Research Contribution 34

Enhanced Mortality Equations for Trees in the Mixed Conifer Zone of Southwest Oregon

by

David W. Hann
Mark L. Hanus

November 2001

Oregon State University
College of Forestry

Forest Research Laboratory

The Forest Research Laboratory of Oregon State University, established by the Oregon Legislature, conducts research leading to sustainable forest yields, innovative and efficient use of forest products, and responsible stewardship of Oregon's resources. Its scientists conduct this research in laboratories and forests administered by the University and cooperating agencies and industries throughout Oregon. Research results are made available to potential users through the University's educational programs and through Laboratory publications such as this, which are directed as appropriate to forest landowners and managers, manufacturers and users of forest products, leaders of government and industry, the scientific community, the conservation community, and the general public.

The Authors

David W. Hann is Professor of Forest Biometrics, and Mark L. Hanus is Faculty Research Assistant, in the Department of Forest Resources, Oregon State University, Corvallis.

Acknowledgments

This study was funded by the Forest and Rangeland Ecosystem Science Center of the Biological Resources Division, US Geological Survey, US Department of the Interior.

Disclaimer

To Order Copies

Copies of this and other Forest Research Laboratory publications are available from:

Forestry Communications Group
Oregon State University
256 Peavy Hall
Corvallis, Oregon 97331-7401

Phone: (541) 737-4271
FAX: (541) 737-4077
email: forspub@cof.orst.edu
Web site: http://www.cof.orst.edu/cof/pub/home/

Please indicate author(s), title, and publication number if known.

Editing, word processing, design, and layout by Forestry Communications Group.

Recycled Paper

Research Contribution 34

November 2001

Enhanced Mortality Equations for Trees in the Mixed Conifer Zone of Southwest Oregon

by

David W. Hann and Mark L. Hanus

OREGON STATE UNIVERSITY

COLLEGE OF FORESTRY

Forest Research Laboratory

Abstract

Hann, David W., and Mark L. Hanus. 2001. *Enhanced mortality equations for trees in the mixed conifer zone of southwest Oregon.* Research Contribution 34, Forest Research Laboratory, Oregon State University, Corvallis.

Equations for predicting the probability of a tree's dying in the next 5 years are presented for eight conifer and eight hardwood tree species from southwest Oregon. A logistic equation form was used to characterize the probability of mortality. The parameters of the equation were estimated using weighted, maximum likelihood procedures. These equations are being incorporated into the new southwest Oregon version of ORGANON, a model for predicting stand development. In particular, the equations extend the previous model to older stands and stands with a heavier component of hardwood tree species.

Contents

Introduction

Tree mortality is an integral part of stand dynamics that produces open space which leads to: (1) increased growth of surrounding trees through reduced competition, (2) opportunity for regeneration by the creation of gaps, and (3) the addition of large woody debris to the structure of the stand (Franklin et al. 1987, Oliver and Larson 1996). Mortality is classified as either regular or catastrophic in occurrence (Hamilton 1980, Vanclay 1994). Regular mortality is the relatively slow loss of individuals from the stand because of suppression due to competition, senescence, or random, endemic occurrences that result from insects, diseases, animals, lightning, etc. In contrast, the catastrophic mortality of a substantial number of individuals in a short period of time results from epidemic events, e.g., severe insect and disease outbreaks, or from uncommon but severe events, such as wildfire or major storms.

Because mortality is important to the dynamics of stand development, all models used to project stand development over time have included equations for predicting tree mortality rates. For example, ORGANON (Hann et al. 1997) is an individual-tree/distance-independent stand development model (Munro 1974) for use in three regions of the Pacific Northwest, including southwest Oregon. The original southwest Oregon version (SWO-ORGANON) predicted stand development in relatively young, conifer stands of mixed-species and mixed-stand structures. These stands typically are found in an area situated between the North Umpqua River and the California border to the south, and between the crests of the Cascade Mountains to the east and the Coast Range/Siskiyou Mountains to the west. The targeted conifer species for this work were Douglas-fir, grand and white firs, ponderosa and sugar pines, and incense-cedar. However, non-targeted species were also measured if they fell on the sampling unit.

The U.S. Fish and Wildlife Service has listed the northern spotted owl as a threatened species under the Endangered Species Act of 1973. This decision has had a major impact on forestry practices in the Pacific Northwest. In response, research was started in southwest Oregon to: (1) identify target stand structures and spatial relationships that were effectively utilized by the northern spotted owl and that could contribute to maintaining a stable population over time, and (2) develop silvicultural systems and associated mensurational tools for applying this knowledge at the stand level. One such tool for managing northern spotted owl habitat was the extension of SWO-ORGANON, and its associated mortality equations, into stands with older trees (250+ years), into stands with a higher component of hardwood species, and into stands with more complex spatial structure than was included in the original version.

This report describes the development of equations to predict the probability of individual tree mortality for the following species found in southwest Oregon:

Conifers:

Douglas-fir	[*Pseudotsuga menziesii* (Mirb.) Franco]
Grand fir	[*Abies grandis* (Dougl.) Lindl.]
Incense-cedar	*Calocedrus decurrens* Torr.
Pacific yew	*Taxus brevifolia* Nutt.
Ponderosa pine	*Pinus ponderosa* Laws.
Sugar pine	*Pinus lambertiana* Dougl.
Western hemlock	[*Tsuga heterophylla* (Rafn.) Sarg.]
White fir	[*Abies concolor* (Gord. & Glend.) Lindl.]

Hardwoods:

Bigleaf maple	*Acer macrophyllum* Pursh
California black oak	*Quercus kelloggii* Newb.
Canyon live oak	*Quercus chrysolepis* Liebm.
Golden chinkapin	*Castanopsis chrysophylla* (Dougl.) A. DC.
Pacific dogwood	*Cornus nuttallii* Aud. ex T. & G.
Pacific madrone	*Arbutus menziesii* Pursh
Tanoak	[*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.]
Willow	*Salix* spp.

Both the original and the new extended data sets were used for deriving the equations in our revision of SWO-ORGANON.

Data Description

Study Area

Data for this analysis are for the southwest Oregon region of the Pacific Northwest, U.S.A. A unique combination of weather conditions and geologic features means that the coniferous forests in the PNW are some of the most productive (site indices of up to 150 ft at a breast height age of 50 yr) and ecologically complex in the world. The southwest Oregon forests grow in the widest range of soil and climatic conditions of any region within the PNW (Franklin and Dyrness 1973). In addition, a number of different floras converge in southwest Oregon, making these forests probably the most complex of the PNW (Franklin and Dyrness 1973). A total of 27 coniferous species and over 17 hardwood species are found within southwest Oregon (Burns and Honkala 1990a,b), often growing in mixed-species stands with a variety of stand structures.

The modeling data are from two studies associated with the development of the southwest Oregon version of ORGANON (Hann et al. 1997). The first set was collected during 1981, 1982, and 1983, as part of the southwest Oregon Forestry Intensified Research (FIR) Growth and Yield Project. That study included 391 plots in an area extending from near the California border (42° 10' N) in the south, to Cow Creek (43° 00' N) in the north, and from the Cascade crest (122° E 15' W) on the east to approximately 15 miles west of Glendale, OR (123° 50' W). Elevation of the plots ranged from 900 to 5100 ft. Sampling was limited to stands under 120 yr and having at least 80% basal area (BA) in dominating conifer species. The second study covered about the same area, but extended the selection criteria to include stands with trees over 250 yr as well as younger stands with a greater component of hardwoods. An additional 138 plots were measured in this study. Stands treated in the past 5 yr were not sampled in either study.

Thirty tree species were identified on the 529 plots in the two studies. The most common conifers were Douglas-fir (527 plots), incense-cedar (244 plots), grand fir (235 plots), ponderosa pine (191 plots), sugar pine (191 plots), and white fir (161 plots). The most common hardwood species were Pacific madrone (270 plots), golden chinkapin (156 plots), California black oak (88 plots), canyon live oak (82 plots), Pacific dogwood (81 plots), and tanoak (75 plots). An average of nearly five species were found on each plot, with a range from 1 to 12.

Structures in the sample area varied from even-aged stands of one or two stories to uneven-aged stands. Of the 529 stands sampled, 363 had an even-aged overstory while 166 were classified as uneven-aged.

Sampling Design

In both studies, each stand was sampled with 4 to 25 points at 150-ft spacings. The sampling grid was established so that all sample points were at least 100 ft from the edge of the stand. For each point, a nested-plot design comprised four subplots: trees $\leq$ 4.0 in. DBH were selected on a 1/229-ac fixed subplot; trees 4.1 to 8.0 in. DBH on a 1/57-ac fixed-area subplot; trees 8.1 to 36.0 in. DBH on a 20 BAF variable-radius subplot; and trees > 36.0 in. DBH on a 60 BAF variable-radius subplot.

Tree Measurements

The measurements recorded at the end of the previous 5-yr growth period (indicated by a subscript of 2 on the variables) included an indicator of individual tree mortality over the past 5 yr, DBH_2, total tree height (H_2), height to live-crown base (HCB_2), and horizontal distance from plot center to tree center (DIST). In addition, the previous 5-yr radial and height growths were measured on subsamples of trees.

The dating of mortality was based on physical features of the dead tree, as described by the USDA Forest Service (1978) and Cline et. al. (1980). DBH_2 was recorded to the last whole tenth of an inch with a diameter tape. H_2 and HCB_2 were measured to the nearest 0.1 ft on all trees, either directly with a 25- to 45-ft telescoping fiberglass pole or, for taller trees, indirectly via the pole-tangent method (Larsen et al. 1987).

For trees with broken or dead tops, H_2 was measured to the top of the live crown. To determine the HCB_2 for trees of uneven crown length, the lower branches on the longer side of the crown were mentally transferred to fill in the missing portion of the shorter side of the crown. Epicormic and short internodal branches were ignored in this process. Procedures for measuring H_2 and HCB_2 of leaning trees depended on the severity of the lean, with all measurements taken at right angles to the direction of the lean. If lean was ≤15°, it was ignored and H_2 and HCB_2 were measured directly to the leaning tip and crown base. If the lean was >15°, the tree tip and crown base were mentally swung to a vertical position and H_2 and HCB_2 were measured to those imaginary points.

It can be difficult to accurately and precisely determine a tree's H_2 and HCB_2 at the time of death, especially if it has been dead for several years and, as a result, is missing foliage or part of the top at the time of the measurement. Therefore, the measured H_2 and HCB_2 for the dead trees were compared with predicted H_2 and HCB_2 for severely damaged but living trees with the same class of damage. We could then determine if the values for the dead tree were biased and, if so, develop adjustments for this bias. These procedures are described in detail in the Appendix.

Our comparison revealed that the measured H_2 for dead trees did not differ significantly from the predicted value. However, the HCB_2 for dead trees was significantly different from the predicted HCB_2. Hanus et al. (2000) found that severely damaged trees often had higher HCB_2 values than those predicted for undamaged trees. In the current study, the HCB_2 for dead trees always was higher, on average, than the predicted HCB_2 for severely damaged, living trees with the same class of damage. This difference was deemed a result of measurement error. Therefore, the HCB_2 for dead trees was adjusted downward to those values expected for severely damaged, living trees, and these adjusted values were used in all subsequent analyses.

DIST was determined by adding one-half the value of DBH_2 to the horizontal distance from plot center to tree face. Past radial growth at breast height was measured with an increment borer on all trees having a large enough DBH_2. Five-yr height growth of all undamaged Douglas-fir, grand fir, white fir, ponderosa pine, sugar pine, and incense-cedar trees under 25 to 45 ft (based upon the size of the telescoping pole used to measure H_2 and HCB_2) was measured directly with the pole if the top of the tree was clearly visible. For trees taller than the telescoping pole, a subsample of up to six trees on each plot were felled for stem analysis. This involved sectioning the pole at the first and sixth whorls, and determining the ages at these whorls to ensure a true 5-yr growth period. Finally, distance between the two whorls was recorded as the 5-yr height growth.

The expansion factor ($EXPAN_2$), or number of trees per acre (tpa), for any particular sampled tree alive at the end of the growth period was assigned according to rules based on sampling design:

1. $DBH_2 \leq 4.0$ in., $EXPAN_2$ is 229.18 tpa;

2. $DBH_2 > 4.0$ in. but ≤ 8.0 in., $EXPAN_2$ is 57.30 tpa;

3. $DBH_2 > 8.0$ in. but ≤ 36.0 in., $EXPAN_2 = 3666.93\,(DBH_2)^{-2}$;

4. $DBH_2 > 36.0$ in., $EXPAN_2 = 11000.79\,(DBH_2)^{-2}$.

Point and Plot Measurements

Aspect and slope were measured at each sampling point. Measurements for the plot or stand included ownership of the stand, elevation at the center of the stand (from USGS topographic maps), area of the stand (from aerial photographs), the number of previous cuts on the stand, and the number of years since the last cut (YCUT). The last two items were gained from the appropriate managing agencies. One of the selection criteria was that the stand could not have been treated within the past 5 yr. Therefore, 5 yr was the smallest value possible for YCUT.

Backdating of Tree Attributes

Because our objective was to predict future rather than past mortality rates, we had to backdate all the measurements for each sample tree on the plot. Values could then be estimated for the start of the previous 5-yr growth period, as indicated by a subscript of 1. Procedures used in backdating each variable are described in the Appendix.

Derivation of Additional Tree and Stand Attributes

After the basic tree measurements had been backdated, a number of tree and stand variables previously used in modeling mortality were calculated. A dichotomous mortality variable was formed for each tree by giving it a value of '1' if the tree died in the next 5-yr growth period, or a value of '0' if it did not. Crown ratio, a measure of tree vigor previously used by Hann and Wang (1990) and Monserud and Sterba (1999) to model mortality, was determined at the start of the growth period (CR_1) for each tree:

$$CR_1 = 1.0 \times \frac{HCB_1}{H_1},$$

where

HCB_1 = Height to live crown base at the start of the growth period

H_1 = Total tree height at the start of the growth period

BA in larger trees ($SBAL_1$) is a variable used to quantify the amount of one-sided competition for light experienced by relatively smaller trees within the stand at the start of the growth period (Weiner 1986, 1990; Vanclay 1994). $SBAL_1$ has been previously included in tree mortality equations (Hann and Wang 1990, Monserud and Sterba 1999), and is the sum of the BA in trees with DBH_1s larger than the subject tree's DBH_1. Therefore, the largest-diameter tree in the stand would have a $SBAL_1$ value of '0', while the smallest-diameter tree would have a $SBAL_1$ value near but somewhat less than the stand's total BA.

Another variable for quantifying the amount of one-sided, within-stand competition for light is crown closure at the top of the tree at the start of the growth period ($SCCH_1$). $SCCH_1$ has been previously implemented by Hann and Wang (1990) to characterize tree mortality of ponderosa pine. To calculate $SCCH_1$ of a particular tree, its H_1 was used to define a reference height (RH). Crown widths at RH for all other trees in the stand were estimated with equations described in the Appendix. Crown width was converted to crown area according to πr^2. The crown areas were then summed across all sample trees in the stand and expressed as a percentage of acreage covered. This procedure was repeated for all trees in the stand.

To better characterize within-stand variation in competition, Stage and Wykoff (1998) have proposed rescaling $SBAL_1$, i.e., multiplying it by the ratio of the appropriate plot BA (PBA_1) divided by stand basal (SBA_1):

$$\text{Scaled } PBAL_1 = SBAL_1 \times \frac{PBA_1}{SBA_1}$$

Another measure of within-stand variability is the direct calculation of BA in larger-diameter trees at the point level ($PBAL_1$). Both Scaled $PBAL_1$ and $PBAL_1$ were calculated to evaluate their effectiveness in characterizing within-stand variability.

Other variables calculated included the Douglas-fir site index (SI) (from Hann and Scrivani 1987) for the stand, and the average height ($H5_1$) and DBH ($D5_1$) at the start of the growth period of the five largest-diameter trees per acre in Douglas-fir, grand fir, white fir, ponderosa pine, sugar pine, or incense-cedar on each plot. To separate the "younger" and "older" stands, $H5_1$ and $D5_1$ were combined into an index of stand maturity (OG) through the following transformation (Hanus et al. 2000):

$$OG = \frac{(D5_1)(H5_1)}{10{,}000}$$

A summary of the stand-level variables used in developing the individual-tree mortality equations is presented in Table 1; tree-level variables are summarized in Table 2.

Data Analysis

The original mortality equations for southwest Oregon used the following logistic model form (Hann and Wang 1990):

$$PM = \frac{1.0}{\{1.0 + EXP[-Z]\}}, \qquad [1]$$

where

PM = The probability of a particular tree dying in the next 5-yr growth period

Table 1. Means and ranges of the plot-level explanatory variables in the mortality data sets.

Species	Number of plots	Douglas-fir site index	OG	Proportion treated	Yr since treatment
Conifers					
Douglas-fir	527	98.9 41.5 - 146.9	0.330 0.003 - 1.523	0.31	17.5 5.0 - 54.0
Grand/white firs	261	100.0 61.6 - 146.9	0.367 0.003 - 1.402	0.49	15.9 5.0 - 54.0
Incense-cedar	236	96.8 41.5 - 146.9	0.325 0.004 - 1.249	0.40	17.7 6.0 - 52.0
Pacific yew	29	96.8 66.2 - 135.2	0.445 0.004 - 1.523	0.45	15.4 6.0 - 33.0
Ponderosa pine	187	95.1 41.5 - 146.9	0.272 0.000 - 0.978	0.41	17.5 5.0 - 52.0
Sugar pine	183	92.7 47.2 - 138.8	0.307 0.002 - 1.168	0.43	17.5 5.0 - 54.0
Western hemlock	38	104.8 74.0 - 135.6	0.382 0.016 - 1.207	0.50	13.7 7.0 - 30.0
Hardwoods					
Bigleaf maple	34	106.1 74.0 - 142.5	0.501 0.039 - 1.523	0.21	13.4 5.0 - 30.0
California black oak	84	90.4 41.5 - 134.9	0.284 0.002 - 0.978	0.37	17.3 6.0 - 47.0
Canyon live oak	72	93.7 47.2 - 138.8	0.342 0.002 - 1.248	0.21	16.5 7.0 - 33.0
Golden chinkapin	153	100.1 61.7 - 135.5	0.289 0.002 - 1.249	0.29	16.3 5.0 - 39.0
Pacific dogwood	78	102.0 66.2 - 135.2	0.342 0.009 - 1.345	0.44	15.5 6.0 - 52.0
Pacific madrone	265	98.6 41.5 - 146.9	0.288 0.000 - 1.249	0.28	16.5 6.0 - 52.0
Tanoak	72	99.1 47.2 - 138.8	0.386 0.002 - 1.523	0.18	17.7 8.0 - 30.0
Willow	39	104.1 66.2 - 135.0	0.133 0.031 - 0.826	0.44	14.7 6.0 - 29.0

Table 2. Means and ranges for tree-level explanatory variables in the mortality data sets.

Species	DBH	HT	HTCB	CR	BAL	Point BAL	Scaled BAL	CCH
Conifers								
Douglas-fir	13.9 0.1 - 80.8	76.0 4.5 - 251.3	42.5 0.0 - 178.1	0.46 0.02 - 1.0	113.4 0.0 - 516.0	115.3 0.0 - 700.0	122.8 0.0 - 688.1	43.7 0.0 - 368.9
Grand/White firs	12.3 0.1 - 51.1	69.3 4.5 - 201.5	35.8 0.0 - 126.3	0.49 0.05 - 1.0	133.9 0.0 - 542.0	136.3 0.0 - 720.0	145.8 0.0 - 715.4	47.6 0.0 - 361.0
Incense-cedar	9.2 0.1 - 83.5	37.4 4.5 - 183.7	19.9 0.0 - 114.8	0.47 0.05 - 1.0	142.6 0.0 - 402.8	146.4 0.0 - 608.1	175.4 0.0 - 926.8	97.0 0.0 - 338.8
Pacific yew	5.6 0.1 - 22.5	17.8 4.6 - 45.0	7.1 0.0 - 19.1	0.56 0.15 - 1.0	128.1 0.0 - 358.5	143.1 0.0 - 420.0	177.2 0.0 - 565.1	89.0 4.42 - 209.4
Ponderosa pine	14.0 0.1 - 59.6	72.5 4.7 - 221.3	41.5 0.0 - 146.3	0.44 0.03 - 1.0	83.0 0.0 - 285.9	83.3 0.0 - 460.0	99.8 0.0 - 869.7	23.4 0.0 - 311.1
Sugar pine	18.2 0.1 - 69.6	78.6 4.6 - 177.5	41.5 0.0 - 115.6	0.50 0.05 - 1.0	71.6 0.0 - 340.0	76.2 0.0 - 460.0	92.7 0.0 - 654.0	26.6 0.0 - 377.9
Western hemlock	9.0 0.1 - 30.0	50.5 4.6 - 153.8	16.2 0.0 - 75.4	0.64 0.05 - 1.0	129.6 0.0 - 349.7	143.2 0.0 - 452.0	185.4 0.0 - 843.1	54.7 0.0 - 264.7
Hardwoods								
Bigleaf maple	7.2 0.1 - 28.4	46.5 4.5 - 100.0	28.1 0.0 - 63.5	0.41 0.05 - 1.0	167.3 2.0 - 375.0	148.1 0.0 - 400.0	154.2 0.0 - 446.3	76.1 0.3 - 205.4
California black oak	10.9 0.1 - 42.3	42.5 4.5 - 116.3	26.6 0.0 - 76.1	0.38 0.02 - 1.0	107.3 0.0 - 294.7	100.3 0.0 - 400.0	110.0 0.0 - 729.2	71.5 0.0 - 257.7
Canyon live oak	2.5 0.1 - 22.4	15.9 4.5 - 56.1	8.3 0.0 - 41.0	0.50 0.03 - 1.0	164.5 0.0 - 402.3	152.0 0.0 - 580.0	161.0 0.0 - 876.0	125.4 2.4 - 316.2
Golden chinkapin	3.8 0.1 - 27.6	22.3 4.5 - 84.4	13.1 0.0 - 61.0	0.43 0.02 - 1.0	118.4 0.0 - 390.0	115.8 0.0 - 420.5	133.7 0.0 - 628.2	96.7 0.0 - 331.7
Pacific dogwood	1.1 0.1 - 6.8	12.1 4.7 - 42.7	6.5 0.4 - 25.2	0.50 0.1 - 0.93	117.7 10.0 - 348.1	114.2 0.0 - 460.0	143.3 0.0 - 649.2	92.1 4.7 - 258.1
Pacific madrone	8.2 0.1 - 44.5	42.4 4.6 - 102.1	28.1 0.4 - 79.2	0.35 0.01 - 0.97	118.2 0.0 - 365.0	116.3 0.0 - 560.0	136.4 0.0 - 845.8	60.6 0.0 - 278.8
Tanoak	2.4 0.1 - 36.4	16.5 4.5 - 107.7	8.8 0.0 - 56.2	0.48 0.05 - 1.0	177.8 0.0 - 401.5	176.9 0.0 - 557.2	194.4 0.0 - 1222.4	144.6 0.0 - 372.3
Willow	1.0 0.1 - 8.7	13.6 4.5 - 41.9	8.6 1.0 - 28.4	0.39 0.04 - 0.77	74.1 11.4 - 252.0	57.0 0.0 - 247.0	71.5 0.0 - 402.2	70.5 3.8 - 237.4

$Z = f(\underline{X}, \underline{b})$

$\underline{X}$ = array of independent variables

$\underline{b}$ = array of additional regression parameters

This model form has been used extensively in individual-tree models (Hamilton and Edwards 1976, Monserud 1976, Ferrell 1980, Wykoff et al. 1982, Hamilton 1986, Monserud and Sterba 1999, Cao 2000).

The dichotomous mortality variable was the dependent variable in equation [1]. The regression coefficients, b, can be estimated by either the weighted least squares or the weighted maximum-likelihood estimation procedure (Hamilton 1986). Here we used the maximum-likelihood estimation procedures in SAS to estimate the parameters. Because the sampling design resulted in trees having unequal sampling probabilities, depending on their DBH_1 and DIST (see Appendix), each observation was weighted by $EXPAN_1$.

After carefully examining numerous alternatives, Hann and Wang (1990) selected the following two functions for Z to predict mortality:

$$Z = b_0+b_1(DBH_1)+b_2(CR_1)+b_3(SI)+b_4(SBAL_1) \quad [2]$$

$$Z = b_0+b_1(DBH_1)+b_2(CR_1)+b_3(SI)+b_4(SCCH_1) \quad [3]$$

Choice of particular function depended on the species being modeled. The resulting logistic models predicted a decline in mortality with increases in DBH_1 and CR_1, and an increase in mortality with increasing $SBAL_1$ and SI. All of these responses met behavioral expectations for the population being modeled then.

The decline in mortality with increasing DBH_1 is consistent with the relative youthfulness of the trees and stands in the data set of Hann and Wang (1990). However, as a tree matures into old age, the probability of mortality should begin to increase with age or size (Buchman et al. 1983, Harcombe 1987, Monserud and Sterba 1999), thereby producing a U-shaped mortality curve. To mimic this behavior in their older stands, Monserud and Sterba (1999) added 1/DBH and DBH^2 to the following function for equation [1] to predict mortality in Norway spruce (*Picea abies* L. Karst.):

$$Z = b_0+b_1(DBH_1)^{-1}+b_2(DBH_1)+b_3(DBH_1)^2+b_4(CR_1)+b_5(SBAL_1) \quad [4]$$

Function [4] can be modified to include the SI and $SCCH_1$ variables in the functions of Hann and Wang (1990):

$$Z = b_0+b_1(DBH_1)^{-1}+b_2(DBH_1)+b_3(DBH_1)^2+b_4(CR_1)+b_5(SI)+b_6(SBAL_1) \quad [5]$$

$$Z = b_0+b_1(DBH_1)^{-1}+b_2(DBH_1)+b_3(DBH_1)^2+b_4(CR_1)+b_5(SI)+b_6(SCCH_1) \quad [6]$$

The expected U-shaped behavior will occur in these two functions if the sign on one of the DBH_1 parameters is opposite from the others.

The Douglas-fir data set (the largest available for modeling) was used to evaluate these four functions in equation [1] and to develop additional functions for evaluation. This evaluation was based on: (1) whether the parameters were significantly different from zero at $P = 0.05$, (2) whether the predicted behavior met expectations, and (3) the size of the reduction in the sum of maximum-likelihood loss function reported by SAS for each model. We chose a P-value of 0.05 for these t-tests because we did not wish to remove a predictor variable from the equation unless evidence was strong that the variable was not significantly different from zero.

All the parameters for the four alternative functions were significantly different from zero. The predicted behavior of functions [2] and [3] met expected behavior for younger stands (i.e., predicted mortality rates decreasing with DBH_1). However, the predicted mortality rates from functions [5] and [6] over DBH_1 did not meet behavioral expectations for both younger and older stands (i.e., predicted mortality rates first decreasing and then increasing over DBH_1). For function [5], the mortality rate first increased, then decreased and, finally, increased again over DBH_1. In contrast, function [6] first predicted an increase and then a decrease in mortality over DBH_1.

Apparently, the inclusion of three DBH_1 terms in functions [5] and [6] was an overparameterization of the functions. Therefore, the following simplified functions were evaluated next:

$$Z = b_0+b_1(DBH_1)+b_2(DBH_1)^2+b_3(CR_1)+b_4(SI)+b_5(SBAL_1) \quad [7]$$

$$Z = b_0+b_1(DBH_1)+b_2(DBH_1)^2+b_3(CR_1)+b_4(SI)+b_5(SCCH_1) \quad [8]$$

Again, the predicted behavior of function [8] over DBH_1 did not meet the expectation, with the predicted mortality rate first increasing, then decreasing over DBH_1. Therefore, function [3] was the only one involving $SCCH_1$ that gave behavior meeting expectations over DBH_1 for younger stands (but not older stands).

The predicted behavior of function [7] did meet behavioral expectations for both young and old stands. Unfortunately, the sum of loss for function [7] was considerably larger than that for function [3] (76,841 versus 71,598). Apparently, CCH_1 better characterized the competitive impact on mortality than did BAL_1.

Previous work by Hanus et al. (2000) on predicting height to crown base for the same data set showed that older stands (characterized by large OG values) displayed longer crowns than did younger stands (with small OG values), using the same values for the competition variables. The following model, therefore, was fitted to the Douglas-fir data set to evaluate whether including OG might explain some of the difference in sum of loss between function [3] and function [7]:

$$Z = b_0+b_1(DBH_1)+b_2(DBH_1)^2+b_3(CR_1)+b_4(SI)+b_5(SBAL_1)+b_6(SBAL_1)(OG) \quad [9]$$

All parameters in this function were significantly different from zero, and the sum of loss for the function was reduced to 74,305. The sign on b_6 was negative, which indicates that the impact of $SBAL_1$ on mortality rate decreases as OG increases. This formulation, however, would allow the impact of $SBAL_1$ to reduce the rate of mortality if OG increased enough. The following formulation was created to avoid this potential problem:

$$Z = b_0+b_1(DBH_1)+b_2(DBH_1)^2+b_3(CR_1)+b_4(SI)+b_5(SBAL_1)+b_6(SBAL_1)(e^{b_7(OG)}) \quad [10]$$

All of the b regression parameters in this function were significantly different from zero, and the sum of loss for the function was further reduced to 74,252. Therefore, function [10] was chosen as one of the base functions that would be fitted to all of the species-specific mortality data sets.

The data sets to be used in this analysis included stands that previously had been cut. Our past experience with fitting mortality models to thinned research plots indicated that, if the thinning was done carefully, the mortality rate of those stands could be predicted by equations developed for unthinned stands (i.e., thinning had no additional impact on the rate of mortality other than how it changed DBH_1, CR_1, and BAL_1 over time). This lack of a cutting impact may not be true in operational cuts if the treatment either damaged the residual trees or degraded the site. Because quality of treatments may differ by ownership, the following approach was applied to each species' data set to evaluate the impact of operational cuttings on predicted mortality, and to correct for the impact if it was found to be statistically significant:

1. Seven indicator variables were defined according to ownership of the stand:

   IO_i = 1.0 if Ownership was i, i = 1,7;

   = 0.0 Otherwise

2. The following Z function was fitted in equation [1] to each species' data set:

$$Z = b_0+b_1(DBH_1)+b_2(DBH_1)^2+b_3(CR_1)+b_4(SI)$$
$$+b_5(SBAL_1)+b_6(SBAL_1)(e^{b_7(OG)})+\sum_{i=1}^{7} o_i IO_i \quad [11]$$

3. The parameters of the indicator variables were tested for significance from zero at P = 0.01 using the t-test. In this case, a P-value of 0.01 was used to reduce the amount of data removed in the next step. We wanted very strong proof that the data were different before they were removed.

4. For those ownerships in which the parameters were not significantly different from zero, the cutting data were kept in the modeling data set and treated as if they were uncut data.

5. Those ownerships with significant parameters were pooled together. The following five indicator variables were then defined to determine how long the impact of cutting remained:

   IC_1 = 1.0 if $6 \leq YCUT \leq 10$,

   = 0.0 Otherwise;

$$IC_2 = 1.0 \text{ if } 11 \leq YCUT \leq 15,$$
$$= 0.0 \text{ Otherwise;}$$

$$IC_3 = 1.0 \text{ if } 16 \leq YCUT \leq 20,$$
$$= 0.0 \text{ Otherwise;}$$

$$IC_4 = 1.0 \text{ if } 21 \leq YCUT \leq 25,$$
$$= 0.0 \text{ Otherwise;}$$

$$IC_5 = 1.0 \text{ if 26 or greater;}$$
$$= 0.0 \text{ Otherwise.}$$

6. The following Z function was then fitted to each species' data set:

$$Z = b_0+b_1(DBH_1)+b_2(DBH_1)^2+b_3(CR_1)+b_4(SI) +b_5(SBAL_1)+b_6(SBAL_1)(e^{b_7(OG)})+\sum_{i=1}^{5} o_i IO_i \quad [12]$$

7. The parameters of the indicator variables again were tested for significance from zero using the t-test. A P-value of 0.01 was used to reduce the amount of data removed in the next step.

8. If c_1 was significantly different from zero, those data were removed from the modeling data set. If c_2 also differed significantly from zero, they too were removed from the modeling data set. This process continued until the data for all significant parameters contiguous to the previous parameter's YCUT values were removed from the data. The resulting, reduced data set formed the final modeling data set for the species in question.

With the final modeling data sets defined, two other base functions that included the Scaled $PBAL_1$ and the $PBAL_1$ variables were formed:

$$Z = b_0+b_1(DBH_1)+b_2(DBH_1)^2+b_3(CR_1)+b_4(SI) +b_5(\text{Scaled } PBAL_1)+b_6(\text{Scaled } PBAL_1)(e^{b_7(OG)}) \quad [13]$$

$$Z = b_0+b_1(DBH_1)+b_2(DBH_1)^2+b_3(CR_1)+b_4(SI)+b_5(PBAL_1)+b_6(PBAL_1)(e^{b_7(OG)}) \quad [14]$$

Functions [10], [13], and [14] were then fitted in equation [1] to the final modeling data sets. Parameters not significantly different from zero at $P = 0.05$, or parameters that provided unreasonable predictive behavior, were removed, and the reduced function was fitted again to the final modeling data.

The equations were then tested in ORGANON by performing 200-yr projections on 96 plots with different stand structures. The pattern and rates of mortality for the various species were then examined. The behavior from the equations of Hann and Wang (1990) were used as the basis for comparison. In making these runs, no limit was placed on maximum stand density index.

Results And Discussion

Of the 15 species or species-groups data sets for which significant mortality equations were found, 11 had significant cutting-effects indicator variables. The four exceptions were Pacific yew, tanoak, willow, and Pacific dogwood. When significant, the signs of the parameters were always positive, indicating that cutting increased mortality. In general, the effect of cutting was most severe in the first 5-yr period after treatment; the effect declined as time since cutting increased. Total duration of the cutting effect ranged from 15 yr (for ponderosa pine and incense-cedar) to 25 yr (for California black oak), with the remaining species having durations of 20 yr each.

The final number of observations, 5-yr mortality rates, and annual mortality rates for each species are presented in Table 3. Annual mortality rates were computed from the 5-yr rates under the assumption that mortality was a compounding process (Hamilton and Edwards 1976). Table 3 also includes Minore's (1973, 1979) ranking of tolerance for the conifer species, with a ranking of '1' indicating the most tolerant and '7' indicating the most intolerant. The rate of mortality generally increases with intolerance. The most notable exception was sugar pine, which had a much larger mortality rate than any other species.

Table 3. Final number of observations, 5-yr mortality rate, annual mortality rate, and ranking of tolerance for conifers in the mortality data sets.

Species	N	5-yr mortality rate (%)	Annual mortality rate (%)	Ranking of tolerance (conifers only)[1]
Conifers				
Douglas-fir	17,271	12.17	2.56	5
Grand fir	1,610	6.01	1.23	2
Incense-cedar	1,403	10.76	2.25	4
Pacific yew	78	4.25	0.86	1
Ponderosa pine	1,382	13.13	2.78	7
Sugar pine (w blister rust)	423	17.78	3.84	6
Sugar pine (w/o blister rust)	295	12.98	2.74	6
Western hemlock	118	3.70	0.75	1
White fir	925	6.66	1.37	3
Hardwoods				
Bigleaf maple	111	0.87	0.17	
California black oak	471	6.84	1.41	
Canyon live oak	472	7.55	1.56	
Golden chinkapin	1,127	6.22	1.28	
Pacific dogwood	334	3.41	0.69	
Pacific madrone	2,118	6.27	1.29	
Tanoak	803	11.89	2.50	
Willow	352	0.45	0.09	

[1] from Minore (1973, 1979)

White pine blister rust (*Cronartium ribicola*) caused almost 35% of the mortality in sugar pine. Of the five-needled pines, that species is the most susceptible to infection by this agent, with the widest incidence and most serious infections occurring in southwest Oregon and northern California (Kinlock and Scheuner 1990). When plots with white pine blister rust infection were removed, the resulting mortality rates fell into line with the other conifer species (Table 3).

Tables 4, 5, and 6 show the parameter estimates, their standard errors, the mean square error for the species group-specific equation, and the number of trees in a particular data set used to estimate the parameter values for functions [10], [13], and [14], respectively. If none of the BAL_1 parameters in those functions differed significantly from zero, the statistics for the species group were reported only for function [10] in Table 4.

Except for the sugar pine plots infected with white pine blister rust, the signs of the statistically significant parameters reported in Table 4 met the expectations defined previously. When the infected sugar pine plots were included, the signs on CR_1 and $SBAL_1$ were opposite those expected. This resulted in predicted mortality increasing with CR_1 and decreasing with BAL_1.

White pine blister rust is an airborne disease that infects a tree through its needles (Bega and Scharpf 1993). When infection reaches the main stem, death is inevitable (Bega and Scharpf 1993). It is hypothesized that trees with large crowns located in the overstory (and thereby exposed to more wind) are more likely to be infected by this rust and, therefore, more likely to die. This hypothesis was supported in our study because sugar pine mortality increased with crown size and with the level of dominance of sugar pine in the stand.

Its widespread occurrence in southwest Oregon may suggest that white pine blister rust in sugar pine is an endemic rather than epidemic cause of mortality. Therefore, two mortality equations are presented for sugar pine: one includes infected plots for those users who believe it is endemic; the other equation omits those plots. For the latter case, the probability of death simply decreases with an increase in DBH_1.

In general, increasing the sample size by adding the "hardwood" and "older" stand data from the second study in southwest Oregon has resulted in more species with significant mortality models and more significant parameters for each species compared with the equations of Hann and Wang (1990). Equations will now be available for western hemlock, Pacific yew, bigleaf maple, canyon live oak, Pacific dogwood, and willow. In the current version of SWO-ORGANON, western hemlock, bigleaf maple, and canyon live oak use Hann and Wang (1990) mortality equations that had been developed for other species. Therefore, the new equations should provide more realistic predictions of mortality for these species. It also may be possible to extend SWO-ORGANON to include Pacific yew, Pacific dogwood, and willow as well.

The DBH_1^2 variable has been added to the equations for six species groups that also include DBH_1: Douglas-fir, grand/white firs, incense-cedar, ponderosa pine, sugar pine (including plots infected with white pine blister rust), and California black oak. The first five groups represent the most common and long-lived conifer species in southwest Oregon. When inserted into SWO-ORGANON, the new equations will now predict the expected increase in mortality as stands with these species reach old age. Predicted mortality will increase for a DBH greater than 37.6 in. for Douglas-fir, 24.6 in. for white and grand firs, 27.4 in. for incense-cedar, 25.6 in. for ponderosa pine, 33.9 in. for sugar pine (including infected plots), and 15.7 in. for California black oak.

Hann and Wang (1990) reported that SI was significant only for their combination Douglas-fir/ grand fir/white fir equation. In the new equations, SI is significant in eight species groups. These include five for which SI had not been contained in the equations of Hann and Wang (1990): ponderosa pine, California black oak, golden chinkapin, Pacific madrone, and tanoak.

The effect of the OG modifier on BAL was significant only for Douglas-fir. This is probably a consequence of the species' very large sample size relative to the other species. The

Table 4. Parameter estimates, standard errors (in parentheses), and mean square error (MSE) for function [10] in mortality equation [1].

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	MSE
Conifers									
Douglas-fir	-4.64848327 (0.0516754294)	-0.26655869 (0.0041315857)	0.00369911 (0.0001732051)	-2.11802664 (0.0392978371)	0.02549943 (0.0003994000)	0.00336134 (0.0001967200)	0.01355395 (0.0001952000)	-2.72347095 (0.1033026621)	15.3532
Grand & white firs	-2.215777201 (0.1653001308)	-0.162895666 (0.0138823838)	0.003317290 (0.0006824856)	-3.561438261 (0.1319803748)	0.014644689 (0.0015799608)	0.0 (NA)	0.0 (NA)	0.0 (NA)	10.5555
Incense-cedar	-1.922689902 (0.0630499884)	-0.136081990 (0.0118550268)	0.002479863 (0.0003763121)	-3.178123293 (0.1230330849)	0.0 (NA)	0.004684133 (0.0001859774)	0.0 (NA)	0.0 (NA)	21.3494
Pacific yew	-4.072781265 (0.3636921570)	-0.176433475 (0.0533270349)	0.0 (NA)	-1.729453975 (0.690116660)	0.0 (NA)	0.012525642 (0.0012353761)	0.0 (NA)	0.0 (NA)	64.8402 5
Ponderosa pine	-1.050000682 (0.1948048965)	-0.194363402 (0.0129714103)	0.003803100 (0.0005613940)	-3.557300286 (0.1913091324)	0.003971638 (0.0016885821)	0.005573601 (0.0005790102)	0.0 (NA)	0.0 (NA)	85.8063
Sugar pine blister rust	-2.40647803 (0.02453)	-0.15123037 (0.0189)	0.00223010 (0.000605)	3.02030959 (0.2646)	0.0 (NA)	-0.00363243 (0.000808))	0.0 (NA)	0.0 (NA)	8.9467
Sugar pine w/o blister rust	-1.56693022 (0.0816)	-0.06699767 (0.0123)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	7.3016
Western hemlock	-1.166211991 (0.2483227747)	0.0 (NA)	0.0 (NA)	-4.602668157 (0.6069289903)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	12.3025
Hardwoods									
Bigleaf maple	-2.976822456 (0.4864771611)	0.0 (NA)	0.0 (NA)	-6.223250962 (2.008602232)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	9.1528
California black oak	-3.108619921 (0.3090192157)	-0.570366764 (0.0442865751)	0.018205398 (0.0017538041)	-4.584655216 (0.3437951975)	0.014926170 (0.0028476315)	0.012419026 (0.0012069319)	0.0 (NA)	0.0 (NA)	28.9583
Canyon live oak	-2.990451961 (0.0695619436)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.002884841 (0.0003577709)	0.0 (NA)	0.0 (NA)	35.0413
Golden chinquapin	-4.317549852 (0.1380966365)	-0.057696253 (0.0101992533)	0.0 (NA)	0.0 (NA)	0.004861355 (0.0014322494)	0.009981290 (0.0002761742)	0.0 (NA)	0.0 (NA)	34.2166
Pacific dogwood	-3.020345211 (0.3903407556)	0.0 (NA)	0.0 (NA)	-8.467882343 (0.4099997016)	0.013966388 (0.0032721125)	0.009461545 (0.0006991445)	0.0 (NA)	0.0 (NA)	41.9018
Pacific madrone	-6.089598985 (0.2044554528)	-0.245615070 (0.0098144079)	0.0 (NA)	-3.208265570 (0.1566764025)	0.033348079 (0.0017021096)	0.013571319 (0.0004061227)	0.0 (NA)	0.0 (NA)	11.0222
Tanoak	-2.410756914 (0.1113043309)	0.0 (NA)	0.0 (NA)	-1.049353753 (0.0812453491)	0.008845583 (0.001011258)	0.0 (NA)	0.0 (NA)	0.0 (NA)	43.5278
Willow	-5.405408462 (0.1238847547)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	41.6955

Table 5. Parameter estimates, standard errors (in parentheses), and mean square error (MSE) for function [12] in mortality equation [1].

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	MSE
Conifers									
Douglas-fir	-5.38649449	-0.28003440	0.00409382	-1.51668068	0.02643448	0.00171588	0.01455205	-1.56689518	16.9772
	(0.0523060226)	(0.0042178193)	(0.0001414214)	(0.0408975549)	(0.0004000000)	(0.0004123106)	(0.0003605551)	(0.085297362)	
Incense-cedar	-1.501347358	-0.181385405	0.003228499	-3.443048475	0.0	0.004013294	0.0	0.0	20.4929
	(0.0648869948)	(0.0131995574)	(0.0003876953)	(0.1245710484)	(NA)	(0.0001885654)	(NA)	(NA)	
Pacific yew	-5.212446667	-0.270170161	0.0	0.0	0.0	0.011460069	0.0	0.0	65.5807
	(0.3242496014)	(0.0545730691)	(NA)	(NA)	(NA)	(0.0011498471)	(NA)	(NA)	
Ponderosa pine	-1.403522614	-0.214394845	0.004386839	-3.097308699	0.004258693	0.006539455	0.0	0.0	9.4558
	(0.1952254398)	(0.0129997552)	(0.0005324613)	(0.1902810529)	(0.0017320380)	(0.0004499393)	(NA)	(NA)	
Hardwoods									
California black oak	-1.830621137	-0.537933085	0.016276425	-5.575407756	0.015671529	0.005278349	0.0	0.0	23.7258
	(0.2657850123)	(0.0427437418)	(0.0017078027)	(0.3700257073)	(0.0027711035)	(0.0004694367)	(NA)	(NA)	
Canyon live oak	-3.335972770	0.0	0.0	0.0	0.0	0.004969014	0.0	0.0	34.2483
	(0.0674938812)	(NA)	(NA)	(NA)	(NA)	(0.0003316625)	(NA)	(NA)	
Golden chinquapin	-3.365036438	-0.066234104	0.0	0.0	0.0	0.005482566	0.0	0.0	33.5973
	(0.0343536730)	(0.0100270658)	(NA)	(NA)	(NA)	(0.0001517137)	(NA)	(NA)	
Pacific dogwood	-1.248518817	0.0	0.0	-6.438761155	0.0	0.001740046	0.0	0.0	30.5497
	(0.1293003935)	(NA)	(NA)	(0.3362969207)	(NA)	(0.0002836452)	(NA)	(NA)	
Pacific madrone	-4.284459866	-0.211131160	0.0	-3.392092352	0.026160877	0.005131440	0.0	0.0	12.5727
	(0.1775216055)	(0.0092313562)	(NA)	(0.1477757958)	(0.0015969796)	(0.0002041257)	(NA)	(NA)	

Table 6. Parameter estimates, standard errors (in parentheses), and mean square error (MSE) for function [13] in mortality equation [1].

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	MSE
Conifers									
Douglas-fir	-5.39790336	-0.26236693	0.00373162	-1.50462193	0.02677936	0.00176102	0.01460688	-1.62346585	16.6534
	(0.0522501675)	(0.0041928511)	(0.0001732051)	(0.0407889691)	(0.0004020000)	(0.0003872983)	(0.0003316625)	(0.0857886356)	
Incense-cedar	-1.510643606	-0.171031206	0.003044578	-3.442827857	0.0	0.004050958	0.0	0.0	20.3510
	(0.0644405834)	(0.0131292766)	(0.0003918537)	(0.1245781271)	(NA)	(0.0001866197)	(NA)	(NA)	
Pacific yew	-5.097342714	-0.228694780	0.0	0.0	0.0	0.012833385	0.0	0.0	78.5160
	(0.3135053450)	(0.0513483999)	(NA)	(NA)	(NA)	(0.0011816484)	(NA)	(NA)	
Ponderosa pine	-1.563080332	-0.207492097	0.004198603	-2.927784885	0.004371725	0.007301331	0.0	0.0	9.7468
	(0.1981106648)	(0.0128971148)	(0.0005324778)	(0.1893095954)	(0.0017532891)	(0.0004509964)	(NA)	(NA)	
Hardwoods									
California black oak	-2.410944381	-0.594827393	0.018740327	-5.265000906	0.013292850	0.010869297	0.0	0.0	34.4674
	(0.2824207611)	(0.0458948036)	(0.0017677997)	(0.3709927999)	(0.0028610258)	(0.0008006009)	(NA)	(NA)	
Canyon live oak	-3.117522956	0.0	0.0	0.0	0.0	0.003316205	0.0	0.0	34.2812
	(0.0533344729)	(NA)	(NA)	(NA)	(NA)	(0.0002144761)	(NA)	(NA)	
Golden chinquapin	-3.649440322	-0.069124455	0.0	0.0	0.0	0.008550996	0.0	0.0	33.3104
	(0.0395453617)	(0.0098838263)	(NA)	(NA)	(NA)	(0.0002200637)	(NA)	(NA)	
Pacific dogwood	-1.459483565	0.0	0.0	-7.544102784	0.0	0.006387861	0.0	0.0	38.1444
	(0.1255981727)	(NA)	(NA)	(0.3648066327)	(NA)	(0.0005912812)	(NA)	(NA)	
Pacific madrone	-5.423263791	-0.274631784	0.0	-3.046670914	0.029516734	0.012163980	0.0	0.0	10.5506
	(0.1938173248)	(0.0103620369)	(NA)	(0.1505141726)	(0.0016814726)	(0.0003437265)	(NA)	(NA)	

OG modifier reduced the impact of BAL on the predicted mortality rate to roughly one-third of a very young stand's BAL value as OG approached infinity. Most of this reduction occurred very quickly as OG increased. When OG reached 1.523 (the largest value in the data set; Table 1), the reduction was almost 100%.

Ten of the fifteen species groups had significant BAL_1 parameters in functions [10], [13], and/or [14] (Tables 4, 5, or 6). For eight of these groups, using either $PBAL_1$ or Scaled $PBAL_1$ provided a modest reduction in sum of loss when compared with the usage of $SBAL_1$. The exceptions were sugar pine (including infected plots) and Pacific dogwood. For six of the eight groups (i.e., Douglas-fir, incense-cedar, ponderosa pine, Pacific yew, California black oak, and canyon live oak), function [14] with $PBAL_1$ was superior to function [13] with Scaled $PBAL_1$. Both functions were superior to function [10] with $SBAL_1$. For golden chinkapin and Pacific madrone, function [14] with $PBAL_1$ also provided the lowest sum of loss values, but function [10] with $SBAL_1$ was superior to function [13] with Scaled $PBAL_1$. The only species group for which function [14] with $PBAL_1$ did not provide the lowest sum of loss value was Pacific dogwood. There, function [10] with $SBAL_1$ was superior to function [14] with $PBAL_1$ and both of these were superior to function [13] with Scaled $PBAL_1$.

The Z function for willow included only a constant value, b_0. Therefore, its predicted mortality rates were constant across all tree and stand conditions.

We compared the EXPAN values for trees after 200-yr projections using the new mortality equations versus those of Hann and Wang (1990) and found that:

1. for Douglas-fir, mortality from the new equation was less in the 10- to 30-in. DBH range, but was about the same as Hann and Wang (1990) for both smaller and larger DBH classes;
2. for white and grand firs, mortality from the new equation was lower for trees with <10 in. DBH and higher for DBH >10 in.;
3. for ponderosa pine, mortality from the new equation was lower for trees with DBH <40 in. and higher for DBH >40 in.;
4. for sugar pine, mortality from the new equation was nearly the same across all DBH classes;
5. for tanoak, bigleaf maple, and California black oak, mortality from the new equation was greater across all DBH classes;
6. For incense-cedar, western hemlock, Pacific madrone, golden chinkapin, and canyon live oak, mortality from the new equation was less across all DBHs, so that these species persisted longer in the stands.

The 200-yr projections using the new mortality equations showed almost 91% of the 96 plots had more trees per acre, 55% had higher BA, and 90% had smaller quadratic mean diameters.

Literature Cited

Bega, RV and RF Scharpf. 1993. Chapter 4: Rusts. pp. 83–111 in *Diseases of Pacific Coast Conifers*, RF Scharpf, ed. *Agriculture Handbook* No. 521, USDA, Washington, D.C.

Buchman, RG, SP Pederson, and NR Walters. 1983. A tree survival model with application to species of the Great Lakes region. *Canadian Journal of Forest Research* 13: 601-608.

Burns, RM and BH Honkala. 1990a. *Silvics of North America: Volume 1, Conifers. Agriculture Handbook* No. 654, USDA, Washington, DC.

Burns, RM and BH Honkala. 1990b. *Silvics of North America: Volume 2, Hardwoods. Agriculture Handbook* No. 654. USDA, Washington, D.C.

Cao, QV. 2000. Prediction of annual diameter growth and survival for individual trees from periodic measurements. *Forest Science* 46: 127–131.

Cline, SP, AB Berg, and HM Wight. 1980. Snag characteristics and dynamics in Douglas-fir forests, western Oregon. *Journal of Wildlife Management* 44: 773–786.

Ferrell, GT. 1980. Risk-rating systems for nature red fir and white fir in northern California. *General Technical Report* PSW-39, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

Franklin, JF and CT Dyrness. 1973. Natural vegetation of Oregon and Washington. *General Technical Report* PNW-GTR-8. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Franklin, JF, HH Shugart, and ME Harmon. 1987. Tree death as an ecological process. *BioScience* 37 (8): 550–556.

Hamilton, DA., Jr. 1980. Modeling mortality: A component of growth and yield modeling. pp. 82–99 in *Forecasting forest stand dynamics*, KN Brown and FR Clarke, eds. School of Forestry, Lakehead University, Thunder Bay, ON, Canada.

Hamilton, DA., Jr. 1986. A logistic model of mortality in thinned and unthinned mixed conifer stands of northern Idaho. *Forest Science* 32: 989–1000.

Hamilton, DA, Jr., and BM Edwards. 1976. Modeling the probability of individual tree mortality. *Research Paper* INT-RM-185. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Hann, DW. 1997. Equations for predicting the largest crown width of stand-grown trees in western Oregon. *Research Contribution* 17. Forest Research Laboratory, Oregon State University, Corvallis.

Hann, DW. 1999. An adjustable predictor of crown profile for stand-grown Douglas-fir trees. *Forest Science* 45: 217–225.

Hann, DW and DR Larsen. 1991. Diameter growth equations for fourteen tree species in southwest Oregon. *Research Bulletin* 69. Forest Research Laboratory, Oregon State University, Corvallis.

Hann, DW and JA Scrivani. 1987. Dominant height growth and site index equations for Douglas-fir and ponderosa pine in southwest Oregon. *Research Bulletin* 59. Forest Research Laboratory, Oregon State University, Corvallis.

Hann, DW and C-H Wang. 1990. Mortality equations for individual trees in the mixed-conifer zone of southwest Oregon. *Research Bulletin* 67. Forest Research Laboratory, Oregon State University, Corvallis.

Hann, DW, AS Hester, and CL Olsen. 1997. ORGANON User's manual edition 6.0. Department of Forest Resources, Oregon State University, Corvallis.

Hanus, ML, DW Hann, and DD Marshall. 1999. Predicting height for undamaged and damaged trees in southwest Oregon. *Research Contribution* 27. Forest Research Laboratory, Oregon State University, Corvallis.

Hanus, ML, DW Hann, and DD Marshall. 2000. Predicting height to crown base for undamaged and damaged trees in southwest Oregon. *Research Contribution* 29. Forest Research Laboratory, Oregon State University, Corvallis..

Harcombe, PA. 1987. Tree life tables. *Bioscience* 37: 557–568.

Kershaw, JA and DA Maguire. 1996. Crown structure in western hemlock, Douglas-fir and grand fir in western Washington: horizontal distribution of foliage within branches. *Canadian Journal of Forest Research* 26: 128–142.

Kinlock, BB, Jr. and WH Scheuner. 1990. *Pinus lambertiana* Dougl.: Sugar pine, pp. 370–379 in *Silvics of North America: Volume 1, Conifers*. RM Burns and BH Honkala, eds. *Agriculture Handbook* No. 654. USDA, Washington, DC.

Larsen, DR and DW Hann. 1985. Equations for predicting diameter and squared diameter inside bark at breast height for six major conifers of southwest Oregon. *Research Note* 77. Forest Research Laboratory, Oregon State University, Corvallis.

Larsen, DR and DW Hann. 1987. Height-diameter equations for seventeen tree species in southwest Oregon. *Research Paper* 49. Forest Research Laboratory, Oregon State University, Corvallis.

Larsen, DR, DW Hann, and SC Stearns-Smith. 1987. The tangent method of measuring tree height--how accurate and precise is it? *Western Journal of Applied Forestry* 2: 26–28.

Minore, D. 1973. Mixed conifers of southwestern Oregon, pp. 10-12 in *Silvicultural systems for the major forest types of the United States. Agricultural Handbook No. 445*. USDA Forest Service, Division of Timber Management Research, Washington, DC.

Minore, D. 1979. Comparative autecological characteristics of northwestern tree species - A literature review. *General Technical Report* PNW-87. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Monserud, RA. 1976. Simulation of forest tree mortality. *Forest Science* 22: 438–444.

Monserud, RA and H Sterba. 1999. Modeling individual tree mortality for Austrian forest species. *Forest Ecology and Management* 113: 109–123.

Munro, DD. 1974. Forest growth models — a prognosis, pp. 7–21 in *Growth models for tree and stand simulation*, J. Fries, ed. *Research Note* 30. Department of Forest Yield Research, Royal College of Forestry, Stockholm, Sweden.

Oliver, CW and BC Larson. 1996. *Forest stand dynamics: Update edition*. Wiley & Sons, New York.

Press, WH, BP Flannery, SA Teukolsky, and WT Vetterling. 1989. pp. 509–528 in *Numerical recipes: The art of scientific computing*. Cambridge University Press, Cambridge, United Kingdom.

Ritchie, MW and DW Hann. 1987. Equations for predicting height to crown base for fourteen tree species in southwest Oregon. *Research Paper* 50. Forest Research Laboratory, Oregon State University, Corvallis.

Ritchie, MW and DW Hann. 1990. Equations for predicting the 5-year height growth of six conifer species in southwest Oregon. *Research Paper* 54. Forest Research Laboratory, Oregon State University, Corvallis.

Stage, AR and WR Wykoff. 1998. Adapting distance-independent forest growth models to represent spatial variability: Effects of sampling design on model coefficients. *Forest Science* 44: 224B238.

USDA Forest Service. 1978. Region one field instructions for stand examination and forest inventory. Chapter 300 in *Handbook* 2409.21. USDA Forest Service, Region One, Missoula, MT.

Vanclay, JK. 1994. *Modelling forest growth and yield: Applications to mixed tropical forests*. CAB International, Wallingford, United Kingdom.

Weiner, J. 1986. How competition for light and nutrients affects size variability in *Ipomea tricolor* populations. *Ecology* 67: 1425–1427.

Weiner, J. 1990. Asymmetric competition in plant populations. *Trends in Ecology and Evolution* 5(11): 360–364.

Wykoff, WR, NL Crookston, and AR Stage. 1982. User's guide to the Stand Prognosis Model. *General Technical Report* INT-133. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Appendix

Evaluating Potential Bias in Total Height Measurements on Dead Trees

The following process was developed to determine if a bias existed in the measurement of dead tree H_2 and to correct for that bias. With one exception, the first two steps of the process closely parallel the one described by Hanus et al. (1999). The exception is the definition of the modeling data sets to which the procedure is applied. Hanus et al. (1999) have defined the modeling data sets by species, detailed damage codes, and severity of damage. In the current application, the modeling data sets were defined by species and by broad damage and death classes, and were restricted to severely damaged living trees and to dead trees. For each species, multiplicative adjustment factors (AF_H) to H_2 for severely damaged trees in a particular class of damage were calculated as follows:

1. The regional height-diameter prediction equation for undamaged trees (i.e., Equation [1] with parameters from Table 5 in Hanus et al. 1999) was calibrated to each plot to reduce variation caused by between-plot differences in the height-diameter relationship. Each plot's undamaged tree heights were regressed on predicted tree heights, using the regression model:

   $$CPH_i = c_{1,i}(PH_i - 4.5) \qquad [A1]$$

   where

   CPH_i = predicted height above breast height calibrated to the i^{th} plot's undamaged, living trees for a particular species

   PH_i = Predicted height for undamaged, living trees from the i^{th} plot from Eq. [1] and parameters from Table 5 of Hanus et al. (1999).

   Parameter $c_{1,i}$ was estimated by using linear regression through the origin and a weight of $1.0/DBH_2$. The parameter was then tested for significance from 1.0 with a t-test ($P = 0.10$). A P-value of 0.10 was used in the test to assure broad usage of the plot-level calibration. Values of c_1 judged not significant were set to 1.0 (i.e., the regional equation was used for the plot).

2. For a given damage class, the multiplicative CF_H (correction factor) for those severely damaged, living trees was calculated across all plots containing the class of damage by regressing the damaged tree heights on CPH from Step 1:

   $$DPH - 4.5 = (CF_H)(CPH) \qquad [A2]$$

   where

DPH = predicted height above breast height for living trees severely damaged by a particular class of agents.

If CF_H was not significantly different from 1.0 using a t-test (P=0.01), then it was set to 1.0 for that class of damaging agent.

3. For a given damage/death class, AF_H for dead trees from that class was calculated across all plots containing the class of damage/death by regressing the dead tree heights on DPH from Step 2:

$$MPH - 4.5 = (AF_H)(DPH - 4.5) \quad [A3]$$

where

MPH = predicted height above breast height for dead trees killed by a particular class of agents.

AF_H was tested for significance from 1.0 using a t-test (P=0.01). For all species and classes of killing agents, AF_H was not significantly different from 1.0. Therefore, the H_2 measurements on dead trees were unbiased.

Evaluating Potential Bias In Height-To-Crown-Base Measurements On Dead Trees

The following process was developed to determine if a bias existed in the measurement of dead tree HCB_2 and to correct for that bias. With one exception, the first two steps of the process closely parallel the one described by Hanus et al. (2000). The exception is the definition of the modeling data sets to which the procedure is applied. Hanus et al. (2000) defined the modeling data sets by species, detailed damage codes, and severity of damage. In this current application, the modeling data sets were defined by species as well as broad damage and death classes, and were restricted to severely damaged living trees and to dead trees. For each species, multiplicative adjustment factors (AF_{HCB}) to height-to-crown-base for severely damaged trees in a particular damage class were calculated as follows:

1. The regional HCB prediction equations (i.e., Equations [1], [2], and [3] with parameters from Tables 6, 7, or 8 in Hanus et al. 2000) were calibrated to each plot to reduce variation caused by between-plot differences in the height-to-crown-base relationship. Here, each plot's undamaged tree height-to-crown-base was regressed on predicted tree height-to-crown-base, using the regression model:

$$CPHCB_i = \frac{H_i}{[1.0 + \exp(\underline{\beta x} + d_i)]} \quad [A4]$$

where

$CPHCB_i$ = predicted HCB calibrated to the i^{th} plot's undamaged, living trees for a particular species

$\underline{\beta X}$ = the vector predictors for that species from Equations [1], [2], or [3] and their respective coefficients from Tables 6 or 7 in Hanus et al. (2000)

d_i = plot-level calibration for the i^{th} plot estimated using the weighted, nonlinear regression routine of Press et al. (1989).

The parameter d_i was set to '0' unless more than three undamaged trees were found on the plot and the predicted value was significantly different from zero using a t-test. A p-value of 0.10 was used in the t-test to assure broad usage of plot-level calibration.

2. The species-specific correction factor (CF_{HCB}) for severely damaged trees from a given class of damaging agents was calculated by regressing the measured HCB for all severely damaged trees from a given damaging agent to the calibrated predicted HCB:

$$DPHCB = \frac{H}{[1.0 + \exp(\underline{\beta X} + d_i + CF_{HCB})]} \quad [A5]$$

where

DPHCB = Predicted HCB for trees of a certain species damaged by a particular agent

CF_{HCB} was estimated using weighted, nonlinear regression. The value was then tested for significance from 0.0 with a t-test (P = 0.01). If it was not significant, then CF_{HCB} was set to 0.0 for the specific class of damaging agent.

3. For a given class of damage/death, AF_{HCB} for dead trees from that class was calculated across all plots containing the damage/death class by regressing the dead tree height-to-crown-base on DHCB from Step 2:

$$MPHCB = \frac{H}{[1.0 + \exp(\underline{\beta x} + d_i + CF_{HCB} + AF_{HCB})]} \quad [A6]$$

where

MPHCB = Predicted HCB for dead trees of a certain species killed by a particular agent

AFHCB = Predicted HCB for dead trees of a certain species killed by a particular agent

AF_{HCB} was estimated using weighted, nonlinear regression. The value was then tested for significance from 0.0 with a t-test (P = 0.01). If it was not significant, then AFHCB was set to 0.0 for the specific class of damaging agent.

4. Results of Step 3 in the analysis showed that HCB_2 for dead trees was significantly higher than HCB_2 for living trees with severe damage from the same class of damage/death. For those species and damage classes with a significant AF_{HCB}, an adjustment was made to the dead tree's measured HCB_2:

$$AMPHCB = H - \frac{H}{\left[1.0 + \frac{MHCB}{H - MHCB} \exp\left(AF_{HCB}\right)\right]} \qquad [A7]$$

where

AMPHCB = Adjusted predicted HCB for dead trees of a certain species killed by a particular agent

MHCB = Measured HCB for dead trees of a certain species killed by a particular agent

Procedures for Backdating Variables

DBH_1

For trees with a radial-growth measurement, DBH at the start of the growth period was estimated according to:

$$DBH_1 = \left\{\frac{A_1(DBH_2)^{A_2} - 2(RG)}{A_1}\right\}^{1.0/A_2} \qquad [A8]$$

where

DBH_1 = DBH at the start of the growth period

DBH_2 = DBH at the end of the growth period (i.e., measured DBH)

RG = Measured 5-yr radial growth of the tree, inside bark

A_1, A_2 = Regression coefficients from Larsen and Hann (1985) for predicting DBH inside bark from DBH outside bark

Two alternative methods were used to compute DBH_1 when radial growth was not measured on the tree. If a 5-yr height growth measurement was available for the tree, then DBH_1 was computed as:

$$DBH_1 = \frac{DBH_2[(H_2 - HG - 4.5)]}{(H_2 - 4.5)} \qquad [A9]$$

where

H_2 = Total tree height at the end of the growth period (i.e., measured total tree height)

HG = 5-yr height growth measurement

This relationship assumed that the DBH-to-HT ratio remained constant over the 5-yr growth period.

If HG was not measured, a calibration value for the predicted future 5-yr diameter-growth-rate equations of Hann and Larsen (1991) was calculated for each species in the stand that had at least five measured diameter growth (MDG) rates, as follows:

$$DGCAL = \frac{\Sigma(MDG_i)}{\Sigma(PDG_i)} \quad [A10]$$

where

DGCAL = Calibration factor for a particular species in the stand having at least five MDGs

MDG_i = Measured past 5-yr diameter growth for a particular species = DBH_2 - DBH_1

PDG_i = Predicted future 5-yr diameter growth from Hann and Larsen (1991) at the end of the growth period for trees of a particular species having at least five MDGs

For species in which diameter growth had been measured on less than five trees in the stand, an average calibration factor across all species was used. DBH_1 was then computed for trees without either a measured RD or HG by:

$$DBH_1 = DBH_2 - (DGCAL)(PDG) \quad [A11]$$

H_1

For trees with measured HG, total tree height at the start of the growth period was determined by:

$$H_1 = H_2 - HG \quad [A12]$$

where

H_1 = Total tree height at the start of the growth period

The approach chosen for predicting H_1 for a tree without a measured 5-yr height growth rate depended upon species, the severity of any damage to the tree, and whether the tree had a missing or dead top. Two initial estimates of HG were made for Douglas-fir, grand/white firs, ponderosa pine, sugar pine, and incense-cedar. The first estimate (EHG1) used the height-growth-rate equations of Ritchie and Hann (1990) to estimate the future 5-yr height growth rate at the end of the growth period. A calibration value for the Ritchie and Hann (1990) equation was also calculated for each species in the stand having at least five measured height growth (MHG) rates:

$$HGCAL = \frac{\Sigma(MHG_i)}{\Sigma(EHG1_i)} \quad [A13]$$

where

HGCAL = Calibration factor for a particular species in the stand having at least five MHGs

MHG_i = Measured past 5-yr height growth rate for a particular species

$EHG1_i$ = Estimated future 5-yr height growth rate from Ritchie and Hann (1990) at the end of the growth period for trees of a particular species having at least five MHGs

For species in which height growth rate had been measured on less than five trees in the stand, an average calibration factor across all species was used.

The second initial estimate was used for all species, and applied the height/diameter equations of Larsen and Hann (1987) as follows:

$$EHG_2 = H_2 - \left[4.5 + \frac{PH_1 - 4.5}{PH_2 - 4.5} \times (H_2 - 4.5)\right] \quad [A14]$$

where

PH_1 = Predicted H_1 from DBH_1 for a particular species, using the height/diameter equations of Larsen and Hann (1987)

PH_2 = Predicted H_2 from DBH_2 for a particular species, using the height/diameter equations of Larsen and Hann (1987)

For Douglas-fir, grand/white firs, ponderosa pine, sugar pine, and incense-cedar, the predicted height growth rate (PHG) was set to EHG_1 if the tree was undamaged; to the average of EHG_1 and EHG_2 for trees with light damage; and to EHG_2 for severely damaged trees. For all other species, PHG was set equal to EHG_2 and HGCAL was set equal to 1.0. For all species, PHG was set to 0.0 for trees with missing or dead tops. H_1 was then estimated by:

$$H_1 = H_2 - (HGCAL) \times (PHG) \quad [A15]$$

HCB_1

Height-to-crown-base at the start of the growth period (HCB_1) was computed via the HCB equations of Ritchie and Hann (1987). First, the predicted crown ratios at both the start (PCR_1) and the end (PCR_2) of the growth period were computed from the following relationship to HCB:

$$PCR_i = 1.0 - \frac{PHCB_i}{PH_i} \quad [A16]$$

where

$PHCB_i$ = Predicted HCB from Ritchie and Hann (1987) for the i^{th} measurement

PH_i = Predicted H for the i^{th} measurement

i = 1 for the start of the growth period, = 2 for the end of the growth period

PCR_2 was then calibrated to each species in the stand having a measured CR_2, using the following equation:

$$CRCAL = \frac{\Sigma (PCR_2)(MCR_2)}{\Sigma \quad (PCR_2)^2} \qquad [A17]$$

where

CRCAL = Calibration factor for a particular species in the stand having at least five MCR_{2s}

MCR_2 = Measured crown ratio at the end of the growth period for a particular species

The predicted change in HCB could then be computed by:

$$PHCBG = H_2[1.0 - (PCR_2)(CRCAL)] - H_1[1.0 - (PCR_1)(CRCAL)] \qquad [A18]$$

where

PHCBG = Predicted 5-yr change in HCB

Finally, HCB at the start of the growth period was computed by:

$$HCB_1 = HCB_2 + PHCBG \qquad [A19]$$

If HCB_1 was predicted to be greater than $0.95H_1$, then HCB_1 was set equal to $0.95H_1$.

$EXPAN_1$

The expansion factor, or number of trees per acre (tpa), for a tree at the start of the growth period ($EXPAN_1$) was used to calculate a number of point-level and stand-level attributes at the start of the growth period (i.e., PBA_1, SBA_1, $PBAL_1$, Scaled $PBAL_1$, $SBAL_1$, $SCCH_1$, $H5_1$, and $D5_1$; see definitions under Data Description). The value of $EXPAN_1$ was based on DBH_1, the distance to the center of the tree (DIST), and the following rules derived from the sampling design:

1. For a tree with $DBH_1 \leq 4.0$ in., if DIST is ≤7.78 ft, then $EXPAN_1$ is 229.18 tpa; otherwise $EXPAN_1$ is 0.0.

2. For a tree with $DBH_1 > 4.0$ inches but ≤8.0 in., if DIST is ≤15.56 ft, then $EXPAN_1$ is 57.30 tpa; otherwise $EXPAN_1$ is 0.0.

3. For a tree with DBH_1 >8.0 inches and ≤36 in., a critical distance (CDIST20) is first computed by:

$$CDIST20 = 1.944544\ (DBH_1)$$

If the tree's DIST is less than or equal to CDIST20, then $EXPAN_1$ is computed by:

$$EXPAN_1 = 3666.93\ (DBH_1)^2$$

otherwise, $EXPAN_1$ is 0.0.

4. For a tree with DBH_1 > 36.0 in., a critical distance (CDIST60) is first computed by:

$$CDIST60 = 1.122683\ (DBH_1)$$

If the tree's DIST is less than or equal to CDIST, then $EXPAN_1$ is computed by:

$$EXPAN_1 = 11000.79\ (DBH_1)^2$$

otherwise, $EXPAN_1$ is 0.0.

If $EXPAN_1$ was zero, the tree was excluded from the analysis.

Procedures For Calculating Crown Widths

The crown width of a tree for any reference height (RH) above the ground was calculated from the following equation form described by Hann (1999):

$$CWA = LCW \times RP^{[a_0 + a_1 RP^{1/2} + a_2 (H/DBH)]} \quad [A20]$$

where

CWA = Crown width above HLCW for RH within the crown

LCW = Largest crown width of the tree (in ft) predicted by the equations of Hann (1997)

HLCW = Height above the ground (in ft) to where LCW occurs, = HCB + a3(H - HCB)

RP = RH/H, if LCW ≤ RH < H; = 0.0, if RH ≥ H; = 1.0, if RH ≤ LCW

Parameters a_0, a_1, a_2, and a_3 for the equation are given in Table 7. The values for Douglas-fir are the English equivalents of the metric values given in Hann (1999). The parameters for grand fir, white fir, and western hemlock were determined according to analytical procedures described by Hann (1999).

Parameter estimates for grand and white firs were computed from data collected on 30 felled trees measured on 13 stands in southwest Oregon. DBH ranged from 5.1 to 17.5 in. The final equation had an adjusted coefficient of determination of 0.8225.

Table 7. Parameter estimates for the crown-width equation [A20].

Species	a_0	a_1	a_2	a_3
Douglas-fir	0.929973	-0.135212	-0.0157579	0.0620
Grand/White firs	0.999291	0.0	-0.0314603	0. 0284
Pines	0.755583	0.0	0.0	0.05
Hemlock/Incense-cedar	0.629785	0.0	0.0	0.2098
Hardwoods	0.5	0.0	0.0	0.0

The parameter estimate, a_0, for western hemlock was computed from data collected by Kershaw and Maguire (1996) on 18 standing western hemlock trees on two untreated stands in western Washington. DBH ranged from 6.0 to 9.8 in. The final equation had an adjusted coefficient of determination of 0.6696.

The a_0 values for the remaining species were based on personal observations of the profiles of those species. Incense-cedar was deemed similar to western hemlock, so its value was set to that for western hemlock. The values for ponderosa and sugar pines were derived from a fit of the Hann (1999) Douglas-fir data set to the simplified equation form (with just a_0). These pine values were chosen because the resultant predicted profile had a more rounded top than did profiles predicted from the full Douglas-fir equation.

The values for all of the hardwood species were selected based on the assumption that their crown profiles could be described by a parabola (Hann 1999). Likewise, the a_3 values for the remaining species were determined based on personal observations of their profiles. The incense-cedar value was set to that for western hemlock. The pines were set to a value between Douglas-fir and grand/white firs, and the hardwood values were set based on the assumption that LCW occurred at the base of the crown.