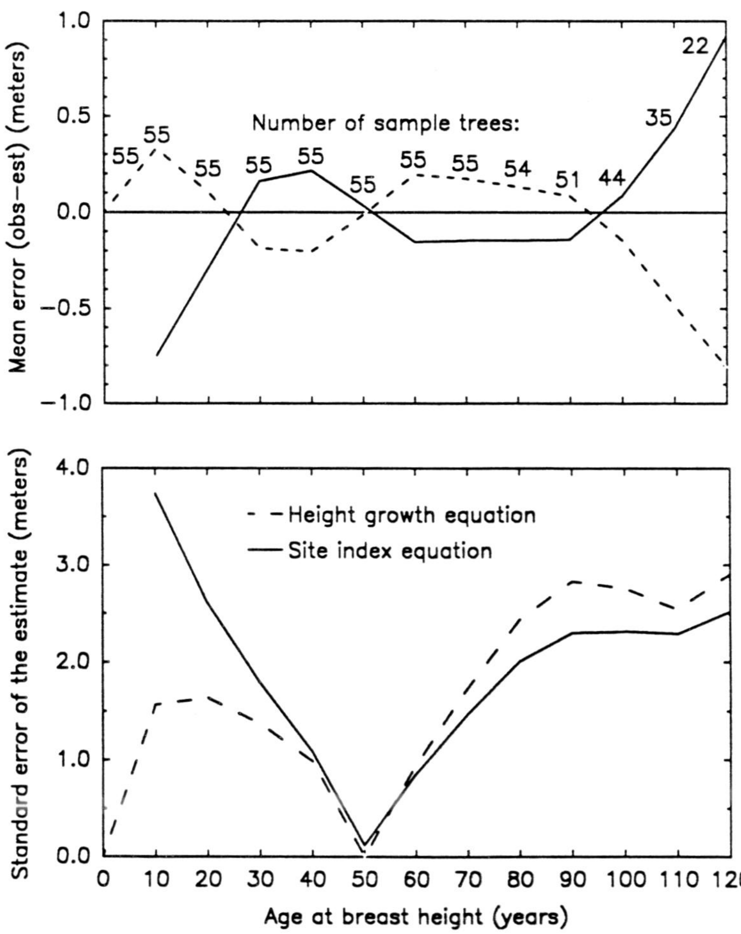

Fig. 6. Mean error (observed minus estimated values) and standard error of the estimate over age for the height-growth (equation 4) and site-index curves (equation 6) for the combined data.

CONCLUSIONS

Douglas-fir height growth curves (King 1966 and probably also Bruce's 1981 curves since they are quite similar) for the western Oregon and Washington region differed significantly from height growth patterns of Douglas-firs in the central Oregon Coast Range selected for this study. Regional curves may give biased estimates in other areas within this region, or for trees selected using criteria (such as the Siuslaw National Forest's) different than King's.

We suggest managers seriously consider building local height-growth and site-index curves if these are important in estimating stand yield or site productivity. Trees used to build such curves should be selected with the same criteria used on the inventory plots to which the new curves will be applied.

Though trees are sampled from a limited geographic area, environmental variation within that area may cause differences in height growth curve form. Incorporating plant association into the prediction system may significantly decrease prediction errors on sites with different environments. Monserud (1984) found a similar effect in the northern Rockies where climate ranges from maritime to continental in an area five times the size of the Siuslaw National Forest. Our work indicates this can occur in a smaller area over a narrower range in environment.

More accurate estimates of potential productivity on a site-by-site basis will allow more efficient allocation of forest management resources, more appropriate silvicultural treatments, and better estimates of the capabilities of stands and landscapes to produce nontimber as well as timber outputs. □

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APPENDIX: EQUATIONS IN FEET

The height growth equation for the combined data (equation 4), expressed in feet, is

$$HT = (b_0 + b_1\,SI)\,[1 - \exp(b_2\,SI\,AGE)]^{(b_3 + b_4 SI)} \quad (8)$$

where $b_0 = 123.25$, $b_1 = 0.71698$, $b_2 = -0.00016770$, $b_3 = 0.95516$, $b_4 = 0.0022182$, HT = height above breast height in feet, AGE = breast height age, and $SI = HT$ at $AGE = 50$.

The following height growth equation provides different estimates for the two vegetation classes (equation 5), expressed in feet;

$$HT = (c_0 + c_1\,SI)\,[1 - \exp(b_2\,SI\,AGE)]^{(b_3 + c_4 SI)} \quad (9)$$

where $c_0 = 138.90$, $c_1 = 0.52223$ and $c_4 = -0.0097789$ for vegetation class I; $c_0 = 161.71$, $c_1 = 0.46223$ and $c_4 = 0.0$ for class II; $b_2 = -0.00016499$ and $b_3 = 1.2625$ for both classes; and HT, AGE, and SI are as defined for equation (8).

The site index equation for the combined data (equation 6), expressed in feet, is

$$SI = \overset{130.48}{\cancel{39.77}} + [b_0/\exp(AGE/50) + b_1\exp(AGE/300)]\,\{HT - b_2[1 - \exp(b_3\,AGE)]^{b_4}\} \quad (10)$$

where $b_0 = 1.42956$, $b_1 = 0.37900$, $b_2 = 213.62$, $b_3 = -0.022733$, and $b_4 = 1.27157$; and HT, AGE, and SI are as defined for equation (8).

The following site index equation provides different estimates for the two vegetation classes (equation 5), expressed in feet;

$$SI = \overset{130.48}{\cancel{39.77}} + [b_0/\exp(AGE/50) + b_1\exp(AGE/300)]\,\{HT - b_2[1 - \exp(c_3\,AGE)]^{c_4}\} \quad (11)$$

where $b_0 = 1.2508$, $b_1 = 0.44688$ and $b_2 = 213.68$ for both vegetation classes; $c_3 = -0.19440$ and $c_4 = 1.0596$ for class I; $c_3 = -0.023795$ and $c_4 = 1.3470$ for class II; and f, HT, AGE, and SI are as defined for equation (8).

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