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# Height Growth and Site Index Curves for Red Alder

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## Abstract

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New height growth and site index curves for red alder (*Alnus rubra* Bong.) were developed from stem analysis data. The analyses use a reference (site index) age of 20 years and are applicable to natural stands between 5 and 50 years of age in western Washington and northwestern Oregon. The new curves are polymorphic and provide a better fit to observed patterns of height growth than the previously available curves. Although differences from previously available curves are not large, the new curves should be an improvement, particularly for use in short-rotation management. Recommendations associated with the new curves for converting breast height age to total age vary with site quality. Relationships between red alder height growth or site index and selected site characteristics are briefly discussed.

Keywords: Increment (height), site index, site class, red alder, *Alnus rubra*.

## Summary

New height growth and site index estimation curves were developed for red alder (*Alnus rubra* Bong.) using stem analysis data from two sources: (1) new data from 23 natural stands in western Oregon and Washington and (2) previously published stem analysis data from western Washington. The new curves are polymorphic and use an index age of 20 years total age. The new height growth curves are recommended over previous curves because:

1.They are based on a much larger sample of trees covering a greater geographic range and a somewhat greater range in site index.
2. The reference age of 20 years is more appropriate to future short rotation management of the species than the 50 years formerly used.
3. The more flexible growth function used in the new curves provides a better expression of observed height growth trends.

The new red alder site index estimation curves, rather than the height growth curves, are recommended for use in estimating site index ($S_{20}$). Differences in estimates obtained from the two types of curves between ages 15 and 40 are of theoretical rather than practical importance; however, somewhat more accurate estimates of $S_{20}$ can be made using the site index estimation curves, particularly for stands that are outside these limits.

We found the difference between total age and breast height age to vary somewhat with site quality and recommend only a 1-year adjustment for average sites.

Selected site characteristics were examined for possible effects on patterns of height growth or site index. We concluded that:

1. The data suggest a possible, but statistically nonsignificant, relationship of soil drainage class with shape of height growth curves. Other site characteristics had no apparent effect. A considerably larger sample would be needed to reach any conclusions.
2. There is no close relationship between red alder site index and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site class, for the areas studied. This is probably primarily a result of differences in species site requirements.

# Contents

## Introduction

Red alder (*Alnus rubra* Bong.) is the most common hardwood species in the Pacific Northwest. The species makes rapid juvenile growth, has the ability to fix atmospheric nitrogen, and appears adaptable to some sites not well suited to conifers. These characteristics have aroused interest in alder as a short-rotation (15-25 years or less) crop, both in pure stands and in rotation or in mixture with conifers.

The rapid juvenile height growth of the species makes it a prime prospect for short-rotation biomass production and a severe competitor with associated species. There is, therefore, interest in its pattern of juvenile height growth. The published site curves for the species (Bishop and others 1958, Worthington and others 1960) use an index age of 50 years, and the tables and graphs presented do not extend below 10 years of age.

This report presents new height growth and site index curves for red alder. These are based on a combination of new stem analysis data from trees in western Washington and northwestern Oregon and of the western Washington data used to construct the earlier curves. Index age used is 20 years total age.

## The Data

### New Data

Twenty-three natural red alder stands in western Washington and northwestern Oregon were selected to provide a range in geographic location, site quality, and soil conditions. The information collected on each stand included: (1) elevation, (2) slope, (3) aspect, (4) soil drainage class, and (5) estimated Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site class (King 1966). Where possible, Douglas-fir site class was determined by measuring heights and ages of 5 to 10 dominant and codominant Douglas-fir in an adjacent stand growing on the same soil series. When suitable Douglas-fir trees were not available, site class was estimated from information available for that series[1/] (Anderson and others 1956, Ness and others 1960, Steinbrenner and Gehrke 1964, and other available soil-site information). The range of site characteristics is shown in table 1.

In each stand, four to six dominant or codominant trees were selected that appeared free from evidence of past damage. These were felled and sectioned at 0.5-m intervals of height. The sections were labeled in the field with tree number and section height and then transported to the laboratory for immediate processing. Age of each section was determined by counting annual rings. When necessary, sections were sanded or recut to expose a fresh surface.

For each tree, heights were plotted over ages, and trees with irregular growth patterns suggesting past damage or suppression were rejected. For the remaining 117 trees, the years required to reach breast height (1.3 m) and the heights attained at ages 2, 4, 8, 12, 16, 20, 24, . . . were read from the graphs and used in subsequent analyses.

### Old Data

A supplemental set of red alder stem analysis data, used to construct the earlier red alder curves, is given in table 5 of Johnson and Worthington (1963). The data are from western Washington. No other information is available on site characteristics. We plotted heights over ages for each tree. Values of heights corresponding to ages 4, 8 16, 24, 32, 40, 48, and 56 were read from these graphs and used in portions of later analyses. The total number of trees represented at each age, by data sets, is given in table 2.

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[1/] Unpublished information on potential productivity by soil type furnished by Private Land Grading Program, Washington Department of Natural Resources, Olympia, WA. 1982.

**Table 1—Range of site characteristics in red alder stands sampled for height growth**

| Characteristic | Range |
| --- | --- |
| Latitude | 45°-49° N. |
| Elevation | 0-750 meters |
| Slope | 0-30 percent |
| Aspect | 0°-360° azimuth |
| Soil drainage | poorly drained to well drained[1/] |
| Douglas-fir site class | I-VI[2/] |

[1/] Coded for purposes of analysis as:
1 = SCS class very poorly drained,
2 = SCS classes poorly drained and somewhat poorly drained, and
3 = SCS classes moderately well-drained and well-drained.
SCS classes are from USDA Soil Conservation Service 1975.
[2/] Site classes I-V as in King (1966); sites judged unsuitable for Douglas-fir were designated VI.

**Table 2—Number of red alder trees available for data analysis, by age and source of data**

| | Number of trees | | |
| --- | --- | --- | --- |
| Age | New data | Old data[1/] | Total |
| 2 | 117 | — | 117 |
| 4 | 117 | 39 | 156 |
| 8 | 117 | 39 | 156 |
| 16 | 117 | 39 | 156 |
| 20 | 117 | 39 | 156 |
| 24 | 87 | 39 | 126 |
| 32 | 51 | 39 | 90 |
| 40 | 11 | 39 | 50 |
| 48 | 3 | 28 | 31 |
| 56 | 0 | 20 | 20 |

— = no data.
[1/] From Johnson and Worthington (1963).

## Analysis

Height attained at age 20 ($S_{20}$) was selected as the reference age for indexing curves because it seemed a reasonable index age for use with the short rotations anticipated for the species, and because all locations had a mean age of at least 20 years. Distribution of the data by mean values of $S_{20}$ for each location is shown in figure 1.

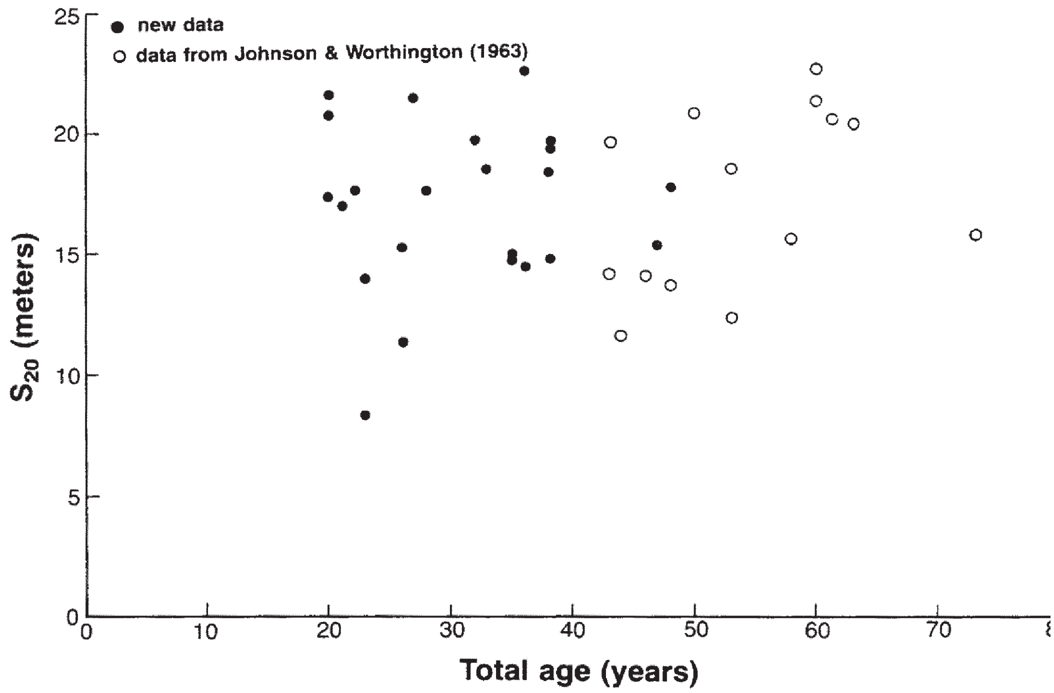


Figure 1.—Distribution of data (location means) by age, $S_{20}$, and data set.

## Preliminary Graphic Curves

Preliminary height growth curves were prepared using Heger's (1968) method for (1) the new data, (2) the old data, and (3) both data sets combined. For each age, sample trees were pooled and regressions of the form $H = a + b\ S_{20}$ were fit. The simple linear regression appeared to adequately describe the relationship between H and $S_{20}$. Next, the values 10, 15, 20, and 25 meters were substituted for $S_{20}$ for the successive ages, and the resulting height estimates were plotted over age. These points were then connected with freehand curves to give a first estimate of the desired system of height growth curves. These curves—referred to below as the Heger or graphic curves—were used for initial comparisons among data sets and as guides in selection of algebraic form of height growth curves.

## Height Growth Regressions: New Data

Initial trials with the preliminary curves indicated that a suitable equation would be (Prodan 1968, p. 370):

$$H = a(1.0 — e^{bAge})^c, \qquad (1)$$

in which "e" is the base of natural logarithms and "a," "b," and "c" are parameters to be estimated. Trials also indicated that at least two of the three constants were functions of $S_{20}$,. Exploration led to the curve form,

$$H = (a+ bS_{20})(1.0 — e^{(c+bS_{20})(Age)})^f. \qquad (2)$$

By definition, curves must pass through index height at index age; that is, when age = 20, H = $S_{20}$. Therefore,

$$S_{20} = (a + bS_{20})(1.0 — e^{(c+bS_{20})(20.0)})^f. \qquad (3)$$

Subtracting equation 3 from equation 2 and adding $S_{20}$ to both sides of the equation gives:

$$H = S_{20} + (a + bS_{20})(1.0 — e^{(c+bS_{20})(Age)})^f \qquad (4)$$

$$— (a + bS_{20})(1 0 — e^{(c+bS_{20})(20.0)})^f.$$

## Comparisons of Curve Shape With Tree and Stand Variables

This was fitted to values of individual tree heights at ages 2, 4, 8, 12, 16, . . ., for the new data only. Standard error of estimate was 0.9496. These curves were used in the comparisons given below, which involve information not available in the old data.

An effort was made to determine whether deviations from average curve shape were associated with measured tree and site variables, which were available for the new data only. Because curves were forced through the points (0,0) and ($S_{20}$,20), any deviations from the average curve shape should be most evident midway between these points. A relative difference ($H_{obs}$ - $H_{est}$)/$H_{est}$, was calculated for each tree at age 12, and used as the measure of deviations from average curve shape.

**Crown classes.—**The deviations from average curve shape gave no indication of differences between trees classed as dominants and those classed as codominants. (This does not imply that there were no differences in growth between crown classes, but rather that the relative shape of the curves did not differ by crown class.) Therefore, the few codominant trees in the sample were combined with the dominants, and plot means of these relative deviations were used in the remaining comparisons.

**Site characteristics.—**Plot mean relative deviations were plotted against elevation, aspect, slope, and drainage class. The only suggestion of a relationship was with drainage class, where mean deviations for drainage class 2 were larger than those for classes 1 and 3. A considerably larger number of observations would be needed, however, to provide an adequate test of the possible effects of various site characteristics, and no definite conclusions can be drawn.

## Comparison of Red Alder $S_{20}$ Among Douglas-Fir Site Classes

Mean values of $S_{20}$ were calculated for each location, and these were grouped by Douglas-fir site index classes I-VI Analysis of variance indicated no significant difference ($p = 0.10$) for differences in mean red alder $S_{20}$ among Douglas-fir site index classes. Sites classified as excellent for Douglas-fir (I and II) consistently had above average $S_{20}$ values for alder; however, some of the highest red alder $S_{20}$ values were on sites classified as unsuitable for Douglas-fir.

## Adjustment of Breast Height Age

Bishop and others (1958) recommend adding 2 years to breast height age to estimate total age. The new data, however, suggest that only a 1-year adjustment is necessary for average sites ($S_{20}$ of 15 or 20 m). No adjustment to breast height age is necessary when $S_{20}$ is 25 m or higher, while a 2- or 3-year adjustment is needed for the poorest sites ($S_{20}$ less than 15 m).

## Height Growth Regressions: Combined Data

Although our primary interest was in young stands, it seemed clearly desirable that the final curves should represent as wide an age range as feasible. The graphic (Heger) curves for the new and old data sets were compared. Small differences were observed at young ages (under age 5), which may be attributable to minor differences in the procedures used to determine total age. Larger differences between the curves were present beyond about age 32. Past age 32, the Heger curves for the new data are primarily extrapolations beyond the available data; thus, differences between the curves probably do not represent actual differences in height growth. We chose to use the combined data sets in preparing the final curves.

Data used for the final curves were the 902 heights corresponding to ages 2, 4, 8, 16, 24, 32, 40, 48, and 56. Those for age 2 were from the new data only because there were some irregularities and interpolation difficulties at this age in the old data. The combined data were used for all other ages. Values for ages 12, 28, 36, 44, and 52 in the new data were omitted to keep the number of observations within the limits of the nonlinear fitting program used and to provide consistency between data sets.

A regression of the form of equation 4 was fitted to these data and gave the following coefficient estimates (metric units):[2/]

$$\begin{aligned} a &= 18.1622, \\ b &= 0.7953, \\ c &= 0.001940, \\ d &= -0.002441, \\ f &= 0.9198, \text{and} \\ \text{standard error of estimate}^{3/} &= 1.1963. \end{aligned} \qquad (5)$$

Height growth curves corresponding to this equation are shown in figures 2 (metric) and 3 (English units).

[2/] Coefficients for English units are:
a = 59.5864,
b = 0.7953,
c = 0.001940,
d = -0.0007403,and
f = 0.9198.

[3/] Calculated standard errors of estimate are not very meaningful because observations were not independent (which probably results in underestimates) and because variances were not homogeneous (see appendix).

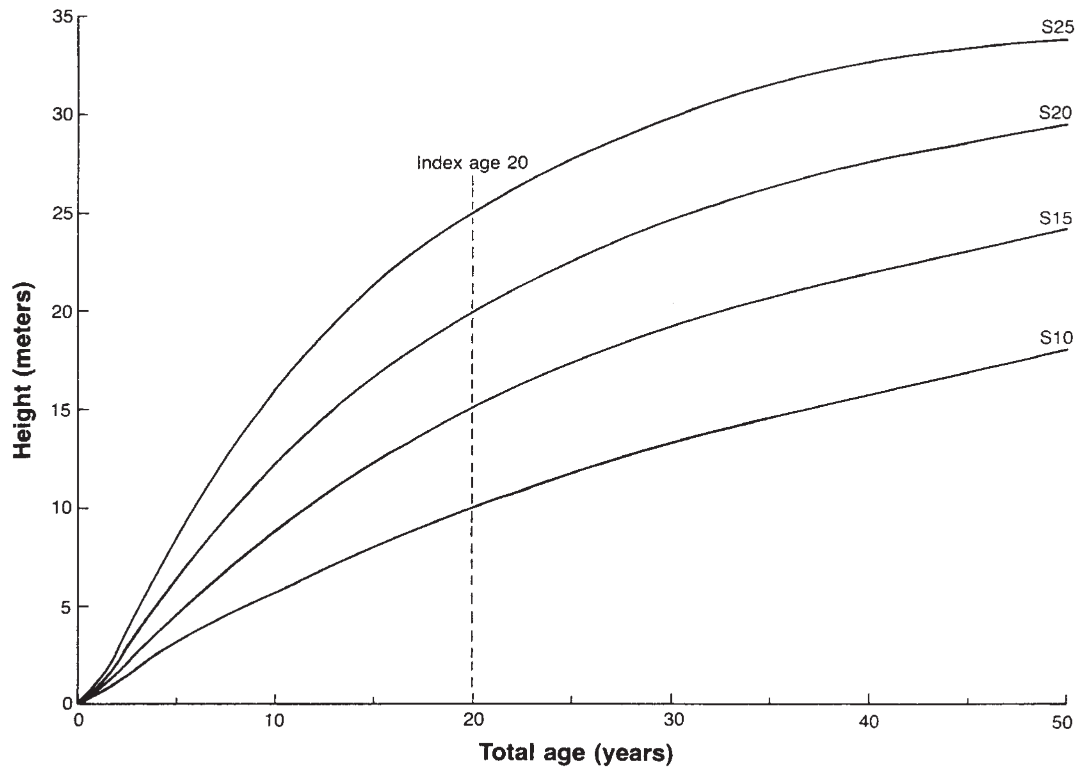


Figure 2.—Height growth curves corresponding to equation 5, combined data, in metric units.

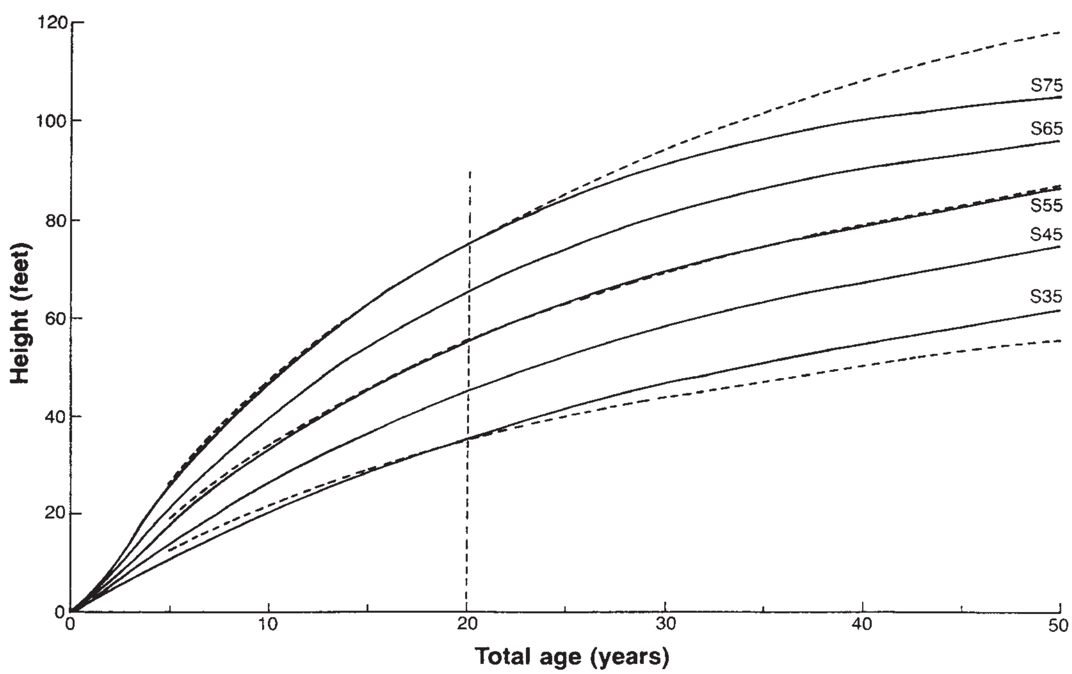


Figure 3.—Solid curves represent height growth curves corresponding to equation 5, combined data, in English units. Dotted curves are those of Bishop and others (1958) plotted from the equation given in Johnson and Worthington (1963).

**Site Index Estimation Curves**

Regressions of the form $S_{20} = a + bH$ were fitted to the combined data for each age and were used to construct preliminary site index estimation curves. These preliminary curves were used as guides to selection of equation forms expressing “a” and “b” as functions of age, conditioned to meet the logical requirement that $S_{20} = H$ when age = 20. This led to a regression, fitted to the combined data, of the form:

$$(S_{20} - H) = f_1(\text{age}) + f_2(\text{age})H;$$

with standard error of estimate of 1.90.

This can be written as :[4/]

$$S_{20} = a + bH;$$

with :

$$a = 16.5158 - 1.40726(\text{age}) + 0.033727(\text{age})^2 - 0.00023267(\text{age})^3$$

and:

$$b = 1.25934 - 0.012989(\text{age}) + 3.5220(1/\text{age})^3$$

Corresponding graphs for estimation of site index are given in figures 4 (metric) and 5 (English units).

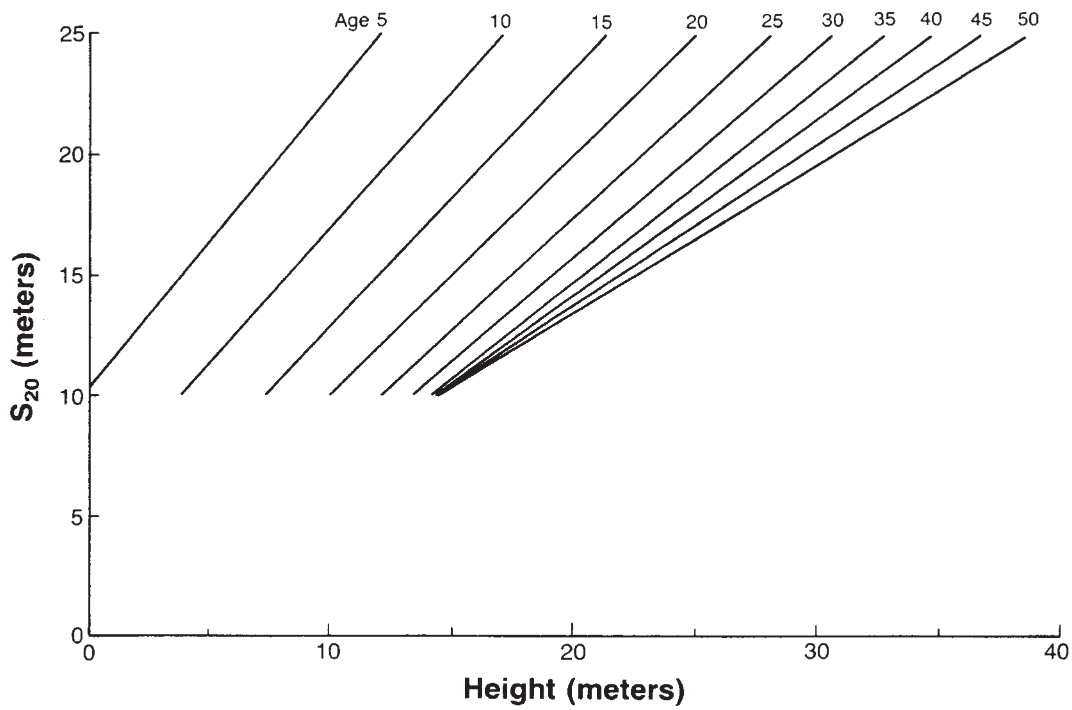


Figure 4.—Site index estimation curves corresponding to equation 6, combined data, in metric units.

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[4/] The corresponding expressions in English units are:
$a = 54.1850 - 4.61694\,(\text{Age}) + 0.11065\,(\text{Age})^2 - 0.0007633(\text{Age})^3$, and
$b = 1.25934 - 0.012989\,(\text{Age}) + 3.5220\,(1/\text{Age})^3$

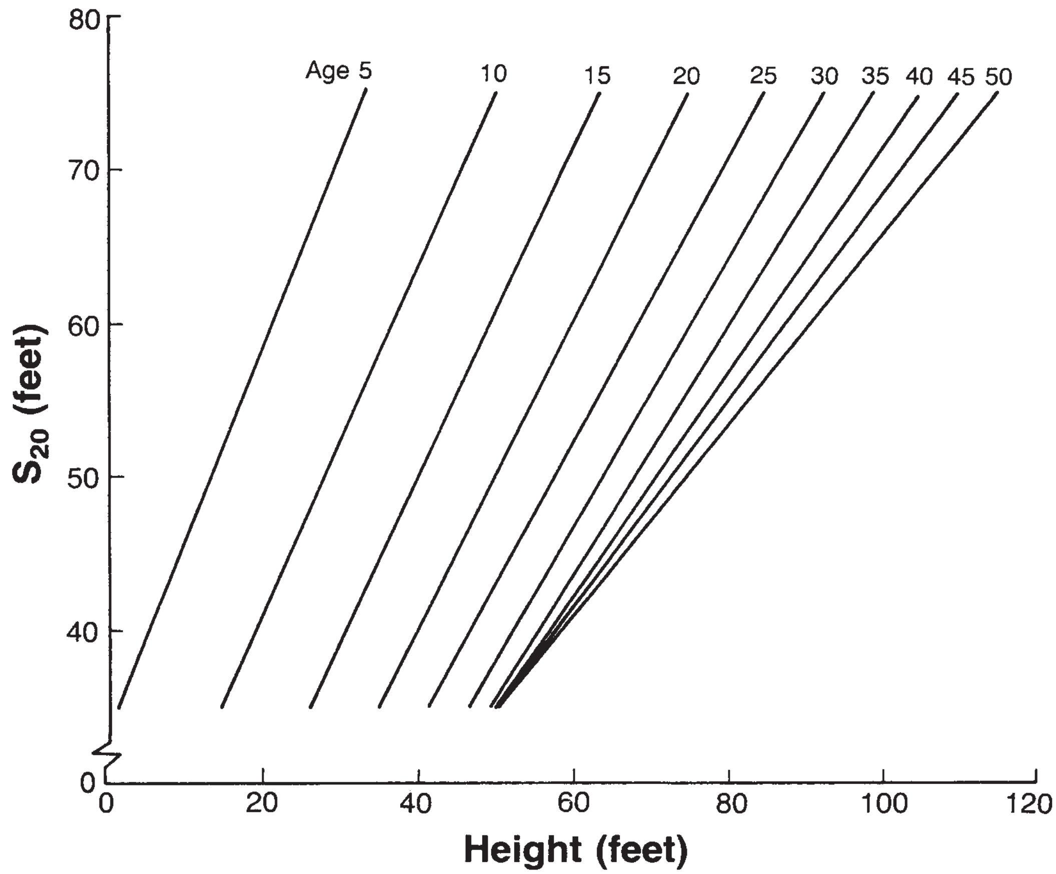


Figure 5.—Site index estimation curves corresponding to equation 6, combined data, in English units.

## Discussion

### Red Alder Site Index and Douglas-Fir Site Class

Differences in red alder $S_{20}$ among Douglas-fir site classes were not significant. This result can be attributed to some combination of error in classification of Douglas-fir sites and differences in species characteristics and site requirements. For example, some sites may have been misclassified as to their Douglas-fir site classification because of the variation in site quality that occurs within soil mapping units, and because of the uncertain comparability of adjacent areas on which Douglas-fir trees were available for measurement.

Basic differences in species' site requirements are probably also a major factor. Compared to Douglas-fir, red alder is more tolerant of occasional flooding, poor soil drainage, and low soil nitrogen (Minore 1979). Some of the best red alder sites were on flood plains of major rivers. Red alder can also tolerate boggy or marshy situations that would be considered unsuitable for Douglas-fir. And Douglas-fir site quality is partially dependent on soil nitrogen availability, which is of less importance to red alder because of its nitrogen-fixing ability. Douglas-fir, on the other hand, has greater cold-hardiness, especially to unseasonable frosts. In addition, because of its ability to carry on photosynthesis during the winter (Waring and Franklin 1979) and its determinate pattern of height growth, Douglas-fir may be able to better utilize sites with deep, well-drained to somewhat excessively drained soils.

### Comparison of New Height Growth Curves With the Previous Curves

The height growth curves of Bishop and others (1958) are shown as dotted curves in figure 3 and are superimposed on the new height growth curves prepared from the combined data. Although generally rather similar, the curves diverge at advanced ages and also at ages below 10-15 years.

The graphic height growth curves prepared from the old data by the Heger method were compared with the curves of Bishop and others (1958) and with the new height growth curves prepared from the combined data. The pattern of height growth shown by the Heger curves was in much closer agreement with the new curves than with the old curves. We think the improvement in fit with the new curves is mainly a result of using a more flexible function that is capable of representing polymorphic curves and an inflection at young ages.

The new curves are clearly an improvement over the old. They incorporate an extensive new sample that considerably extends the geographic range, and yet they also appear to better represent the old data.

## Height Growth and Site Index Estimation Curves: Differences and Applications

Height growth curves provide estimates of the average growth pattern of trees and stands on land of known site index. They represent the pattern of biological growth. Although foresters customarily refer to such curves, derived as regressions of height on age and site index, as “site index curves,” according to accepted biological terminology they are “growth curves.

Foresters commonly estimate site index—height at a specified reference age—by inverting the growth equation and solving for site index. This violates the general principle that the quantity to be estimated should be the dependent variable in regression. Estimating equations fitted with site index as the dependent variable give different and better estimates of site index for trees of measured present height and age (Curtis and others 1974), although the differences may often be of minor practical importance. See the appendix for a comparison of residuals for the two methods, using these data.

If the objective is to estimate the sequence of heights over time expected on land of a given site index, the height growth equation (equation 5; figures 2 and 3) is appropriate. Conversely, if the objective is to estimate future or past height of a tree at age 20 ($S_{20}$), given its present height and age, then the site index estimating equation (equation 6; figures 4 and 5) is superior. For the latter, the plot or stand site index estimate is obtained as an average of individual tree estimates.

The height growth and site index estimation equations presented in this paper were based on measurements of dominant and codominant trees in unmanaged stands of natural origin. Possible forest management practices—such as planting, cultivation, or early spacing control—could be expected to increase tree height and to result in less variable and possibly different juvenile growth patterns. If growth patterns are altered by intensive management practices, both the height growth and site index estimation relationships could be affected.

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Pope and Talbot, Inc.
USDA Forest Service, Pacific Northwest Region
State of Washington, Department of Natural Resources
Washington Irrigation and Development Co.
Weyerhaeuser Co.

## English Equivalent

1 meter = 3.28 feet

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# Appendix

## Comparison of Residuals

For the height growth equation, variances are zero at origin and index age; for the site index estimation equation, variance is zero at index age. Variances increase with distance from these points, and calculated standard errors of estimate are not very informative. We therefore calculated means and standard deviations of the residuals, ($Y_{obs}$ - $Y_{est}$), for each age 2, 4, 8, . . .,56, using the combined data. These values are shown in figures 6 and 7.

Site index estimates are often calculated by inversion of the height growth equation. Although algebraic inversion of equation 5 is not possible, equivalent estimates can be calculated iteratively. Means and standard deviations of residuals for such estimates are shown as dotted lines in figure 7. This provides a comparison of residuals from direct estimates of site index using equation 6 with those for the indirect estimates obtained by inversion of the height growth equation, equation 5. Differences at advanced ages are rather erratic reflecting the changing sample with declining number of trees at successive ages. The general pattern is as expected, however, with differences between estimates increasing with distance from the reference age.

The best estimates of $S_{20}$ are obtained by using the site index estimation equation. It is evident from figure 7, however, that there is little practical difference in estimates of $S_{20}$ using either the height growth equation or the site index estimation equation, within the age range of 15-40 years. The site index estimation equation will provide substantially better estimates of $S_{20}$ for ages outside these limits. Because the standard deviation of actual heights at age 20 ($S_{20}$) is about 3.4, it is also obvious that neither equation gives useful estimates of $S_{20}$ for stands below about age 5. Measurements of height and age alone cannot provide useful site estimates in very young stands.

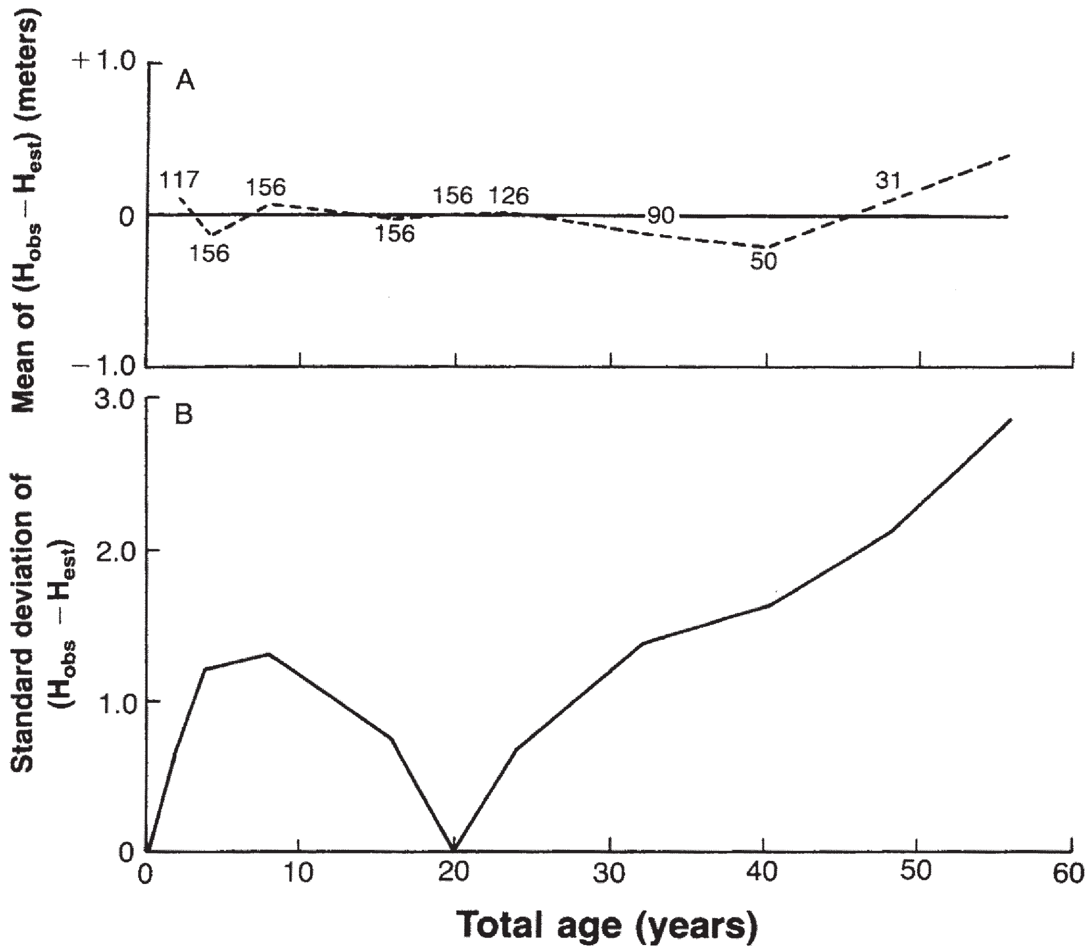


Figure 6.—Means (**A**) and standard deviations (**B**) of differences (observed height - estimated height), from height growth equation 5, combined data.

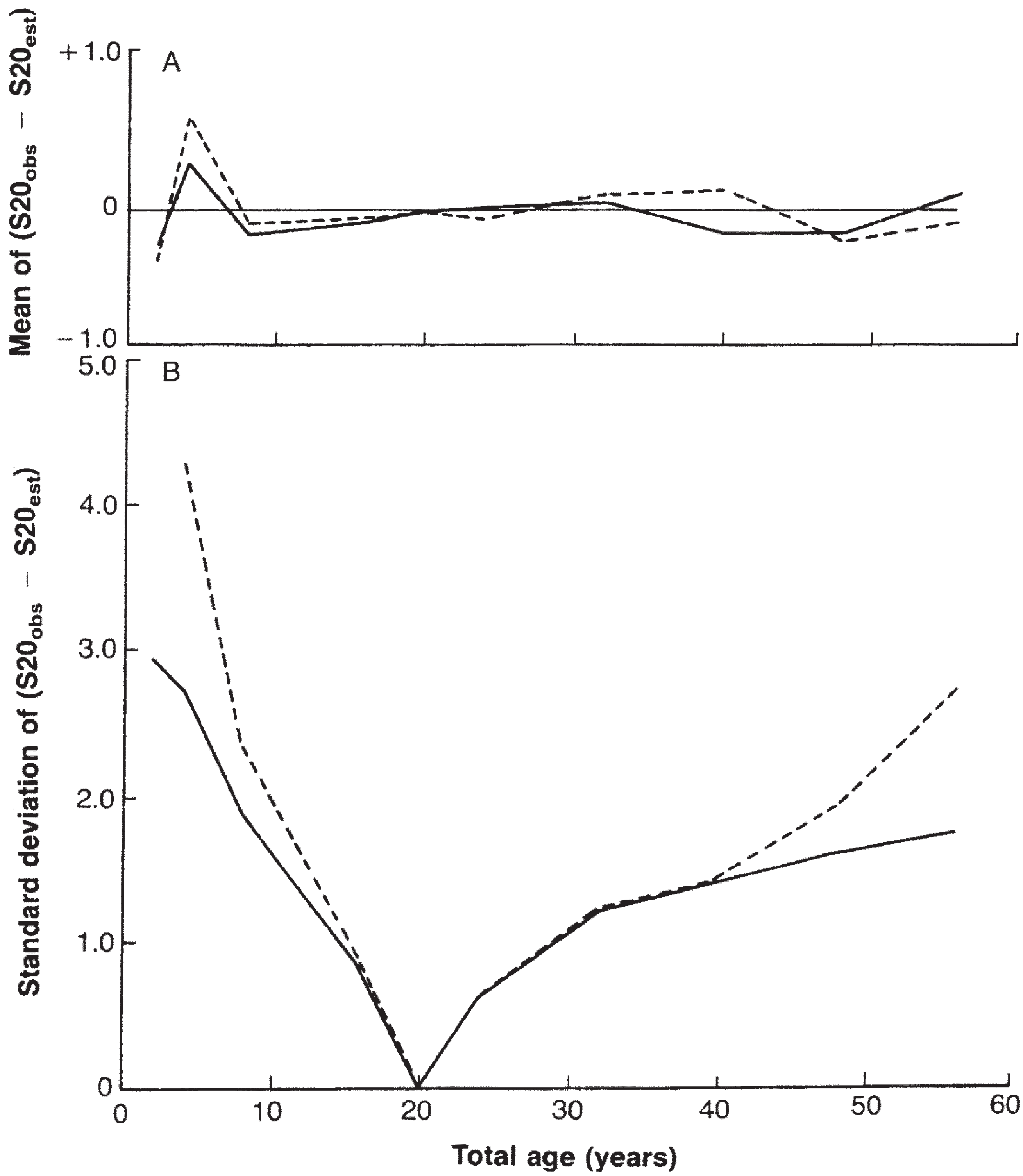


Figure 7.—Means and standard deviations of differences (observed $S_{20}$ - estimated $S_{20}$) based on:

**A**—site index estimation equation (equation 6), shown by solid lines; and

**B**—inverse estimates from height growth equation (equation 5), shown by dotted lines.

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