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# Tree Taper Models for Major Commercial California Conifers


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## ABSTRACT

Equations are developed for eight conifer species to estimate the stem taper of inside-bark diameters from breast height to the tip of the tree. Separate equations are developed to estimate the diameter inside bark at the stump. Equations are fitted and tested on separate halves of a data set composed of tree taper data from previous studies, both from the forest industry and USDA Forest Service surveys. This composite data set extends from Southern California to the National Forests of southern Oregon.

After an extensive examination of existing taper equations, two taper equations were selected for further analysis, one by Biging and the other by Wensel and Krumland. Coefficients for both equations are given for the eight conifer species examined. Because of a lower residual sum of squares, and a lack of correlation of the residual with the available predictors, the Wensel and Krumland equation is recommended for use.

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# Tree Taper Models for Major Commercial California Conifers[1]

## INTRODUCTION

THE VOLUME OF standing trees must be estimated from measurements on these trees for general forest land planning (harvest scheduling) and for appraisal. Particularly for appraisal purposes, volumes must be estimated by log quality (grade) classes with appropriate deductions for defect. Whether one estimates volume in cubic or board foot scale, a flexible volume estimation process is made possible by use of tree taper equations—equations that predict the diameter inside-bark of a tree at any height. Given these estimated diameters, either board foot or cubic foot volumes can be computed for any section. This process of tree volume determination is beginning to replace the scaling of felled trees for U.S. Forest Service and private timber sales requiring a new look at the procedures used for such estimates.

The USDA Forest Service—Region 5 (California) has been using tree taper equations developed by Stadelman (1986) for this purpose while industry members of the California Forest Research Association have been using equations by Biging (1984) that have been incorporated in CACTOS, the California Conifer Timber Output Simulator (Wensel, Daugherty, and Meerschaert, 1986). These equations have different forms and they produce different predictions. While there is a "wealth" of tree taper data available from various sources, existing taper models were fit to only a small subset of the data presented in this paper.

Our original objective was to test these two taper models as well as other local equations for estimating tree taper and, if necessary, develop recommendations for both the best model form to use and the coefficients to use in each region within the state. It was our expectation that we would likely find local differences in which a model performed best and there would be local differences in coefficients due to measurement methods, elevation, site index, stand density, and other factors. Thus, the analysis of the various models was designed to test for such differences. A recommended model form is presented along with a discussion of attempts to localize the predictions.

Species considered are Douglas-fir (DF), *Pseudotsuga menziesii* (Mirb.) Franco; ponderosa pine (PP), *Pinus ponderosa* Dougl. ex Laws.; Jeffrey pine (JP), *P. jeffreyi* Grev. & Balf.; lodgepole pine (LP), *P. contorta* Dougl. ex Loud.; sugar pine (SP), *P. lambertiana* Dougl.; white fir (WF), *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.; red fir (RF), *A. magnifica* A. Murr.; and incense-cedar (IC) *Calocedrus decurrens* (Torr.) Florin.

## DATA SOURCES

Taper data for this study came from previous studies at the University of California, Berkeley, and from other researchers in California and Oregon. These

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data are of two types, either from stem analysis of felled trees or from optical measurements on standing trees with an optical dendrometer. In pooling the data for taper analysis, the origin of the data elements was preserved so we could look for differences in the performance of the various models to the individual data sets. The numbers of trees in the data set for each species by DBH size class are shown in Table 1.

TABLE 1. NUMBER OF TREES BY SPECIES AND DBH SIZE CLASSES

| DBH Class | Species | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | DF | PP | SP | JP | LP | WF | RF | IC |
| *(inches)* | *no. of trees* | | | | | | | |
| 5–10 | 203 | 310 | 69 | 36 | 52 | 373 | 92 | 161 |
| 10–20 | 1196 | 1890 | 486 | 308 | 434 | 2854 | 817 | 528 |
| 20–30 | 1032 | 1725 | 594 | 600 | 96 | 2460 | 576 | 493 |
| 30–40 | 450 | 712 | 385 | 1017 | 27 | 888 | 285 | 318 |
| 40–50 | 246 | 267 | 163 | 536 | 3 | 207 | 112 | 164 |
| 50 + | 158 | 111 | 84 | 92 | | 71 | 49 | 73 |

These data sets are described briefly as follows:[2]

*BULLETIN 1883.* These data were collected in 1976 from 598 standing trees using optical dendrometers. The data set is made up of data collected from lands then managed by American Forest Products, Southern Pacific Land Company, the Plumas National Forest, and the Stanislaus National Forest. The data were used to develop volume tables for young-growth conifers (Wensel 1977).

*COOP.* The Coop data come from a stem analysis study of 1044 trees by the members of the Northern California Forest Yield Cooperative on industry forest lands in the Sierra, Southern Cascade, Shasta-Trinity, and Mendocino regions of California. This Coop research group, formed in 1978 to produce growth-prediction models for California conifers, includes the University of California, Berkeley; private industry; and public forestry agencies. The inside-bark measurements in these data were used for the initial growth models for CACTOS (Wensel, Meerschaert, and Biging, 1987) and to produce stem taper models (Biging 1984).

*DOLPH.* Stem analysis measurements of 1486 trees, described by Dolph (1988 and 1989), were used for tree taper and growth studies in California's Sierra Nevada.

*LEVITAN.* Optical dendrometer measurements on 98 incense-cedar trees from the Klamath, Lassen, and Mendicino National Forests were collected by Jack Levitan in 1990.

*LINDQUIST.* Optical dendrometer measurements from 851 Douglas-fir trees were received from James Lindquist. The data were collected in northern California National Forests.

*MICH-CAL.* These data were collected by scaling 5464 felled trees and were used by the Michigan-California Lumber Company to compute new coefficients for the taper and volume equations developed by Biging (1984).

[2]The numbers of trees for each data set refer only to the number of trees used in the current study.

*MILL STUDY.* Stem taper data for 1735 trees came from a series of utilization studies conducted in California by the USFS PNW Research Station. Trees were felled and scaled in the field, then scaled again in the mill before being sent through the mill for conversion. The primary purpose of the collection was for lumber recovery to make adjustments in the timber sale appraisal process and get the highest value. Product recovery research results, where these data are described in more detail, have been published by Ernst and Pong (1985), Pong (1982), and Pong and Cahill (1988).

*OLIVER.* These data were received from Bill Oliver, USDA Forest Service. They were collected with an optical dendrometer from 589 trees located on National Forest lands of northern California to determine the growth responses to silviculture treatments (Oliver 1988).

*TARIF.* The TARIF data were collected from 1685 trees as a cooperative effort prior to the forming of the Northern California Forest Yield Cooperative. The data were collected from standing trees using optical dendrometers for the purpose of developing an "access table" for a Northern California TARIF system. Biging (1981) examined these data for a previous version of his taper equation.

*USDA Forest Service—Region 5.* These data were collected from 8763 sample trees located on 15 National Forests in California, with most of the data coming from the northern forests. Measurements were made using optical dendrometers for various regional studies and aggregated by Charles Stadelman, USDA Forest Service, San Francisco.[3]

*USDA Forest Service—Region 6.* The stem taper data come from felled-tree measurements from 1490 trees randomly chosen from clearcut operations in nine National Forests in southern Oregon. The purpose of the data collection was to adjust regional gross volume estimates for inventory to reflect local utilization. The data were received with the cooperation of Ralph Johnson, John Teply, and Susan Willits, USDA Forest Service.

# TAPER EQUATIONS CONSIDERED

We examined the performance of existing tree taper models with their published coefficients for west coast conifers. Separate models were used for above versus below breast height diameters. Only the model forms for the recommended equations are given here.

## Predictions Above Breast Height

The 9 upper stem taper models considered are shown in Table 2. These include models by Amidon (1984), Biging (1984), Kozak, Munroe, and Smith (1969), Kozak (1988), Max and Burkhart (1976),[4] McTague and Stansfield (1988), Stadelman (1986), Walters and Hann (1986), and Wensel and Krumland (1983). The range of model forms shown in Table 2, all for the purpose of predicting diameter inside bark at various heights, suggests that there is more than one way to do this. Each of the models was examined here. However, the Amidon and Kozak

[3]The data received from Stadelman were edited by the authors to remove duplicate data from related computer files.

[4]Coefficients for the Max and Burkhart model were fit by Biging (1984).

models were dropped from consideration early in the analysis. The Amidon model was discovered to have unreconcilable formulation problems; the Kozak (1988) model required the height to the inflection point at the base of the live crown, this information was not available for the sample trees.

TABLE 2. UPPER STEM TAPER EQUATIONS EVALUATED

**Symbol**

| | |
|---|---|
| dib | diameter inside bark in inches at height HT |
| dibbh | diameter inside bark in inches at breast height (4.5 feet) |
| DBH | diameter outside bark in inches at breast height (4.5 feet) |
| HI | height to the inflection point from the ground |
| HT | height in feet |
| THT | total height in feet |

various lower case letters and α are coefficients

**Amidon (1984)**

$$dib = b_1 DBH\left(\frac{THT - HT}{THT - bh}\right) + b_2 \frac{\left(THT^2 - HT^2\right)\left(HT - bh\right)}{THT^2} \qquad (1)$$

where bh is breast height (1.37 meters)

**Biging (1984)**

$$dib = DBH\left\{b_1 + b_2 \ln\left[1 - \lambda\left(\frac{HT}{THT}\right)^m\right]\right\} \qquad (2)$$

where $\lambda = 1 - \exp\left(\frac{-b_1}{b_2}\right)$ and $m = \frac{1}{3}$

**Kozak, et al. (1969)**

$$dib = \sqrt{DBH\left(b_1 \frac{\left(HT - THT\right)}{THT} + b_2 \frac{\left(HT^2 - THT^2\right)}{THT^2}\right)} \qquad (3)$$

**Kozak (1988)**

$$dib = \left(a_0 DBH^{a_1} a_2^{DBH}\right)\left(X^{b_1 Z^2 + b_2 \ln(Z + 0.0001) + b_3\sqrt{Z} + b_4 e^z + b_5\left(\frac{DBH}{THT}\right)}\right) \qquad (4)$$

where $X = \left(\frac{1 - \sqrt{\frac{HT}{THT}}}{1 - \sqrt{p}}\right)$; $p = \left(\frac{HI}{THT}\right) * 100$; $Z = \frac{HT}{THT}$

(continued on page 5)

TABLE 2 (CONTINUED). UPPER STEM TAPER EQUATIONS EVALUATED

**Max and Burkhart (1976)**

$$\mathrm{dib} = \mathrm{DBH}\sqrt{b_1(R-1) + b_2(R^2-1) + b_3(a_1-R)^2 I_1 + b_4(a_2-R)^2 I_2} \qquad (5)$$

$$\text{where } R = \frac{HT}{THT},\ I_i = 1 \text{ for } R \le a_i,\ \text{else } I_i = 0 \text{ for } R > a_i, \text{ and } i = 1,2$$

**McTague and Stansfield (1988)**

$$\mathrm{dib} = \frac{b_0(THT-HT)^{b_1}\,DBH^{b_2}\,F^{b_3}}{THT^{b_4}} \qquad (6)$$

$$\text{where } F = b_5 + b_6 DBH^2 THT + \frac{b_7}{DBH^2 THT}$$

**Stadelman (1986)**

$$\mathrm{dib} = a + b\,DBH^2 + c\,DBH\,L + d\,DBH^2\,L + eL + f\,Z + G\,(THT-HT) \qquad (7)$$

$$\text{where } L = \frac{THT-HT}{THT} \text{ and } Z = \ln(\text{log position})$$

**Walters and Hann (1986)**

$$\frac{\mathrm{dib}}{\mathrm{dbhib}} = Z_0 + \left[b_{10} + b_{11}\left(\frac{THT-4.5}{DBH}\right) + b_{12}\left(\frac{THT-4.5}{DBH}\right)^2\right] Z_1 + b_{20} \qquad (8)$$

$$Z_0 = 1 - X + I_2\left\{X + I_1\left[\left(\frac{X-1}{k_1-1}\right)\left(1 + \frac{k_1-X}{k_1-1}\right) - 1\right]\right\} - (X-1)(X - I_2 X)$$

$$Z_1 = I_2\left[X + I_1\left(\frac{X-1}{k_1-1}\right)\left(X + k_1\frac{k_1-X}{k_1-1}\right) - X\right] - (X-1)(X - I_2 X)$$

$$Z_2 = I_2\left\{X^2 + I_1\left[k_1\left(\frac{X-1}{k_1-1}\right)\left(2X - k_1 + k_1\left(\frac{k_1-X}{k_1-1}\right)\right) - X^2\right]\right\}$$

$$k_1 = \left(\frac{\alpha\,CB - 4.5}{THT-4.5}\right) \qquad X = \frac{HT-4.5}{THT-4.5} \qquad CB = \text{height to live crown base}$$

$$I_1 = 0 \text{ when } 0 \le X \le k_1 \text{ else } I_1 = 1$$

$$I_2 = 0 \text{ when } k_1 \le 0 \text{ else } I_2 = 1$$

**Wensel and Krumland (1983)**

$$\mathrm{dib} = DBH\left\{c_0 - f\ln\left[1 - \left(\frac{HT-1}{THT-1}\right)^{c_1}\left[1 - \exp\left(\frac{c_0}{f}\right)\right]\right]\right\} \qquad (9)$$

where $f = c_2 + c_3\,DBH + c_4\,THT$.

To illustrate the statistics computed for each model/data set combination, the mean residual (observed minus predicted diameter) and standard deviation for the existing taper models are given for a subset of the data in Tables 3a, 3b, and 3c for Douglas-fir, ponderosa pine, and white fir, respectively.[5] Scanning the residuals for all of the data sets, of which a partial listing is given in Tables 3a to 3c, it became immediately apparent that each of the models performed well (low average residual and low standard error) for some diameter classes within some data sets. However, no model performed uniformly well across all diameter classes for all data sets.[6]

TABLE 3a. MEAN ($\bar{x}$), STANDARD DEVIATION (S) OF RESIDUAL (OBSERVED–PREDICTED INSIDE BARK DIAMETER), AND SAMPLE SIZE BY SIZE CLASS AND OWNERSHIP BY TAPER MODEL FOR DOUGLAS-FIR

| **DBH Class inches** | **5.5–18** | | **18–30** | | **30–40** | | **40+** | | **5.5–18** | | **18–30** | | **30–40** | | **40+** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s |
| | COOP | | | | | | | | Eldorado NF | | | | | | | |
| no. | 903 | | 478 | | 21 | | | | 142 | | 296 | | 54 | | 109 | |
| STA | .1 | .9 | –.3 | 1.8 | –.3 | 1.6 | | | –.1 | 1.1 | .0 | 1.9 | –.1 | 2.6 | 3.7 | 5.7 |
| BIG | .3 | .9 | .2 | 1.3 | –.5 | .7 | | | .4 | .8 | .4 | 1.6 | .5 | 2.3 | .5 | 3.2 |
| M&B | .4 | 1.0 | .3 | 1.4 | –.3 | 1.0 | | | .6 | .9 | .7 | 1.6 | –.1 | 2.3 | .9 | 3.3 |
| W&K | –.2 | .9 | .0 | 1.2 | .3 | .9 | | | .1 | .8 | .4 | 1.7 | .2 | 2.6 | 3.3 | 5.2 |
| Kozak | .1 | 1.0 | –.3 | 1.4 | –1.1 | 1.0 | | | .3 | .8 | .1 | 1.6 | –.8 | 2.3 | .0 | 3.2 |
| W&H | .6 | .9 | .7 | 1.3 | 1.0 | 1.1 | | | .6 | .9 | 1.0 | 1.7 | .7 | 2.5 | 2.9 | 4.6 |
| | Michigan-Cal | | | | | | | | Klamath NF | | | | | | | |
| no. | 132 | | 514 | | 164 | | 103 | | 291 | | 319 | | 144 | | 649 | |
| STA | –.1 | 1.4 | –.4 | 1.9 | –.1 | 2.4 | –.6 | 4.0 | .2 | 1.0 | –.4 | 1.5 | –.8 | 2.6 | .2 | 2.9 |
| BIG | .8 | 1.0 | .3 | 1.6 | –.1 | 1.9 | –1.7 | 3.4 | .3 | .7 | –.1 | 1.1 | –.8 | 2.3 | –2.0 | 3.0 |
| M&B | .9 | 1.0 | .6 | 1.6 | .3 | 1.9 | –1.2 | 3.3 | .5 | .7 | .1 | 1.1 | –.4 | 2.3 | –1.4 | 2.9 |
| W&K | .4 | .8 | .4 | 1.6 | 1.0 | 1.9 | 1.7 | 3.5 | –.1 | .6 | –.2 | 1.1 | –.3 | 2.4 | 1.2 | 3.8 |
| Kozak | .6 | .9 | .1 | 1.6 | –.5 | 1.9 | –2.5 | 3.4 | .2 | .7 | –.4 | 1.1 | –1.1 | 2.4 | –2.7 | 3.3 |
| W&H | .3 | 1.0 | .1 | 1.9 | .1 | 2.2 | –1.2 | 4.5 | .5 | .8 | .6 | 1.2 | .0 | 2.7 | –1.8 | 5.0 |
| | Bulletin 1883 | | | | | | | | Six Rivers | | | | | | | |
| no. | 205 | | 253 | | 164 | | 70 | | 74 | | 94 | | 14 | | 33 | |
| STA | .5 | 1.0 | –.4 | 1.4 | .0 | 1.9 | .9 | 3.2 | –.1 | 1.1 | –.0 | 2.1 | –1.6 | 2.0 | –.5 | 3.5 |
| BIG | .1 | .8 | –.2 | 1.2 | –.3 | 1.4 | –.6 | 2.1 | .7 | .7 | .6 | 1.7 | –1.6 | 2.2 | –2.3 | 3.9 |
| M&B | .3 | .8 | .1 | 1.2 | .1 | 1.4 | –.1 | 2.1 | .8 | .8 | .9 | 1.8 | –1.2 | 2.0 | –1.7 | 3.7 |
| W&K | –.3 | .8 | –.2 | 1.2 | .6 | 1.8 | 1.4 | 2.8 | .3 | .6 | .7 | 1.8 | –.7 | 2.1 | 1.0 | 3.1 |
| Kozak | –.1 | .8 | –.4 | 1.2 | –.6 | 1.4 | –1.1 | 2.1 | .5 | .7 | .3 | 1.7 | –2.0 | 2.3 | –2.9 | 4.1 |
| W&H | .6 | .8 | 1.0 | 1.3 | 1.7 | 1.9 | 2.1 | 3.0 | .7 | .9 | 1.2 | 2.0 | .1 | 2.4 | .3 | 3.9 |

[5]A computer routine, TAPEVAL, was developed to evaluate each of the taper models against any of the data sets. The results given in Tables 4a to 4c represent only a subset of the combinations examined by the authors.

[6]The Wensel and Olson model, W&O, statistics are included in Tables 4a to 4c for comparison. This is the model that was fit to Wensel and Krumland's model form (1983) here in this study.

In Table 3a for Douglas-fir, it is immediately apparent that the models fall into three groups. Least accurate was the Stadelman model. Second, the "best" model/coefficient combinations are the Biging, Max and Burkhart, Walters and Hann, and Wensel and Krumland model/coefficient combinations. Third, the coast and interior British Columbia models/coefficients by Kozak, Munro, and Smith (1969) for Douglas-fir are not too far off target. This is surprising because their data sources in British Columbia are well outside the region studied here.

In Tables 3b and 3c for ponderosa pine and white fir, respectively, again the Biging, Max and Burkhart, and Walters and Hann models performed the best. No statistics appear here for the Wensel and Krumland model because their model was only fitted to Douglas-fir and redwood on California's north coast. The McTague and Stansfield (1988) model for ponderosa pine also proved to be competitive, even though the model was fitted to data well outside the area of study here.

The Walters and Hann (1986) model, W&H, while performing well for some data sets, resulted in uniformly larger residual errors than most models. Further, it has several disadvantages for the current application. First, it requires that one

TABLE 3b. MEAN ($\bar{x}$) STANDARD DEVIATION (S) OF RESIDUAL (OBSERVED–PREDICTED INSIDE BARK DIAMETER), AND SAMPLE SIZE BY SIZE CLASS AND OWNERSHIP BY TAPER MODEL FOR PONDEROSA PINE

| DBH Class inches | 5.5–18 | | 18–30 | | 30–40 | | 40+ | | 5.5–18 | | 18–30 | | 30–40 | | 40+ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s |
| | COOP | | | | | | | | Eldorado NF | | | | | | | |
| no. | 734 | | 892 | | 61 | | | | 317 | | 495 | | 214 | | 114 | |
| STA | .0 | 1.1 | –.2 | 1.5 | –.3 | 2.7 | | | –.2 | 1.4 | –.7 | 1.9 | –.2 | 2.4 | –.0 | 4.4 |
| BIG | .3 | .7 | .5 | 1.1 | .7 | 2.2 | | | .2 | .7 | .5 | 1.3 | .5 | 2.0 | 2.0 | 2.9 |
| M&B | .4 | .7 | .5 | 1.0 | .6 | 2.2 | | | .4 | .7 | .6 | 1.3 | .6 | 1.9 | 2.0 | 2.8 |
| Kozak | –.4 | .7 | –.7 | 1.2 | –1.1 | 2.2 | | | –.3 | .7 | –.5 | 1.3 | –.9 | 2.0 | .2 | 2.7 |
| W&H | .7 | .8 | 1.0 | 1.3 | .9 | 2.3 | | | .3 | .9 | 1.0 | 1.5 | 1.0 | 2.4 | 2.5 | 3.7 |
| | Michigan-Cal | | | | | | | | Klamath NF | | | | | | | |
| no. | 207 | | 1007 | | 439 | | 82 | | 389 | | 459 | | 54 | | | |
| STA | –.4 | 1.8 | –.5 | 1.7 | –.9 | 2.3 | –2.3 | 2.9 | –.5 | 1.1 | –2.1 | 1.5 | –1.1 | 1.5 | | |
| BIG | .4 | 1.2 | .3 | 1.2 | .2 | 2.0 | .0 | 2.2 | –.1 | .7 | –.2 | 1.2 | –.0 | 1.1 | | |
| M&B | .3 | 1.2 | .2 | 1.2 | .1 | 1.9 | –.0 | 2.3 | .0 | .7 | .2 | 1.4 | .6 | 1.1 | | |
| Kozak | –.1 | 1.2 | –.7 | 1.2 | –1.2 | 2.0 | –2.0 | 2.3 | –.6 | .8 | –1.0 | 1.3 | –1.3 | 1.3 | | |
| W&H | .0 | 1.4 | .1 | 1.6 | .2 | 2.3 | .1 | 2.7 | .3 | .7 | .5 | 1.3 | .9 | 1.7 | | |
| | Bulletin 1883 | | | | | | | | | | | | | | | |
| no. | 150 | | 211 | | 102 | | 33 | | | | | | | | | |
| STA | –.5 | 1.4 | –1.1 | 2.0 | .2 | 2.4 | –.6 | 4.1 | | | | | | | | |
| BIG | –.1 | 1.0 | .0 | 1.4 | 1.0 | 1.7 | 1.4 | 3.0 | | | | | | | | |
| M&B | .0 | 1.0 | .2 | 1.3 | 1.1 | 1.6 | 1.6 | 2.8 | | | | | | | | |
| Kozak | –.8 | 1.1 | –1.0 | 1.5 | –.5 | 1.6 | –.7 | 2.9 | | | | | | | | |
| W&H | .5 | 1.0 | 1.1 | 1.6 | 1.9 | 2.3 | 3.3 | 4.0 | | | | | | | | |

TABLE 3c. MEAN ($\bar{x}$), STANDARD DEVIATION (S) OF RESIDUAL (OBSERVED–PREDICTED INSIDE BARK DIAMETER), AND SAMPLE SIZE BY SIZE CLASS AND OWNERSHIP BY TAPER MODEL FOR WHITE FIR

| **DBH Class inches** | **5.5–18** | | **18–30** | | **30–40** | | **40+** | | **5.5–18** | | **18–30** | | **30–40** | | **40+** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s | $\bar{x}$ | s |
| | COOP | | | | | | | | Eldorado NF | | | | | | | |
| no. | 1343 | | 894 | | 39 | | | | 351 | | 515 | | 199 | | 111 | |
| STA | –.5 | 1.1 | –.3 | 2.0 | –1.1 | 2.1 | | | –.9 | 1.3 | .1 | 2.2 | –.3 | 2.8 | .9 | 4.3 |
| BIG | .3 | .9 | –.0 | 1.4 | –1.0 | 1.3 | | | .3 | .9 | .3 | 1.6 | .3 | 2.1 | –.1 | 3.9 |
| M&B | .4 | .8 | .1 | 1.2 | –.8 | .9 | | | .2 | .9 | .2 | 1.6 | .2 | 2.3 | –.3 | 4.1 |
| W&H | .7 | .9 | .9 | 1.4 | .7 | 1.2 | | | .6 | 1.1 | 1.3 | 1.9 | 2.3 | 2.9 | 3.1 | 5.3 |
| | Michigan-Cal | | | | | | | | Klamath NF | | | | | | | |
| no. | 719 | | 1991 | | 560 | | 83 | | 221 | | 212 | | 106 | | | |
| STA | –.4 | 1.6 | –.5 | 2.0 | –1.3 | 2.3 | –1.5 | 7.7 | –.8 | 1.1 | –.9 | 2.0 | –2.1 | 2.0 | | |
| BIG | .6 | 1.0 | .2 | 1.3 | –.7 | 1.9 | –1.2 | 8.2 | .2 | .8 | –.5 | 1.7 | –1.2 | 2.0 | | |
| M&B | .5 | 1.0 | .2 | 1.4 | –.5 | 1.9 | –1.2 | 8.2 | .2 | .8 | –.3 | 1.8 | –.8 | 2.1 | | |
| W&H | .4 | 1.1 | .4 | 1.6 | .3 | 2.2 | .6 | 8.8 | .4 | .9 | .5 | 1.8 | .3 | 2.1 | | |
| | Bulletin 1883 | | | | | | | | Six Rivers | | | | | | | |
| no. | 128 | | 313 | | 125 | | 6 | | 125 | | 168 | | 129 | | | |
| STA | –1.2 | 1.2 | –.6 | 1.7 | –.6 | 2.3 | 2.2 | 3.5 | –.5 | 1.4 | –.0 | 2.2 | –.1 | 2.8 | | |
| BIG | –.5 | 1.1 | –.5 | 1.4 | –.4 | 2.0 | 2.2 | 2.7 | .5 | 1.0 | .1 | 1.7 | .2 | 2.4 | | |
| M&B | –.4 | 1.0 | –.4 | 1.3 | –.2 | 2.0 | 2.5 | 3.6 | .5 | 1.0 | .1 | 1.6 | .1 | 2.4 | | |
| W&H | .6 | 1.0 | 1.1 | 1.6 | 2.1 | 2.6 | 7.4 | 5.4 | .7 | 1.1 | 1.3 | 1.7 | 1.8 | 2.8 | | |

know, or estimate, the length of the live crown of the tree. Second, with the estimation of crown length, the model depends on 10 coefficients that must be estimated for each species.

The Wensel and Krumland (1983) equation, W&K, was developed for redwood and Douglas-fir on California's north coast. It is shown as equation (9) in Table 2. The coefficients were fit to measurements of both standing trees and felled trees and estimates the basis for tree taper computations in CRYPTOS, the Cooperative Redwood Yield Project's Timber Output Simulator (Wensel, Krumland, and Meerschaert, 1987).

The Biging (1984) model is a restricted version of the W&K model formed by fixing one of the coefficients so that it no longer changes with tree size, the BIG model. This equation, shown as equation (2) in Table 2, reduces the number of parameters to be estimated and makes it possible to integrate the taper equation for volume, making the taper and volume equations compatible. The relationship between equations (2) and (9) is seen by relating the following components in the two equations:

$$\left(\frac{\text{HT}-1}{\text{THT}-1}\right) \text{ versus } \left(\frac{\text{HT}}{\text{THT}}\right),\ c_0 \text{ vs. } b_1,\ c_1 \text{ vs.m, and } c_2 + c_3\text{DBH} + c_4\text{H vs. } -b_2$$

Biging fitted his coefficients to measurements taken from trees felled for stem analysis as part of the work of the Northern California Forest Yield Cooperative. Equation (2) is given particular attention here because it has been the principal taper model used in CACTOS, the California Conifer Timber Output Simulator, by Wensel, Daugherty, and Meerschaert (1986).

Biging also fitted coefficients to a segmented polynomial equation proposed by Max and Burkhart (1976), with statistics listed as the M&B model in Table 3a to 3c. Biging found both equation (2) and the M&B equation to perform about the same, but Biging's model is more parsimonious. It uses only two fitted coefficients for each species while the M&B model requires as many as 6 coefficients, depending on how many are fixed in any given solution. Biging's coefficients for both his and the M&B models were considered.

## Predictions Below Breast Height

Predictions of tree diameters at points below breast height are useful for estimating total biomass. However, they are not needed for estimating board foot volume since the scaling volume of the first log is at the small end of the log, usually at 16.5, 20.5, or 33.0 feet above the stump. Researchers have used separate models for predicting the inside-bark diameter below breast height. Walters and Hann (1986) present methods for predicting diameter below breast height either when the height to crown base is known or when it must be predicted.

The below-DBH model used here was introduced for redwood and Douglas-fir by Wensel and Krumland (1983). The stump diameter, $d_s$, at height $h_s$ is predicted by

$$d_s = (1 - b_0X)\,D_i e^{b_i(h_i - h_s)} \tag{10}$$

where $D_i$ is the measured diameter at height $h_i$, X is an indicator variable equal to 0 or 1, depending on whether the $D_i$ is inside- or outside-bark, respectively, and $b_0$ and $b_1$ are coefficients. In cases where the bark thickness is measured, $D_i$ is equal to DBH and $h_i$ = 4.5 feet.

# REFITTING COEFFICIENTS

Based upon the preceding evaluation, both the BIG and W&K models were selected for refitting here. The composite data set was divided into two subsets (every other tree) for each of the major species, one half for fitting and the other for testing. Bark thickness was predicted, where necessary, using the model developed by Wensel and Olson (1995). Wensel and Olson did not provide bark thickness models for Jeffrey pine or lodgepole pine, so the model for ponderosa pine was used for these species. The "fit" data set used, described in Table 4, was developed by combining all of the tree data available and then screening the data for completeness. This resulted in the tree taper measurements for fitting on over eight thousand trees yielding over 38 thousand individual upper stem (≥ 4.5 ft.) taper measurements.

TABLE 4. NUMBER OF TREES, MEAN, MINIMUM, AND MAXIMUM DIAMETER AT BREAST HEIGHT AND TOTAL HEIGHT, AND NUMBER OF OBSERVATIONS BELOW AND AT OR ABOVE BREAST HEIGHT USED TO FIT WENSEL AND KRUMLAND (1983) AND BIGING (1984) STEM TAPER MODELS BY SPECIES

| | | Diameter | | | Height | | | Number of observations | |
|---|---|---|---|---|---|---|---|---|---|
| | Number | | | | | | | *height* | |
| Species | of trees | Mean | Min | Max | Mean | Min | Max | <4.5 ft | ≥4.5 ft |
| Douglas-fir | 995 | 22.5 | 5.5 | 87.9 | 106.6 | 25.5 | 265.0 | 902 | 5249 |
| Ponderosa pine | 1907 | 21.5 | 5.1 | 94.5 | 91.0 | 18.0 | 238.4 | 2038 | 8094 |
| Jeffrey pine | 945 | 30.8 | 5.2 | 60.9 | 83.9 | 14.0 | 175.8 | 1049 | 4951 |
| Sugar pine | 583 | 24.9 | 6.0 | 69.2 | 99.5 | 18.1 | 202.0 | 606 | 2487 |
| Lodgepole pine | 215 | 16.4 | 7.9 | 44.4 | 66.9 | 27.7 | 147.9 | 320 | 940 |
| White fir | 2384 | 21.1 | 5.2 | 75.7 | 91.4 | 18.9 | 249.5 | 2505 | 9640 |
| Red fir | 911 | 23.2 | 5.5 | 65.7 | 88.7 | 20.6 | 207.2 | 956 | 4432 |
| Incense-cedar | 645 | 22.5 | 5.2 | 73.0 | 73.0 | 10.7 | 211.6 | 666 | 2718 |
| TOTAL | 8585 | | | | | | | 9042 | 38511 |

## Data Screening and Editing

The data were received from the various contributors and cooperators in this project and stored in a common data base. They were then retrieved from this data base using a screening process that eliminated trees and/or observations that were obviously in error or would result from grossly misformed trees. This eliminated trees that had forked or broken tops. Since field data sheets for much of the data were not readily available for checking questionable measurements, the data were not otherwise edited or corrected. Since measurement error can have the effect of moving an observation closer or further from the mean, outliers were not deleted as this would result in one-way bias.

## Model Development

The modified Gauss-Newton method of nonlinear model parameter estimation was used to estimate coefficients for the BIG and W&K models considered. Projecting on to the solution surface for Wensel and Krumland's model, being a five parameter model, required searching a grid to ensure that the solution was indeed the global minimum residual sum of squares. Especially for white fir, there were several local minima quite close to the global minimum.

## Coefficients for the Commercially Important Conifer Species

### Upper stem

Tables 5 and 6 show the coefficients calculated using models developed for the BIG and W&K models for the eight species that are both commercially important in California and for which there are sufficient numbers of observations for fitting. Table 5 gives the coefficients and mean squared error (MSE), corrected for degrees of freedom, calculated for Biging's model. The MSE ranged from a low, for lodgepole pine, of 1.78 sq. in. to 3.74 sq. in. for Jeffrey pine. Table 6 gives the coefficients calculated for the W&K model along with MSE. The MSE ranged from 2.91 sq. in. for sugar pine to 1.45 sq. in. for white fir. Douglas-fir lodgepole pine, and incense-cedar showed only small increase in the MSE for the BIG model relative to the W&K model (less than 15%), red and white fir show a 30% increase in MSE for the BIG model, with ponderosa pine showing the greatest increase in MSE.

Plots made of the residual errors for the BIG and W&K models failed to show any significant bias in the predictions relative to any of the predictors for any of the species tested.

There was considerable correlation between coefficients $c_2$, $c_3$, and $c_4$ as these are the coefficients that adjusted for the height-diameter relationship. However, for Douglas-fir, ponderosa pine, Jeffrey pine, and lodgepole pine, the $c_4$ coeffi-

TABLE 5. COEFFICIENTS AND MEAN SQUARE ERROR (MSE) FOR FIT OF STEM TAPER DATA, BREAST HEIGHT AND ABOVE, COLLECTED FROM THROUGHOUT CALIFORNIA TO THE MODEL DEVELOPED BY BIGING (1986)

| Species | $b_1$ | $b_2$ | MSE |
|---|---|---|---|
| Douglas-fir | 0.99007 | 0.32640 | 3.05 |
| Ponderosa pine | 1.04451 | 0.33229 | 1.98 |
| Jeffrey pine* | 1.00691 | 0.30606 | 3.74 |
| Sugar pine | 1.06171 | 0.37902 | 3.21 |
| Lodgepole pine* | 1.17304 | 0.45390 | 1.78 |
| White fir | 1.04442 | 0.33571 | 1.87 |
| Red fir | 1.01513 | 0.31803 | 1.85 |
| Incense-cedar | 1.00459† | 0.40012 | 2.23 |

*Ponderosa pine bark model was used for converting outside-bark observations.
†Not significantly different from 1.0 at $\alpha = 0.05$

TABLE 6. COEFFICIENTS AND MEAN SQUARE ERROR (MSE) FOR FIT OF STEM TAPER DATA, BREAST HEIGHT AND ABOVE, COLLECTED FROM THROUGHOUT CALIFORNIA TO THE MODEL (EQUATION 1) DEVELOPED BY WENSEL AND KRUMLAND (1983)

| Species | $c_0$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | MSE |
|---|---|---|---|---|---|---|
| Douglas-fir | 0.84292 | .97062 | −0.38163 | −0.0074002 | 0.0 | 2.52 |
| Ponderosa pine | 0.87278 | 1.26066 | −1.91214 | 0.020445 | 0.0 | 1.54 |
| Jeffrey pine* | 0.82932 | 1.50831 | −4.08016 | 0.047053 | 0.0 | 2.95 |
| Sugar pine | 0.90051 | 0.91588 | −0.92964 | 0.0077119 | −0.0011019 | 2.91 |
| Lodgepole pine* | 1.0 | 0.84257 | −0.98434 | 0.0 | 0.0 | 1.73 |
| White fir | 0.86039 | 1.45196 | −2.42273 | −0.15848 | 0.036947 | 1.45 |
| Red fir | 0.87927 | 0.91350 | −0.56617 | −0.014480 | 0.0037262 | 1.52 |
| Incense-cedar | 1.0 | 0.31550 | −0.34316 | 0.0 | −0.00039283 | 2.16 |

*Ponderosa pine bark model was used for converting outside-bark observations.

cients were found to be not significant in the model. In these species, the coefficient for total height ($c_4$) was set at zero, resulting in the other four coefficients becoming significant. For lodgepole pine, the coefficients for both DBH and total height ($c_3$ and $c_4$) were zero resulting in a model very similar to Biging's.

To test and compare the W&K and BIG models, the mean residual and the mean squared error was calculated using the observations withheld from the fitting data set. As one would expect with such large data sets, the results for the test data set were similar to those of the fitting data set.

The correlation, r, between the residual error and diameter at breast height is shown by species in Table 7 for the BIG and W&K models. The correlations were consistently low ( $|r| < 0.1$) using the W&K model while the correlation using the BIG model was consistently higher.[7] For the W&K model, these correlation's are not high enough to be important. Also, for several of the species, the same can be said for the Biging model.

## Stump model

The stump model proposed by Wensel and Krumland (1983) produced results with minimal bias and the least overall mean squared error. Although a linear model with a intercept term, using DBH and height as independent variables, was nearly as good at predicting stump diameters (less than 5 percent increase in MSE), such a model is conceptually inappropriate because of the intercept term.

The coefficients and mean squared error computed for Wensel and Krumland's stump model are shown in Table 8. Jeffrey pine and incense-cedar had MSE's in excess of 6.0 sq. in. while Lodgepole pine had a MSE of 1.51 sq. in. The error in predicting stump diameters was much greater than for predicting upper stem diameters. This is to be expected, as the magnitude of the observations was much

TABLE 7. CORRELATION BETWEEN RESIDUAL AND DBH FOR BIG AND W&K MODELS FOR THE "FIT" DATA SET

| Species | BIG | W&K |
|---|---|---|
| Douglas-fir | –0.28 | –0.09 |
| Ponderosa pine | 0.15 | 0.09 |
| Jeffrey pine | 0.12 | 0.10 |
| Sugar pine | 0.07 | –0.09 |
| Lodgepole pine | –0.12 | –0.04 |
| White fir | –0.12 | –0.03 |
| Red fir | –0.24 | –0.09 |
| Incense-cedar | –0.12 | –0.02 |

[7]A 3-parameter version of Biging's model was developed for each species (with m estimated instead of being equal to $\frac{1}{3}$). Compared with the 2-parameter version, this had only slight reductions in the overall residual sums of squares and very little or no reduction in the correlations shown in Table 8. Thus, as discovered by Biging, there is little reason to prefer the 3-parameter version of this model over the 2-parameter version.

TABLE 8. COMPUTED COEFFICIENTS AND MEAN SQUARED ERRORS (MSE) FROM WENSEL AND KRUMLAND'S STUMP MODEL

| Species | $b_0$ | $b_1$ | MSE |
|---|---|---|---|
| Douglas-fir | .1420 | .04302 | 4.11 |
| Ponderosa pine | .1031 | .03068 | 2.50 |
| Jeffrey pine | .1472 | .03880 | 6.20 |
| Sugar pine | .0743 | .02936 | 3.91 |
| Lodgepole pine | .0147 | .03223 | 1.51 |
| White fir | .0844 | .03320 | 3.25 |
| Red fir | .1105 | .05061 | 4.37 |
| Incense-cedar | .1177 | .03894 | 6.33 |

larger, and there is greater variation in taper in the lower stem. However, the residual plots for equation (10) did not show any bias in the predictions.

# INFLUENCE OF SITE AND LOCATION PARAMETERS

It is common practice to produce "localized" versions of tree volume and taper models because of perceived differences in the predicted relationships as one changes location. First, we discuss the effect of latitude and elevation followed by a discussion of the effect of site quality on the predictions.

## Latitude and Elevation

One of the objectives of this study was to adjust taper predictions for each species for changes in geographic location and site quality, if appropriate. California stretches over 9 degrees of latitude; we have data from the San Bernardino National Forest at 34 degrees to the data from Oregon at 43 degrees. Because of this, latitude was used as a measure of relative geographic position. Other approaches to assessing the effect of geographic location on stem taper could have been investigated, such as nonparametric analyses based on the concept of local genetic variation, but these approaches were not possible with the existing information.

Trees in the database were assigned a latitude based upon either specific plot information or, if plot information was not specific with respect to latitude, a latitude was assigned approximating the geographic center of the ownership or National Forest that the tree came from. These approximated or "pseudo" latitudes were then used to determine the effect of latitude and geographic position on stem taper.

Elevation information was less readily available for trees in the database. No attempt was made to approximate elevations if they were absent from the plot data. For assessing the effect of elevation on stem taper, elevation was corrected for latitude. It is generally known that with increasing latitude there is a drop in elevation to maintain equivalent climatic zones. However, there is little reported in the literature as to the specific altitudinal change per unit of latitudinal change for California. Daubenmire (1954) reported that timberline drops 360 feet per degree of latitude increase under a given type of climate regime for the Rocky, Coastal, and Appalachian Mountains. In the absence of a more definitive relationship, Daubenmire's 360 feet per degree of latitude relationship was used to adjust elevation for latitudinal differences in observations.

Correlations of latitude and elevation with residuals from the BIG and W&K models were computed. For this, actual latitude, pseudo-latitude, and latitude corrected for elevation were used. With correlations under 0.05 for Douglas-fir, and true firs and under 0.15 for ponderosa pine and incense-cedar, the examination of the residual plots showed no significant relationship, either linear or nonlinear, between the residuals and latitude and/or elevation. Further, plots of residuals on latitude for the W&K model showed no relationships. As a result, no local geographic adjustment was made to the taper models for each species.

## Site Quality

To see if there was an effect of site quality on the taper of trees, an evaluation of site versus residuals was made. All observations for which a 50-year site was available were used to evaluate the relationship between site index and residuals. The correlations ranged from –0.15 for incense-cedar to 0.05 in Douglas-fir for the BIG and W&K models. These correlations, by inspection, did not appear high enough to warrant the further investigation of site index adjustments to the models. This is particularly true considering the wide range of site qualities present in the data. One cannot say, however, that the trees have the same taper regardless of site quality because the W&K models vary the taper by tree DBH and height, which will themselves vary by site quality.

# DISCUSSION

Taper equations are used for appraisal work by estimating the scaling diameters of logs in the upper stem of trees. These diameters are used to get the scaling volume of trees which, when coupled with defect and log grade, are used to estimate the value of each tree. Here we have attempted to assess the reliability of various taper models that are currently being used for this purpose in California and to estimate the coefficients for two of the taper models.

The coefficients were fit to stem taper data collected throughout California as part of numerous previous individual studies of stem taper involving both felled and standing tree observations. The new models performed generally better throughout California on an overall basis, having generally less bias and variance compared to previously used models. However, other model forms could do as well or better for some species. Also, previously developed models perform well in some diameter size classes for certain data sets. The Wensel and Krumland model is a five-parameter model using relative height, diameter at breast height, and total height as predictive variables. The ability of this model to adjust for a larger range of diameters and heights appears to be the reason for its more general applicability over the 9 degrees of latitude from southern California to central Oregon.

The Wensel and Krumland model has two predictive equations, one for breast height and above and one for breast height and below. The below breast height model is provided for those who wish to predict cubic volume, including the flare below breast height.

Latitude, elevation, and site quality as measured by site index were evaluated to see if there was any need to develop either local models or include these variables into the models. There was little or no relationship between model residual error and latitude corrected for elevation or between residual error and site. Thus, the same coefficients can be used throughout the region.

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