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Height Growth and Site Index Curves for Western White Pine in the Cascade Range of Washington and Oregon

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Abstract

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Height growth and site index curves were constructed from stem analyses of mature western white pine (*Pinus monticola* Dougl. ex D. Don) growing in high-elevation forests of the Cascade Range in the Mount Hood and Gifford Pinchot National Forests of Oregon and Washington, respectively. Alternate systems using reference ages for site index of 50 and 100 years breast height are presented. Differences among systems and their causes are briefly discussed.

Keywords: Site index, height growth curves, stem analysis, western white pine, *Pinus monticola*.

Summary

Height growth and site index curves were constructed from stem analyses of mature western white pine (*Pinus monticola* Dougl. ex D. Don) growing in high-elevation forests of the Cascade Range in the Mount Hood and Gifford Pinchot National Forests of Oregon and Washington. Alternate curves are presented that were fit by using first height and then site index as dependent variables, and by using reference ages for site index of 50 and 100 years breast height. The resulting curves differ considerably. The causes of these differences between systems are briefly discussed.

Introduction

Western white pine (*Pinus monticola* Dougl. ex D. Don) occurs sporadically in western Washington and Oregon, most commonly as scattered individuals growing in stands predominantly composed of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), true firs (*Abies* spp.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Engelmann spruce (*Picea engelmanni* Parry ex Engelm.) and lodgepole pine (*Pinus contorta* Dougl. ex Loud.). It is noteworthy for its ability to produce fine individual trees on sites that are relatively poor for Douglas-fir (Allen 1959). The species has received little attention in the region, however, primarily because the blister rust (*Cronartium ribicola*) hazard has led most foresters to exclude it from consideration in long-term management.

The recent introduction of blister rust-resistant planting stock has renewed interest in the species, particularly as a possible alternative to Douglas-fir on poor sites and in situations susceptible to frost damage. Limited planting is being done, and managers have a need to classify sites for white pine growth potential and predict heights for yield estimates.

There are no yield tables or site classification curves specifically applicable to white pine in western Oregon and Washington. The only existing site curves are those of Haig (1932) for northern Idaho and adjacent Washington and Montana, an ecologically and climatically different area. Also, Haig's site curves, and their formula version (Brickell 1970), are proportional curves prepared by the old guide-curve technique, which is now generally recognized to be unreliable (Monserud 1985).

The objective of the work reported in this paper was to provide height growth and site index classification curves based on local data for use on National Forest lands in the central and northern Cascade Range.

During 1987, personnel of the Mount Hood and Gifford Pinchot National Forests collected a substantial body of white pine stem analysis data. This report covers the analysis procedures and results of this work. We present height growth and site index curves for dominant white pine based on index age of 50 years at breast height (b.h.). We also present supplementary curves based on index age 100 years b.h. and approximate conversions and discuss the nature and causes of differences among these curves.

The Data

Area Sampled

The original intent was to sample throughout the area where white pine is currently being planted. But, because of the limited present occurrence of white pine (in part a result of past salvage operations), most sample trees were from mature, relatively undisturbed upper elevation stands near or slightly east of the crest of the Cascades, in the Mount Hood and Gifford Pinchot National Forests. These sites tend to have a cold climate and a deep snowpack, and to be relatively dry during the growing season. Much of the area is gently rolling, with considerable relatively flat terrain. Frost pockets are frequent after clearcutting, so western white pine (because of its frost tolerance) is considered a desirable species for reforestation.

Selection of Field Samples

One tree was cut per location. Sample trees were generally scattered individuals within mixed species stands and were subjectively selected to meet the following criteria:

1. Dominant or codominant canopy position.
2. Straight bole, with no sign of top breakage.
3. Healthy crown, with minimal flagging from blister rust.
4. No bole conks.
5. No periods of evident suppressed diameter growth on the increment core.
6. No fire or lightning scars.

Tree Measurement Procedures

A paint mark was placed at 4.5 feet above the ground (b.h.). The tree was felled, and additional paint marks were placed at 10-foot intervals up the bole, measured from the b.h. point. When a diameter of less than 5 inches was reached, marks were placed at 5-foot intervals. Total bole length above b.h. was also measured and recorded. Sections were cut at each paint mark, labeled with tree number and section number, and transported to the office.

On each section, two “average” radii were selected and smoothed by sanding or chiseling. The number of annual rings was counted, and age b.h. of the tree at the time it attained that height was calculated as the difference between the ring count on the section and the ring count on the section taken at b.h.

Data Screening

Heights were plotted over ages for each tree. These points were connected by straight lines to show the pattern of growth of the individual tree. Several trees were removed from the sample because of abrupt and unreasonable changes indicating either past damage or errors in ring counts.

The early growth patterns of trees that later attained similar heights were quite variable. Because we had only one sample tree per location, it was not possible to distinguish between unusual individual trees and stand growth patterns. Some trees showed patterns of slow early growth followed by rapid growth in later life that clearly indicated severe competition in early life and gradual emergence to a dominant position. The more extreme and clearly recognizable cases were removed from the data. After this screening, 38 trees were available for analysis.

For those few trees of age slightly less than 100, the individual tree curves were extrapolated to age 100 to provide values allowing use of a 100-year reference age.

Trees had been sectioned at fixed intervals of height, and the ring counts therefore represented height-age observations taken at prespecified intervals of height. This is statistically undesirable for analyses in which height is to be treated as the dependent variable. For each tree, heights at 10-year age intervals were therefore estimated by interpolation; the resulting pairs of height-age values were used in subsequent analyses. Values for ages over 200 years b.h. were omitted from analyses, because of the small number of trees of greater age

The distribution of the sample by age b.h. is shown in table 1. The range in S50 (height attained at age 50 years b.h.) was 30 to 101 feet. The range in S100 (height attained at age 100 years b.h.) was 62 to 142 feet.

Table 1—Number of sample trees and coefficients of determination (r2) between (1) height and S50 and (2) height and S100, by age in decades**

Age b.h.	Number of trees	Height x S50 r**2	Height x S100 r**2
Years			
10	38	0.555	0.258
20	38	.627	.259
30	38	.803	.405
40	38	.929	.530
50	38	1.000	.701
60	38	.964	.770
70	38	.928	.837
80	38	.870	.908
90	38	.793	.971
100	38	.701	1.000
110	30	.597	.976
120	24	.619	.937
130	21	.683	.879
140	19	.620	.824
150	19	.562	.779
160	17	.571	.738
170	16	.447	.608
180	15	.458	.644
190	14	.435	.590
200	10	.422	.592

Analysis

Simple Correlations

For each age b.h. 10, 20,...200, coefficients of determination (r**2) were calculated for (1) height and S50 (height attained at age 50 years b.h.), and (2) height and S100 (height attained at age 100 years b.h.). These values (table 1) represent the fraction of total variation accounted for by regressions of one variable on the other.

Simple regressions were calculated between these variables, and the resulting standard errors of estimate provided the weights used in fitting the final curves.

Analyses Using Reference Age 50 Years B.h.

Preliminary graphic curves—The individual age regressions of form H = a + b * S50 were used to construct preliminary graphic curves (Heger 1968), which were used as guides in selecting height growth functions.

Corresponding site index regressions were fit for each age, of form S50 = a * H ** b (following the procedure used by Hann and Scrivani [1987]), and preliminary curves were constructed by a procedure similar to Heger's.

Height growth equation, base age 50—Height growth regressions were fit to the combined data, with ages over 200 years omitted, as weighted nonlinear regressions:

$$w * H = w * f(A, S50) ,$$

where H is height, A is age b.h., S50 is site index (height at age 50 years b.h.); and w is a weighting factor equal to the reciprocal of the standard error of estimate from the individual age regression, introduced to stabilize variances. Equations were conditioned to meet the requirement that H = S50 at the reference age of 50 years.

The “best” equation obtained, as judged by the criteria of (1) near-minimum sum of weighted squared residuals, (2) absence of unreasonable crossing or other odd behavior at the margins of the data, and (3) general agreement with the graphic curves prepared by the Heger method, was:

$$H = 4.5 + (S50-4.5) * \frac{(1-\exp\{-\exp[a + (b+c)*\ln(A) + d*\ln(S50)]\})}{(1-\exp\{-\exp[a + b*\ln(50) + c*\ln(A) + d*\ln(S50)]\})} \qquad (1)$$

where

a = −9.975053,
b = 1.747353,
c = −0.385830, and
d = 1.119438.

Curves corresponding to this equation are shown in figure 1. (A simple three-parameter equation with 1/S50 rather than ln(S50), corresponding to equation (3) below, gave an equally good fit statistically but was rejected because of anomalous behavior at the upper margin of the range in ages.)

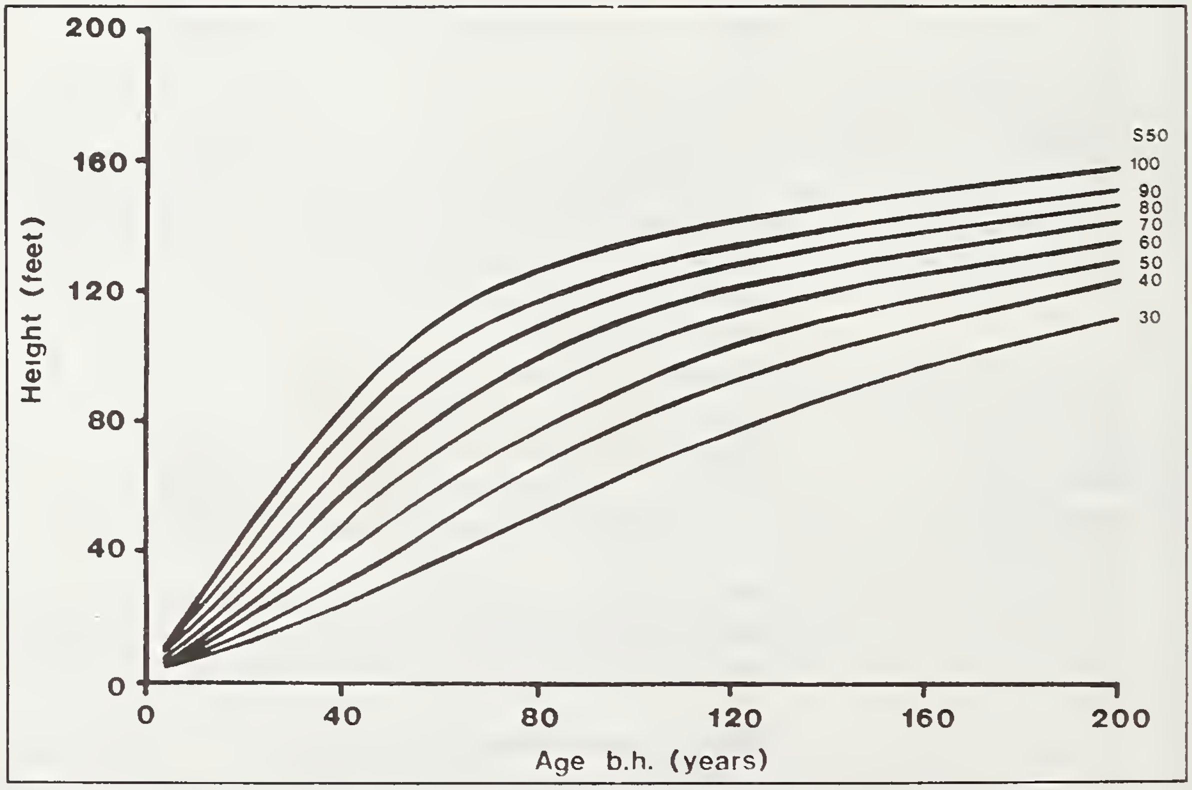

Figure 1—Height growth curves based on index age 50 years b.h., corresponding to equation (1).

Table 2—Mean deviations and root mean squared deviations, by age, from the height growth equation (1) based on index age 50 years b.h.

Age b.h.	Mean deviation (Hobs-Hest)	Root mean squared deviation (RMSD)[a]
Years	- - - - - - - - - - *Feet*	- - - - - - - - - - -
10	1.0	2.5
20	–.6	4.9
30	–1.1	5.2
40	–.2	3.8
50	0.0	0.0
60	–.3	3.2
70	–.6	4.6
80	–.4	6.3
90	.5	8.2
100	1.2	10.2
110	1.8	12.1
120	.6	11.7
130	–2.8	9.4
140	–2.3	10.4
150	–1.9	10.9
160	.6	10.6
170	1.8	11.3
180	1.6	11.2
190	2.9	11.9
200	4.4	14.3

[a] RMSD = $\sqrt{\text{sum(Hobs-Hest)**2/n}}$, where n = number of observations at the given age.

Standard errors of estimate of a weighted, conditioned equation are not readily interpretable, except as indices of comparative fit of alternative equation forms. We therefore calculated unweighted deviations (Hobs-Hest, where Hobs is observed height and Hest is the corresponding estimated height) for successive ages. Mean deviations and root mean squared deviations by ages are given in table 2.

Site index estimation equation, base age 50 years b.h.—A weighted regression of the general form w*S50 = w*f(H, A) was fit to the combined data, conditioned to meet the requirement that S50 = H when age = 50. (w is a weighting factor equal to the reciprocal of the SEE from the individual age regression, S50 = a * H ** b.) The resulting "best" equation, chosen by the same criteria as the height growth equation, was:

$$\begin{aligned} S50 = {} & \exp\{a^*[\ln(A)-\ln(50)] + b^*[\ln(A)-\ln(50)]^{**}2\} \; ^* \; H \; ^{**} \; \{1.0 \\ & + c^*[\ln(A)-\ln(50)] + d^*[\ln(A)-\ln(50)]^{**}2\} \; , \end{aligned} \qquad (2)$$

where

a = −2.608801,
b = −0.715601,
c = 0.408404, and
d = 0.138199.

The set of curves corresponding to equation (2) are shown in figure 2 in a form suitable for field application.

Unweighted deviations were calculated (Sobs-Sest, where Sobs is observed site index and Sest is the corresponding estimated value). Mean deviations and root mean squared deviations, by ages, are shown in table 3.

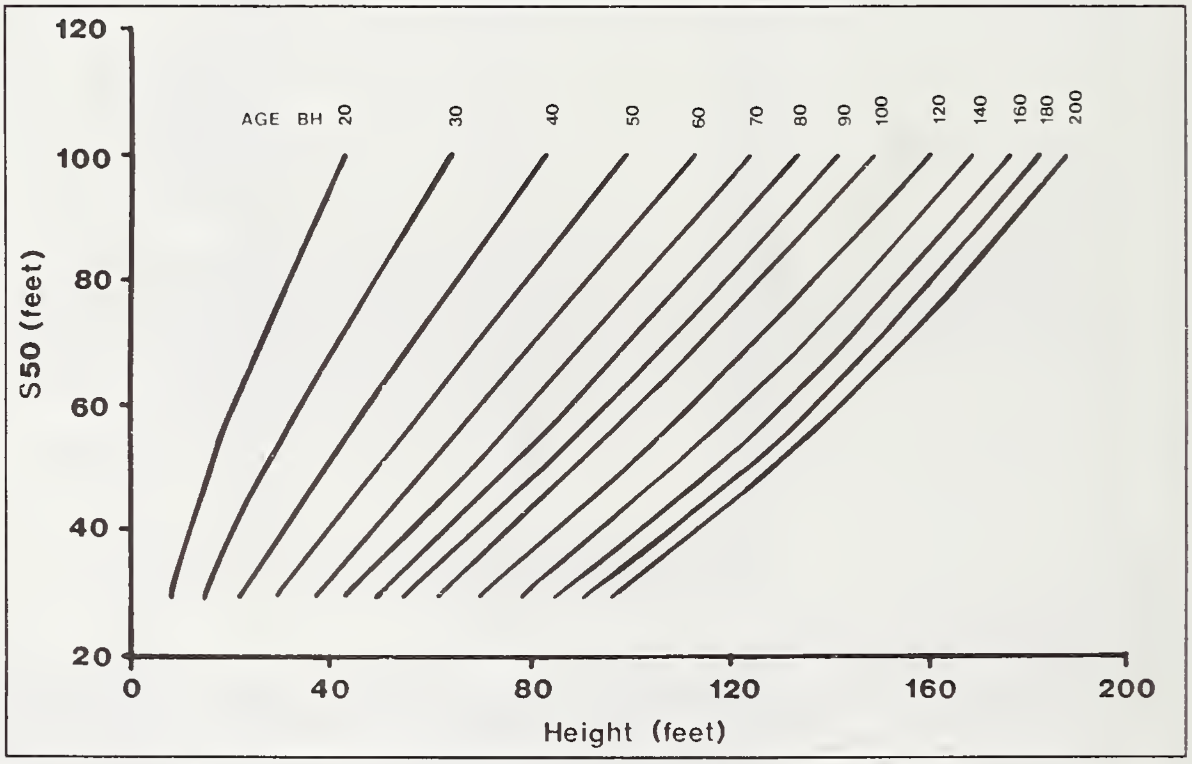

Figure 2—Site index estimation curves using index age 50 years b.h., corresponding to equation (2).

Table 3—Mean deviations and root mean squared deviations, by age, from the site index equation (2) based on index age 50 years b.h.

Age b.h.	Mean deviation (S50obs-S50est)	Root mean squared deviation (RMSD)[a]
Year	*Feet*	
10	–0.7	11.0
20	.8	10.5
30	1.5	7.4
40	.3	4.4
50	0.0	0.0
60	.1	3.0
70	.3	4.3
80	.2	5.8
90	–.3	7.3
100	–.5	9.1
110	–1.3	10.4
120	–.3	10.1
130	1.9	8.5
140	2.1	10.5
150	1.5	9.9
160	.1	10.2
170	.1	11.1
180	.7	11.3
190	–.6	11.5
200	–2.1	13.1

[a] RMSD = $\sqrt{\text{sum(S50obs-S50est)**2/n}}$, where n = number of observations at the given age.

Analyses Using Reference Age 100 Years B.h.

Height growth equation, base age 100—Height growth regressions were fit to the combined data by procedures similar to those used for equation (1), with the equations conditioned to meet the requirement that H = S100 (height at age 100) when age = 100. The best equation obtained was:

$$H = 4.5 + (S100-4.5)^{*} \frac{(1 - \exp\{-\exp[a + b^{*}\ln(A) + c/S100]\})}{(1 - \exp\{-\exp[a + b^{*}\ln(100) + c/S100]\})} \qquad (3)$$

where

a = –4.625365,
b = 1.346399, and
c = –135.354483.

Curves corresponding to this equation are shown in figure 3.

Unweighted deviations (Hobs-Hest) were calculated. Mean deviations, and root mean squared deviations, by ages, are shown in table 4.

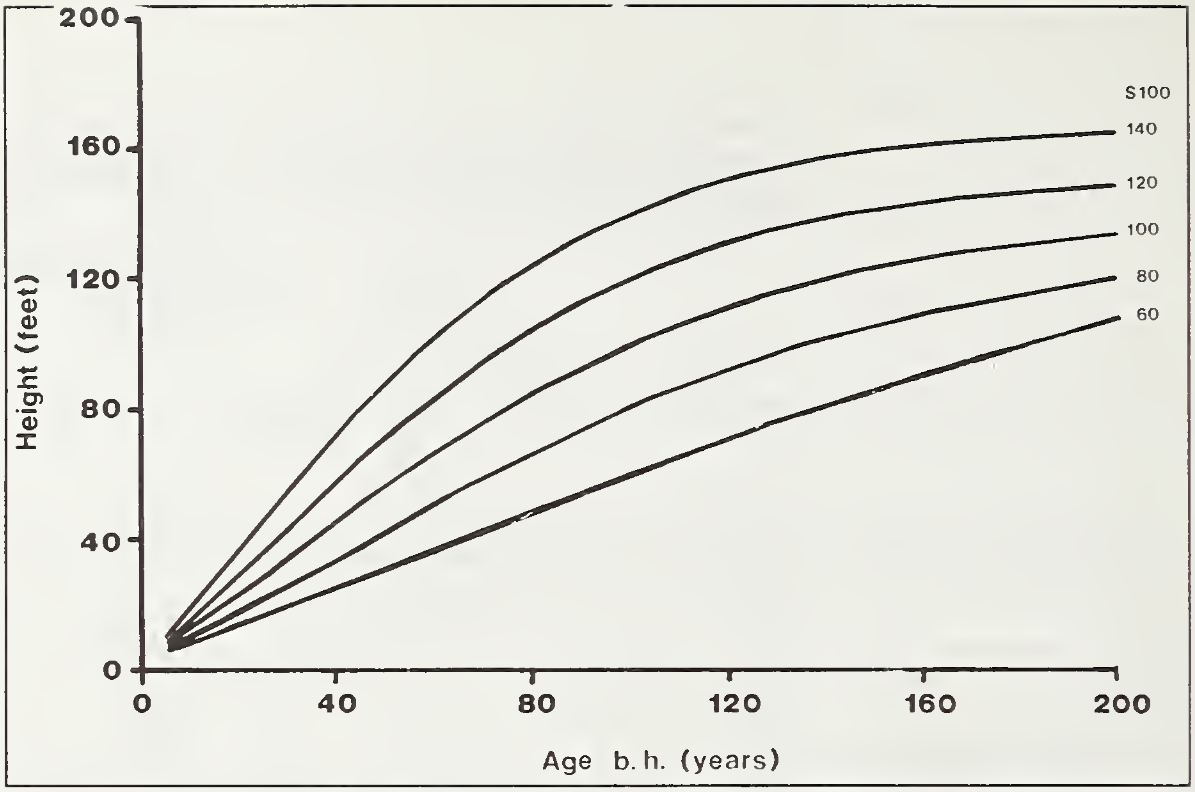

Figure 3—Height growth curves based on index age 100 years b.h., corresponding to equation (3).

Table 4—Mean deviations and root mean squared deviations, by age, from the height growth equation (3) based on index age 100 years b.h.

Age b.h.	Mean deviation (Hobs-Hest)	Root mean squared deviation (RMSD)[a]
Years	*Feet*	
10	0.3	2.8
20	–.9	7.3
30	–.7	8.9
40	.9	10.1
50	1.4	9.0
60	1.1	8.4
70	.1	7.3
80	–.3	5.7
90	0.0	3.3
100	0.0	0.0
110	–.2	3.1
120	–.6	4.9
130	–1.5	5.9
140	–1.5	7.2
150	–1.2	7.8
160	.1	8.5
170	.8	9.4
180	.5	8.9
190	1.9	9.9
200	4.3	12.0

[a] RMSD = $\sqrt{\text{sum(Hobs-Hest)**2/n}}$, where n = number of observations at the given age.

Site index estimation equation, base age 100 b.h.—Regressions were fit with S100 as dependent variable by procedures similar to those used for equation (2). The "best" equation, by the same criteria used elsewhere, was:

$$\begin{aligned} S100 = {} & \exp\{a*[\ln(A)-\ln(100)] + b*(A-100) + c*(A-100)**2\} \\ & *H**[1.0 + d*(A-100) + e*(A-100)**2] \qquad (4) \end{aligned}$$

where

a = 0.370720,
b = −0.0374501,
c = 0.000216448,
d = 0.005936683, and
e = −0.00003879058.

Curves corresponding to this equation, by ages, are shown in figure 4.

Unweighted deviations were calculated by ages. Mean deviations and root mean squared deviations are shown in table 5.

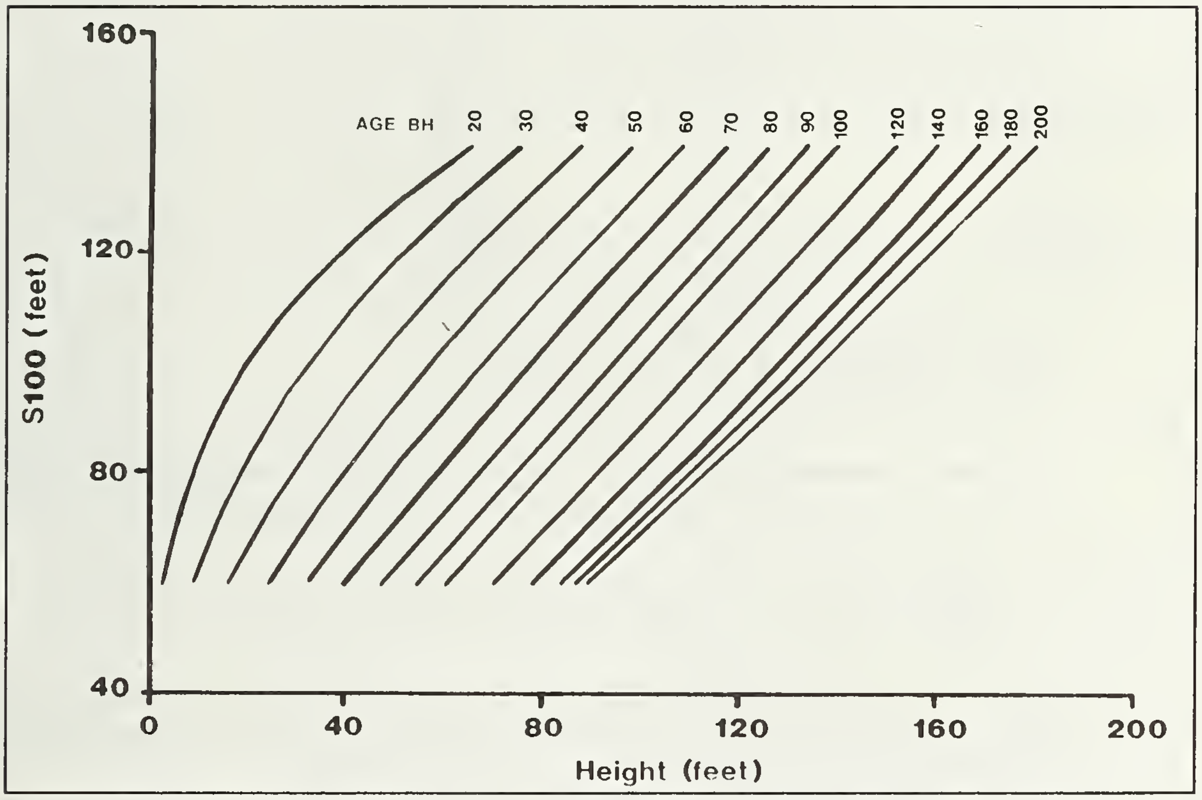

Figure 4—Site index estimation curves using index age 100 years b.h., corresponding to equation (4).

Table 5—Mean deviations and root mean squared deviations (RSMD), by age, from the site index equation (4) based on index age 100 years b.h.

Age b.h.	Mean deviation (S100obs-S100est)	Root mean squared deviation (RMSD)[a]
Years	*Feet*	*Feet*
10	–1.3	17.3
20	.2	16.4
30	1.2	14.5
40	.4	13.0
50	0.0	10.3
60	.2	9.2
70	.5	7.8
80	.6	5.8
90	.1	3.3
100	0.0	0.0
110	.3	3.0
120	.7	4.8
130	1.6	5.8
140	1.5	7.2
150	1.2	8.1
160	.2	9.1
170	–.3	10.3
180	.2	10.0
190	–1.4	11.1
200	–4.7	12.4

[a] RMSD = $\sqrt{\text{sum(Hobs-Hest)**2/n}}$, where n = number of observations at the given age.

Regressions Between the Two Site Indices

The relation between values of S50 and S100 (heights measured at ages 50 and 100) from the same 38 trees can be expressed by the regressions:

$$S50 = -13.10 + 0.7146{*}S100 \qquad r{**}2 = 0.70 \qquad SEE = 9.1\text{ , and} \qquad (5)$$

$$S100 = 43.83 + 0.9810{*}S50 \qquad r{**}2 = 0.70 \qquad SEE = 10.7\text{ .} \qquad (6)$$

Discussion

The above analysis has produced four distinct equations that, when plotted, give systems of curves differing in shape and application. Other methods of analysis exist that would produce yet other curves.

The fact that the same data can be analyzed by different methods and produce multiple sets of curves that are different—while superficially resembling traditional "site index curves"—is initially disconcerting. One feels instinctively that there should be one "correct" set of curves.

Unfortunately, this is not the case. The "correct" set depends on the question asked and on the assumptions that one is willing to accept.

Height Growth Curves vs. Site Index Estimation Curves

Traditional forestry practice has been to use a single set of "site index curves" to provide estimates of both the height expected for a given age and site and the site index value corresponding to an observed height and age. But it is well known that inversion of a regression equation results in biased estimates. Curtis and others (1974) show that, consistent with this principle, better estimates of site index (height at a standard age) are obtained when site index is treated as the dependent variable. The systems of curves obtained have characteristically differing shapes when plotted on comparable axes.

The height growth curves and site index estimation curves presented here have different interpretations and represent answers to different questions.

The height growth curves provide estimates of the average heights at successive ages of trees that attained the specified height (site index) at the specified reference age. (More generally, height growth curves represent average growth trends of trees grouped by some specified criterion, such as site index, soil attributes, plant associations, etc.) Such curves are appropriate for uses like yield table construction, where predictions of average trends for land of known site index are wanted.

Conversely, the site index estimation curves provide estimates of the expected height (site index) at the specified reference age of trees that have a given observed height when measured at some other age. They are appropriate for classifying land by site index. They will not be the same as the height growth curves when plotted on similar axes; the differences depend on both the variability of the data and the index age selected.

We have not attempted to compare these curves with Haig's (1932), because of our belief that differences in methodology and interpretation will obscure any real biological differences that may exist between the regions.

The regression methods used here will lead to somewhat different results than methods such as the technique of Osborne and Schumacher (1935), widely used before the widespread use of stem analyses.

Although the major disadvantage of the Osborne and Schumacher technique is the uncertainty whether sites are equally represented at all ages, there is also a conceptual difference. The Osborne and Schumacher technique classifies sites according to the percentile position of height relative to the distribution of heights at each age. "Site index" is merely a label attached to the curves formed by connecting the corresponding percentile points for successive ages. The curves are therefore age-invariant. This is certainly a plausible way of classifying sites—a site that has above-average heights at one age will probably also have above-average heights at other ages—but assumes that trees near the extremes of the distribution will on average retain the same relative position over time. This is not strictly true, and the regression methods used here do not make this assumption.

Choice of Index Age

Older systems of curves, including Haig's (1932), commonly used age 100 as the basis for site index. Because curves prepared by the old guide curve procedures are index age-invariant, this was merely a handy convention that was roughly consistent with expected rotation ages.

The regression methods of preparing curves from stem analysis data used here are not index age-invariant; the choice of index age influences both shape of the curves and accuracy of site classification. This superficially disconcerting fact, apparently first pointed out by Heger (1973), makes choice of index age a matter of some consequence.

One can argue that, because volume production is closely related to height, the most meaningful index age is one approximating expected rotations. For relatively poor sites on National Forest lands that are likely to be managed on relatively long rotations, an index age of 100 is consistent with this argument and with past practice.

Curves based on index age 100 give poor estimates of early growth, however, and site index estimates made at early ages are necessarily highly inaccurate. It can be argued that in actively managed stands handled on moderate rotations, index age should be selected to give reasonably good height growth estimates over as much of the expected managed stand range in ages as feasible while allowing reasonable accuracy in site index estimates over this range. In recent years, this line of thought has led to adoption of an index age of 50 years b.h. for several associated species.

Inspection of the coefficients of determination (r**2) values in table 1 and the deviations shown in tables 3 and 5 indicates that measurements of over-rotation-age trees will give considerably more precise estimates of S100 than of S50; however, S50 is likely to be more useful as a predictor of behavior of younger, actively managed stands. It therefore seems to us that equations (1) and (2) are the most suitable for general use. Because the choice is a matter of subjective judgment and is somewhat dependent on objectives, we have included alternative equations (3) and (4). These are also of interest as illustrations of the effect of index age on curve shape.

With the small number of sample trees available beyond about age 150, estimates are in any case unreliable for older stands. For estimates based on index age 50, the problem is compounded by the inherently low correlations between S50 and heights at advanced ages.

There is no direct and exact conversion between S50 and S100. If the original height and age values are available in the record, or can be recovered from recorded age and estimated site index, the best procedure is to enter the alternative system of curves using these values. Lacking this information, a rough conversion may be made by using equations (5) and (6).

Some Caveats

The biggest objection to the old guide curve procedures, as used by Haig (1932) and others of that period, is that they depend on the assumption that average site quality in the sample is the same for all age classes. This is generally untestable and sometimes clearly untrue. Stem analysis data and regression methods more or less similar to those used here are now generally accepted as superior, but these also have some drawbacks.

A major and frequently questionable assumption is that past heights of trees now dominant represent average heights of dominants of ages corresponding to past ages of the trees sampled. Because we cannot know the conditions under which trees now mature and dominant were growing in early youth, this assumption may be incorrect. Bias can be minimized by careful selection of sample trees on the bases of (1) external appearance, (2) inspection of annual ring patterns and height growth patterns for anomalies suggesting early suppression or past damage, and (3) comparison of growth patterns with that of other sample trees from the same location.

In our data, we had only one tree per location. It was not possible to use comparisons with other trees at a location as a basis for recognizing trees that were not dominant in early youth. Although we eliminated several trees because of anomalies and early growth patterns that strongly suggested early suppression or damage, there can be no exact and unambiguous criteria, and uncertainty remains.

Even after clearly unacceptable trees were eliminated, the remaining trees still showed much variation in height growth patterns. To the extent that some part of this variation may represent unrecognized differences in early competition and changes in crown position, so that the sample trees are not representative of dominant trees in present young stands, this must introduce biases and exaggerate the differences between the several systems of curves presented here. Bias could also arise from climatic change. It is reasonable to expect that plantations and young stands having early density control will exhibit considerably more regular, and probably somewhat different, growth patterns than did our sample trees.

Because the area from which most sample trees were taken—high elevation stands near the Cascade crest—is more limited than the area where white pine is potentially of interest in the region, application of these curves will unavoidably involve extrapolations beyond the geographic area and sites sampled.

These uncertainties unfortunately cannot be resolved with the data now available. These equations are the best we can do at this time and are recommended for interim use until it becomes possible to develop new curves from remeasurements of young stands.

Applications

Because the trees sampled were scattered individuals in mixed stands, they do not represent any numerically defined stand component, but "typical dominants." Therefore, site index estimates should be based on heights and ages measured on individuals selected as typical dominants. Consistency in application is more important than the exact definition used. Trees showing any external evidence of injury likely to affect height growth, or showing a ring pattern suggesting early suppression, should be excluded. For the measured height and age b.h. of each tree, enter equation (2) or (4) or the corresponding graphs (figures 3 or 5) to obtain an estimate of site index. Average the individual tree site index estimates for a location to obtain the stand site index estimate. Sample enough trees so that the standard error of the mean of the site index estimates for the location is within user-defined acceptable limits.

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Height growth and site index curves were constructed from stem analyses of mature western white pine (*Pinus monticola* Dougl. ex D. Don) growing in high-elevation forests of the Cascade Range in the Mount Hood and Gifford Pinchot National Forests of Oregon and Washington, respectively. Alternate systems using reference ages for site index of 50 and 100 years breast height are presented. Differences among systems and their causes are briefly discussed.

Keywords: Site index, height growth curves, stem analysis, western white pine, *Pinus monticola*.

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