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# PREDICTING WOOD VOLUMES FOR PONDEROSA PINE FROM OUTSIDE BARK MEASUREMENTS

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ABSTRACT

Assumption of a constant diameter inside bark to diameter outside bark ratio along the bole of ponderosa pine results in an underestimate of wood volume determined from optical dendrometer measurements in the STX program. This ratio gradually increases up the stem to a given diameter outside bark to diameter breast high outside bark ratio that varies with tree size and then decreases to the tip. Equations describing this change in bark thickness can be incorporated into the STX program. Resulting estimates of diameters inside bark, volume segments, and whole tree volumes are closer to true values than estimates derived by the constant ratio assumption.

KEYWORDS: Volume estimation (tree), volume determination methods, bark thickness, computer programs, STX, ponderosa pine.

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## INTRODUCTION

Many studies in the Pacific Northwest are concerned with the response of sapling-, pole-, and small sawtimber-size ponderosa pine[1] trees to thinning, fertilization, and treatment of understory vegetation. Assessment of treatment effects on wood production requires conversion of diameter outside bark (dob) at several points along the bole (usually determined with optical dendrometers) to diameter inside bark (dib) used in calculating wood volumes for standing trees.

In Grosenbaugh's (1964) STX program for processing tree measurements, three options are available for the dob to dib conversion: (1) a constant ratio option assuming a uniform dib/dob ratio along the bole; (2) an option assuming that dib/dob increases curvilinearly above diameter breast high (dbh) and decreases curvilinearly below dbh; (3) an option assuming that dib/dob decreases curvilinearly above dbh and increases curvilinearly below dbh. These options use field determinations of dbhib and dbhob.

The constant ratio option (option 1) has been used in the Pacific Northwest for ponderosa pine without evidence to support its use. Wiant and Koch (1974) found that the constant ratio option was most accurate for yellow poplar, red maple, northern red oak, black oak, and scarlet oak. Mesavage (1969) concluded that the second option was best for estimating volumes of loblolly, shortleaf, slash, and longleaf pines.

Grosenbaugh (1964) did arrange his program to receive user supplied options, and the literature indicates that none of the three options describe the change in bark thickness along the bole for some conifers. Saikku (1973, figs. 4 and 5) found that bark thickness of Scots pine decreased with height up the stem below about 6 meters. From between 4 and 6 m to the tip (14 to 20 m), bark thickness remained constant (about 5 m). MacDonald (1973) examined outside and inside bark girths along the bole of Scots pine, Douglas-fir, Sitka spruce, Norway spruce, and European larch. He found in general that the ratio

$$\frac{\text{girth outside bark-girth inside bark}}{\text{girth outside bark}} \times 100$$

decreased with increasing distance above dbh through the lower third of the bole, remained nearly constant from one-third to one-half of the stem, and then increased in the upper one-half of the stem. Brickell (1970) mentioned that the dib/dob ratio may increase, remain nearly constant, then decrease as measurement progresses up the stem. An algebraic rearrangement of Brickell's equation (5) which covers this possibility is

$$\text{dib/dob}=1-\left(\frac{\text{dbhob-dbhib}}{\text{dob}}\right)\left(\frac{\text{b-1}}{\text{b-dob/dbhob}}\right) . \qquad (1)$$

Another equation derived in this study, which also describes this pattern of dib/dob along the stem, is

$$\text{dib/dob}=(\text{dbhib/dbhob})\left[1+(\text{dob/dbhob})^{\text{a-b(dob/dbhob)}}-(\text{dob/dbhob})^{\text{c-d(dob/dbhob)}}\right] . (2)$$

## METHODS

Data for different sites and sizes and ages of trees were collected in Oregon and Washington to determine patterns of dib/dob variation along stems. For each location, at least 10 trees were felled. Age at 1-foot[2] stump and

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[1] Scientific names of trees mentioned are listed on page 8.

[2] Metric unit conversion factors are listed on page 8.

total height to the nearest 0.1 foot were determined. Nails were driven at the 1-foot stump, dbh, and at decile height intervals from dbh to the tip. Diameter ob measurements were taken at these points with a caliper while the inside edge of the graduated portion of the caliper was resting on the nailhead. Then patches of bark were peeled, exposing the wood at 90 and 270 degrees around the bole from the nail, allowing the dib measurements to be made with calipers, again resting on the nail. For each tree, these dob and dib measurements were taken to the nearest 0.05 inch for 11 locations along the bole including stump and dbh.

Diameter ib/dob ratios were calculated for each point on each tree and then plotted as a function of dob/dbhob. Diameter ib/dob ratios gradually increased up the stem to a given dob/dbhob which varied with tree size, then gradually decreased for points progressively farther up the tree. None of the three options in the STX program appeared to describe the resulting pattern. Both equations (1) and (2) resulted in significant fits for points above dbh. Equation (1) could not always be fit significantly to points below dbh. Bark thickness at stump was highly variable for small sawtimber-size trees and not always predictable from dbhib/dbhob. Fortunately, stump bark thickness can be sampled directly in field studies.

Ponderosa pine is a rough-barked species resulting in considerable variability in dib/dob. Equations (1) and (2) were rearranged so that factor (dib/dob)/(dbhib-dbhob) for equation (1) and factor (dib/dob)/(dbhib/dbhob) for equation (2) could be fitted as a function of dob/dbhob for groups of at least 10 trees of similar sizes for each sample location. This rearrangement forces the curves through the point (1, 1) for each tree where dob equals dbhob and produces more homogeneous variances. Fitting by iteration to minimize the sums of squares of the residuals was done as though all data points were independent. Coefficient b in equation (1) and coefficients a, b, c, and d in equation (2) were determined for 10 separate size classes sampled east of the Cascades in Oregon and Washington. Coefficient b in equation (1) and coefficient a in equation (2) varied with tree size. Coefficients b, c, and d in equation (2) did not appear to vary with tree size.

Coefficients b (equation 1) and a (equation 2) were functions of the average dbh in inches squared times total height in feet ($D^2H$) for the 10 or more trees used in their derivation. Equations (1) and (2) with their coefficients were then tested with more tree data collected in additional areas of Oregon and Washington. Diameters ib for these test trees were measured directly and also calculated from corresponding dob's using the constant ratio assumption as well as equations (1) and (2) (after shifting the dob term from the left- to the right-hand side) with respective coefficients b and a determined using the $D^2H$ for each tree. Volumes for stem segments above dbh were then calculated using actual and estimated dib's with Smalian's formula. Volumes of individual tree segments were summed to obtain whole tree volumes above dbh. These calculations were repeated to include the stump dib's, stump to dbh volume segments, and whole tree volumes above stump.

In a further test 206 trees were sampled on the Deschutes National Forest by the timber management staff. Form class (dib at 16 feet above stump height divided by dbhob) was calculated using actual dib's at 16 feet above stump and the dib's estimated from these 16-foot dob's using option 1 and equations (1) and (2).

Comparisons of dib's, volume segments, and whole tree volumes arising from application of the constant ratio assumption as well as equations (1) and (2) were made from calculations of the root mean square deviation (RMSD):

$$\text{RMSD} = \sqrt{\frac{\Sigma(\text{actual value} - \text{estimated value})^2}{\text{number of estimates}}} \qquad (3)$$

for corresponding sets of data. The lower the root mean square deviation for a set of estimated values the closer those values are to the actual values. Freese's (1960) test of accuracy was also applied to estimated whole tree volumes to separate the bias and lack of precision components of inaccuracy where accuracy was not within defined acceptable limits.

## RESULTS AND DISCUSSION

The relationship between coefficient b of equation (1) and $D^2H$ for ponderosa pine in the Pacific Northwest is

$$\log_{10}b=0.280187646-0.040677437(\log D^2H). \quad (4)$$

The relationship between coefficient a of equation (2) and $D^2H$ is

$$\log_{10}a=-0.335135683-0.062052639(\log D^2H). \quad (5)$$

The $r^2$ and F values were 0.73 and 26.42 for regression (4) and 0.65 and 18.67 for regression (5). Coefficients b, c, and d for Northwest ponderosa pine are 0.8037, 0.2111, and 0.5638. Application of equations (1), (2), and the constant ratio option to the 114 trees used in defining the coefficients showed that application of equation (1) was superior to equation (2) in predicting dib's, volume segments, and whole tree volumes above dbh. The constant ratio option (option 1 in the STX program) was far inferior to equations (1) and (2), resulting in a 7.03-percent underestimate of total actual volume and much higher root mean square deviations for dib's, volume segments, and whole tree volumes (table 1).

At each of 39 locations east of the Cascades in Oregon and Washington, 5 to 20 additional trees were sampled to test the equations.

Trees were sampled on every National Forest and on the Warm Springs and Spokane Indian Reservations. Site index[3/] for the sample locations ranged from 67 to 138, representing the range found in eastern Oregon and Washington. Trees in "very small" and "small" size classes (tables 2 and 3) were sampled in the same way as the trees used in deriving equations (4) and (5). Trees in the larger size classes were sampled for site index and yield studies conducted by James W. Barrett, research forester, at the Silviculture Laboratory in Bend. Diameter ob and dib measurements for these trees were taken on sections cut at 1 foot, dbh, 10 feet, and then at 5- or 10-foot intervals up the stem, depending on tree size. Of these "large" trees, 64 had much greater $D^2H$'s than the largest trees used in defining coefficients in equations (1) and (2) (table 2).

For trees with $D^2H$'s larger than 960, the constant ratio option is clearly inferior to both equations (1) and (2) for determining dib's and volumes above dbh (tables 2 and 3). Root mean square deviations were higher for these dib's, and volumes determined by option (1) and total volumes were underestimated. For the "very small" size class, differences between the three methods of determining dib's and volumes are slight; but option 1 was more accurate for a greater number of trees than either equation (table 3). Root mean squares for diameters, volume segments, and whole tree volumes for all but the smallest size class are lower for equation (1) than equation (2) (table 2). Equation (1) did a better job of estimating dib's and volume segments for more trees in the two largest size classes than did equation (2) (table 3).

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3/ Barrett, James W. Site index curves for managed stands of ponderosa pine. Unpublished data on file at Pacific Northwest Forest and Range Experiment Station, Silviculture Laboratory, Bend, Oreg.

Table 1--*Total volumes above dbh, differences between actual and estimated volumes above dbh, and root mean square deviations for dib's, volume segments, and whole tree volumes above dbh for 114 trees used in defining the coefficients in equations (1) and (2)*

| Total actual volume (cubic feet) | Difference between estimated and actual total volumes | | | Root mean square deviations | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Diameters | | | Volume segments | | | Whole tree volumes | | |
| | Constant ratio option | Eq.(1) | Eq.(2) | Constant ratio option | Eq.(1) | Eq.(2) | Constant ratio option | Eq.(1) | Eq.(2) | Constant ratio option | Eq.(1) | Eq.(2) |
| | - - - - - Percent - - - - - | | | - - - - - Inches - - - - - | | | - - - - - - - - - - - Cubic feet - - - - - - - - - - - | | | | | |
| 1,265.35 | -7.03 | -0.21 | -0.79 | 0.267 | 0.150 | 0.171 | 0.198 | 0.077 | 0.112 | 1.650 | 0.559 | 0.826 |

Table 2--*Total volumes above dbh, differences between estimated and actual volumes above dbh, and root mean square deviations for dib's, volume segments, and whole tree volumes above dbh*

| Size class1/ | Number of trees in test | Total actual volume | Difference between estimated and total actual volumes | | | Root mean square deviations | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Diameters | | | Volume segments | | | Whole tree volumes | | |
| | | | CR2/ | Eq. (1) | Eq. (2) | CR2/ | Eq. (1) | Eq. (2) | CR2/ | (Eq. (1) | Eq. (2) | CR2/ | Eq. (1) | Eq. (2) |
| | | Cubic feet | - - - - - Percent - - - - | | | - - - - - Inches - - - - - | | | - - - - - - - - - - - Cubic feet - - - - - - - - - - - | | | | | |
| Very small3/ | 69 | 76.31 | -1.32 | +2.15 | +1.87 | 0.092 | 0.096 | 0.092 | 0.007 | 0.007 | 0.007 | 0.057 | 0.050 | 0.053 |
| Small4/ | 95 | 216.12 | -4.88 | -.76 | -1.06 | .171 | .142 | .142 | .025 | .015 | .017 | .205 | .124 | .144 |
| Medium5/ | 200 | 2,979.16 | -5.34 | +.69 | +.79 | .282 | .169 | .179 | .212 | .110 | .132 | 1.185 | .574 | .716 |
| Large6/ | 64 | 7,142.60 | -6.32 | +1.72 | +1.43 | .638 | .367 | .472 | .759 | .419 | .513 | 9.673 | 4.841 | 6.036 |

1/ Average $D^2H$ is the average for the 5 to 20 trees sampled at each location.

2/ Constant ratio option.

3/ Average $D^2H$ ranged from 436 to 959 $in^2$ ft.

4/ Average $D^2H$ ranged from 1,044 to 2,642 $in^2$ ft.

5/ Average $D^2H$ ranged from 2,400 to 11,300 $in^2$ ft.

6/ Average $D^2H$ ranged from 35,000 to 149,000 $in^2$ ft.

Table 3--*Number of test trees by size class and by equations (1) and (2) when these equations produced estimates closer to true values than did the constant ratio option*

| Size class | Trees | Equation (1) | | | Equation (2) | | |
|---|---|---|---|---|---|---|---|
| | | Dib's | Volume segments | Total volume | Dib's | Volume segments | Total volume |
| Very small1/ | 69 | 21 | 25 | 27 | 30 | 27 | 26 |
| Small2/ | 95 | 67 | 63 | 64 | 67 | 64 | 66 |
| Medium3/ | 200 | 162 | 168 | 166 | 160 | 163 | 161 |
| Large4/ | 64 | 43 | 47 | 46 | 39 | 46 | 49 |
| Total | 428 | 293 | 303 | 303 | 296 | 300 | 302 |

1/ Average $D^2H$ ranged from 436 to 959 $in^2$ ft.

2/ Average $D^2H$ ranged from 1,044 to 2,642 $in^2$ ft.

3/ Average $D^2H$ ranged from 2,400 to 11,300 $in^2$ ft.

4/ Average $D^2H$ ranged from 35,000 to 149,000 $in^2$ ft.

For the 206 trees used to estimate form class, dbh varied from 11.5 to 47.3 inches and heights ranged from 60 to 160 feet. Many of these trees were larger than those used in defining coefficients in equations (1) and (2). Actual form class for these trees was 0.795. Calculated form classes using dib's determined by equations (1) and (2) and the constant ratio option were 0.801, 0.794, and 0.773. RMSD's for calculated dib's at 16 feet were 0.579, 0.620, and 0.811 for equations (1), (2), and the constant ratio option.

The underestimates of volume above dbh that result when the constant ratio option is used to determine dib's become more serious as tree size increases (table 2). Freese's (1960) test shows that this is not a precision error but a bias error. This bias arises because the bark thickness in the middle of the bole is thinner than predicted by the constant ratio method. This error suggests that, when stump bark thickness is not directly available from past dendrometer measurements, volumes should be recalculated for ongoing studies if a reasonable way to estimate stump dib's is available. Use of equation (1) to predict dib's from dob's larger than dbhob may result in serious error because the ratio dob/dbhob can be very close to the value for the b coefficient which is greater than 1. When this occurs, the factor (b-dob/dbhob) in equation (1) can be a very small negative or positive number resulting in a calculated dib that can be much too large--the usual case--or small. This leaves equation (2) to determine all dib's or equation (1) or (2) to estimate dib's above dbh combined with the constant ratio option to estimate stump dib's from dbhob and dbhib. Each of these methods produces reasonable results (table 4), but the errors resulting from application of equation (1) alone are quite evident. Except for the "very small" size class, the lowest root mean square deviations were produced when equation (1) was used for dib's above dbh in combination with the constant ratio option for stump dib's (table 4). It should be pointed out that it is possible to have errors for dib's above dbh when equation (1) is applied in the case of unusual stems with swelling of the bole above dbh.

Table 4--*Total actual volumes, differences between estimated and actual volumes above stump, and root mean square deviations for dib's, volume segments, and whole tree volumes for the test trees*[1/]

| Size class | Total actual volume | Difference between estimated and total actual volumes | | | Root mean square deviations | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Diameters | | | Volume segments | | | Whole tree volumes | | |
| | | CR[2/] | Eq. (1) | Eq. (2) | CR[2/] | Eq. (1) | Eq. (2) | CR[2/] | (Eq. (1) | Eq. (2) | CR[2/] | Eq. (1) | Eq. (2) |
| | Cubic feet | - - - - - | Percent | - - - - | - - - - - | Inches | - - - - - | - - - - - | - - - - - | Cubic feet | - - - - - | - - - - - | - - - - - |
| Very small[3/] | 101.10 | 0.44 | -2.14 | +1.67 | 0.122 | 0.499 | 0.096 | 0.011 | 0.026 | 0.007 | 0.057 | 0.070 | 0.055 |
| | | | +3.05 | +2.85 | | .124 | .122 | | .010 | .010 | | .068 | .068 |
| Small[4/] | 264.11 | -2.82 | -2.13 | -0.65 | .200 | .932 | .149 | .027 | .169 | .018 | .185 | .571 | .145 |
| | | | +0.56 | +0.31 | | .179 | .178 | | .020 | .022 | | .126 | .144 |
| Medium[5/] | 3,531.97 | -4.48 | +427.64 | -.16 | .288 | 37.48 | .327 | .214 | 260.23 | .154 | 1.191 | 674.93 | .673 |
| | | | +.62 | +.70 | | .201 | .208 | | .115 | .136 | | .576 | .720 |
| Large[6/] | 7,764.92 | -5.68 | +32.78 | +1.02 | .599 | 13.98 | .521 | .756 | 51.87 | .529 | 9.456 | 224.862 | 6.042 |
| | | | +1.73 | 1.46 | | .412 | .498 | | .433 | .524 | | 5.077 | 6.300 |

[1/] The first row for each size class presents values determined by using the constant ratio option or equations (1) and (2) to calculate all dib's. The second row for each size class presents values where stump dib's were determined with the constant ratio option in every case.

[2/] Constant ratio option.

[3/] Average $D^2H$ ranged from 436 to 959 $in^2$ ft.

[4/] Average $D^2H$ ranged from 1,044 to 2,642 $in^2$ ft.

[5/] Average $D^2H$ ranged from 2,400 to 11,300 $in^2$ ft.

[6/] Average $D^2H$ ranged from 35,000 to 149,000 $in^2$ ft.

Setting required accuracy equal to 10 percent of the volume of the average size tree within each size class in table 4 (0.14, 0.30, 1.8, and 12 cubic feet for the "very small" to "large" size classes. Freese's (1960) test can be applied to the whole tree volumes estimated by each method. Resulting chi-square values (table 5) show that the constant ratio method is biased for all but the smallest size class. Use of equations (1) and (2) for dib's above dbh combined with the constant ratio for stump dib's produces estimated values for individual trees within the required limits unless a 1-to-20 chance has occurred.

Table 5--*Chi-square values for Freese's (1960) test of accuracy comparing measurements of whole tree volumes above stump*[1/] *with true values*

| Size class[2/] | Constant ratio option | Equation (1) | Equation (2) | Constant ratio option-bias |
|---|---|---|---|---|
| Very small[3/] | 43.904* | 62.525* | 62.525* | 43.342* |
| Small[4/] | 138.783 | 64.378* | 84.085* | 118.859* |
| Medium[5/] | 336.373 | 78.676* | 122.931* | 166.170* |
| Large[6/] | 152.667 | 44.009* | 67.766* | 71.590* |

1/ Determined by the constant ratio option and equations (1) and (2) for dib above dbh and by the constant ratio option for stump dib. Asterisks indicate that accuracy standards were met at the 5-percent level of probability.

2/ Accepted standards were that each tree would fall within 0.14, 0.30, 1.8, or 12 cubic feet of the true value for the smallest to the largest size class unless a 1-in-20 chance occurred.

3/ Average $D^2H$ ranged from 436 to 959 $in^2$ ft.

4/ Average $D^2H$ ranged from 1,044 to 2,642 $in^2$ ft.

5/ Average $D^2H$ ranged from 2,400 to 11,300 $in^2$ ft.

6/ Average $D^2H$ ranged from 35,000 to 149,000 $in^2$ ft.

## CONCLUSIONS

None of the three options in Grosenbaugh's (1964) STX program appear to describe the variation in dib/dob along the boles of ponderosa pine east of the Cascades in Oregon and Washington. The two equations presented here produce lower root mean square deviations for dib than did the constant ratio option which was formerly used. Equation (1) was originally presented by Brickell (1970) without recognition that coefficient b varied with tree size and results in lower root mean square deviations than equation (2) for dib's above dbh for all but "very small" trees. Equation (1) may produce errors for dib's estimated from dob's greater than dbhob. Both equations have one coefficient which varies with $D^2H$ since dib's are predicted at various points along boles of trees with varying heights and forms from a dib and dob measurement at a fixed location. Use of the constant ratio option results in biased estimates of wood volumes which are low for all but "very small" trees. Thus, growth increments in past ponderosa pine studies probably have been slightly underestimated.

Preliminary investigation indicates these equations work with lodgepole pine in Oregon (where equation (2) appears superior to equation (1)) and ponderosa pine from the Black Hills, although the coefficients are different. Since the STX program is widely used, usually with one of the three listed options, investigators elsewhere should be aware that perhaps other equations may more accurately describe dib/dob variation along boles of the species they work with.

## METRIC CONVERSIONS

1 inch = 2.54 centimeters

1 foot = 0.3048 meter

1 $D^2H$ ($in^2$ ft) = 1.9664 $cm^2$ m

When $D^2H$ is expressed in $cm^2$ m rather than $in^2$ ft, equations (4) and (5) are, respectively,

$$\log b = 0.280187646 - 0.04677437 (\log (0.5085 D^2H)),$$

and

$$\log a = -0.335135683 - 0.062052639 (\log (0.5085 D^2H)).$$

## COMMON AND SCIENTIFIC NAMES OF TREES

| | |
|---|---|
| ponderosa pine | *Pinus ponderosa* Laws. |
| yellow-poplar | *Liriodendron tulipifera* L. |
| red maple | *Acer rubrum* L. |
| northern red oak | *Quercus rubra* L. |
| black oak | *Quercus velutina* Lam. |
| scarlet oak | *Quercus coccinea* Muenchh. |
| loblolly pine | *Pinus taeda* L. |
| shortleaf pine | *Pinus echinata* Mill. |
| slash pine | *Pinus elliottii* Engelm. |
| longleaf pine | *Pinus palustris* Mill. |
| Scots pine | *Pinus silvestris* L. |
| Sitka spruce | *Picea sitchensis* (Bong.) Carr. |
| Norway spruce | *Picea abies* (L.) Karst. |
| European larch | *Larix decidua* Mill. |
| Douglas-fir | *Pseudotsuga menziesii* (Mirb.) Franco |
| lodgepole pine | *Pinus contorta* Dougl. |

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