Research Contribution 29

Predicting Height to Crown Base for Undamaged and Damaged Trees in Southwest Oregon

by

Mark L Hanus

David W Hann

David D Marshall

April 2000

Oregon State University
College of Forestry

Forest Research Laboratory

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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.

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Abstract

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.

Equations for predicting height to crown base are presented for tree species from southwest Oregon. Equations for undamaged and damaged trees were estimated with weighted nonlinear regression techniques. The effects of specific damaging agents on the height to crown base were explored, and damage correction factors were estimated. The damage correction factors can be used to correct the predicted crown ratio for specific damaging agents and their severity in samples where damage is noted. These equations are being incorporated into the new southwest Oregon version of ORGANON (ORegon Growth ANalysis and projectiON), a model for predicting the growth of individual trees in forest stands. The equations extend the past model to older stands and stands with a heavier component of hardwood tree species.

Contents

List of Tables

Introduction

A tree's capacity for growth is largely determined by the quantity and quality of its foliage. Because these variables are difficult to measure, live crown length or relative crown length (crown ratio) are often used as surrogates in individual-tree growth equations (Stage 1973; Ritchie and Hann 1985, 1986, 1990; Wensel et al. 1987; Dolph 1988a, 1988b, 1992; Hann and Ritchie 1988; Wykoff 1990; Hann and Larsen 1991; Zumrawi and Hann 1993). In that context, a crown ratio (CR) of 1.0 indicates a full crown, where the leaves or needles reach the ground; a value approaching zero indicates a restricted crown and implies that growth is restrained by the relative lack of foliage or by some factor manifested by reduced foliage. CR has also been used as a predictor variable in individual tree mortality equations (Hann and Wang 1990), volume equations (Walters et al. 1985; Hann et al. 1987), and taper equations (Walters and Hann 1986).

In growth simulations, where projections for a given period are based on stand and tree variables at the beginning of that period, the CR term in component growth equations must be updated for each successive projection period. Crown change (ΔCR) can be predicted directly (e.g., Maguire and Hann 1990), or static equations for predicting height to crown base (HCB) can be used to simulate this change (Stage 1973; Ritchie and Hann 1987; Zumrawi and Hann 1989) by using the relationship:

$$\Delta CR = \frac{(CR_s \times H + \Delta H - \Delta HCB)}{(H + \Delta H)} - CR_s$$

where

CR_S = CR at the start of the period

H = total tree height at the start of the growth period

ΔH = change in tree height

ΔHCB = change in height to crown base.

Static HCB equations can also be used to predict missing HCB measurements so that growth simulations can be made from data that lack those values (Hann et al. 1997). Here, the objective of our analysis was to develop static equations for predicting HCB for the following tree species in southwest Oregon:

Conifers

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

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.
Oregon white oak	*Quercus garryana* Dougl. ex Hook.
Pacific madrone	*Arbutus menziesii* Pursh
Red alder	*Alnus rubra* Bong.
Tanoak	*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.
Willow	*Salix* spp.

These equations are to be used in a revision of the southwest Oregon version of ORGANON (SWO-ORGANON), an individual-tree, distance-independent stand simulator (Hann et al. 1997). The original version of SWO-ORGANON was applicable to predominantly conifer stands with trees less than 120 years old. The revision will extend SWO-ORGANON to stands with up to 60% of their composition in hardwoods and with trees up to 250 years of age.

Data Description

Data for this analysis came from two studies associated with the development of SWO-ORGANON. The first set of data was collected during 1981, 1982, and 1983 as part of the Southwest Oregon Forestry Intensified Research Growth and Yield Project. This 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° 15' W) in the east, to approximately 15 miles west of Glendale (123° 50' W) (Figure 1). Elevations of the sample plots range from 900 to 5,100 feet. Selection was limited to stands under 120 years old and with ≥80% of the basal area in conifers. The second,

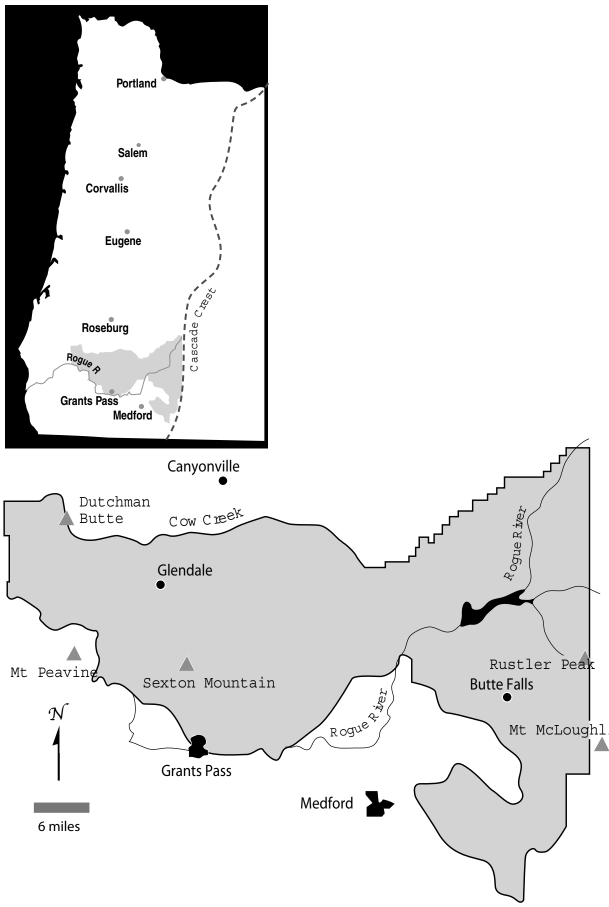

Figure 1. The study area in southwest Oregon.

ongoing study covers about the same area but extends the selection criterion to include stands with trees over 250 years in age and to younger stands with a greater component of hardwoods. An additional 138 plots were measured in this second study.

In both studies, each stand was sampled at four to 10 points. At each point, trees were sampled with a nested plot design that selected trees ≤4.0 in. DBH on a 1/229-acre fixed-area plot, trees 4–18.0 in. on a 1/57-acre fixed-area plot, trees 8.1–36.0 in. on a 20 basal area factor (BAF) variable-radius plot, and trees >36.0 in. on a 60 BAF variable-radius plot. Height and HCB were measured

t 0.1 ft on all trees, either a 25- to 45-ft telescoping e or, for taller trees, indi- g the pole-tangent method 1987).

th broken or dead tops, ıred to the top of the live own compaction" method define crown base for ven crown length. In this method, 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 in order to generate a "full, even crown" (see Figure 2). HCB was then measured to this mentally generated position on the bole (epicormic and short internodal branches were ignored in this process). Procedures for measuring the H and HCB of leaning trees depended on the severity of the lean, with all measurements taken at right angles to the direction of the lean. If the degree of lean was ≤15°, H and HCB were measured directly to the leaning tip and crown base (i.e., the lean was ignored). If the degree of lean was >15°, the tree tip and crown base were visualized in a vertical position and H and HCB measured to those imaginary points. DBH was measured to the last whole 0.1 in. with a diameter tape for all trees taller than 4.5 ft.

We noted the type and severity of any damage on each tree sampled and the dates of past thinnings on each plot. A description of the codes and methods used to denote damage is found in the appendix. Preliminary analysis indicated that some types of damage significantly impacted crown height. Therefore, two data sets were created: one contained undamaged trees (Tables 1 and 3), while the other contained both undamaged and all damaged trees (Tables 2 and 4), except those with damage codes of 72, 73, 77, 78, and 79. Because information on intensity and timing of past thinnings was either lacking or poor in quality, we eliminated from these modeling data sets plots thinned within the past 20 years. Past experience with modeling HCB (Ritchie and Hann 1987; Zumrawi and Hann 1989) indicated that the impact of thinning upon crown lengths (and associated HCBs) could last for 20 years.

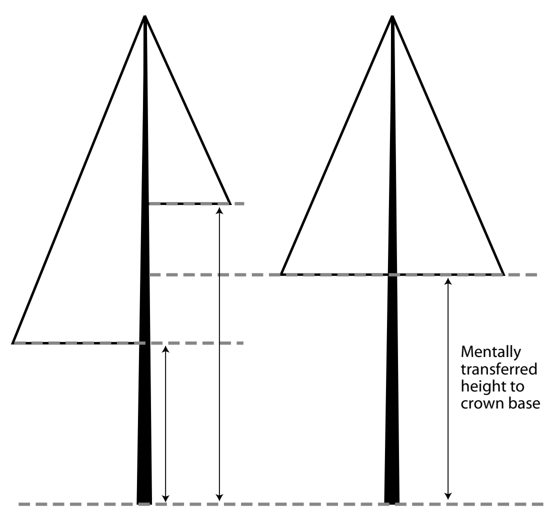

Figure 2. The "crown compaction" method used to define height to crown base for trees of uneven crown length.

Table 1. Means and ranges of the tree-level explanatory variables for undamaged trees.

Species	# Trees	DBH	Height (H)	Crown Ratio (CR)	SCCFL*	Scaled PCCFL*	PCCFL*
Conifers							
Douglas-fir	8,236	14.4	83.9	0.48	104.1	118.8	108.3
		0.1 – 81.3	4.6 – 244.2	0.02 – 1.00	0.0 – 485.6	0.0 – 1,332.5	0.0 –1,327.1
Grand/White fir	1,012	12.8	77.0	0.53	106.2	119.4	107.7
		0.1 – 44.8	4.7 – 200.9	0.1 – 0.98	0.0 – 350.0	0.0 – 665.7	0.0 – 660.2
Incense-cedar	664	9.1	39.9	0.53	136.8	149.3	141.4
		0.1 – 68.8	4.6 – 183.7	0.08 – 0.98	0.0 – 485.6	0.0 – 824.4	0.0 – 817.7
Pacific yew	18	2.36	12.5	0.56	178.3	291.8	251.6
		0.2 – 11.5	5.9 – 30.1	0.37 – 0.71	147.6 – 249.7	160.9 – 332.5	126.6 – 272.3
Ponderosa pine	494	15.2	84.1	0.44	71.4	81.5	72.5
		0.2 – 44.3	4.9 – 178.7	0.12 – 0.96	0.0 – 418.7	0.0 – 648.1	0.0 – 634.8
Sugar pine	135	20.7	92.3	0.48	56.1	58.0	54.0
		0.5 – 53.3	6.4 – 155.9	0.24 – 0.93	0.0 – 342.6	0.0 – 496.4	0.0 – 502.6
Western hemlock	44	11.7	70.4	0.68	163.6	171.5	160.7
		0.3 – 23.6	5.3 – 125.0	0.38 – 0.87	6.4 – 300.0	6.6 – 394.1	0.0 – 408.9
Hardwoods							
Bigleaf maple	36	7.6	51.0	0.43	157.7	212.0	161.4
		0.3 – 20.3	6.0 – 96.4	0.14 – 0.73	1.1 – 283.8	0.8 – 443.6	0.0 – 383.1
California black oak	162	10.5	43.6	0.36	131.7	149.2	130.8
		0.2 – 34.6	5.3 – 111.1	0.12 – 0.83	0.0 – 341.4	0.0 – 384.2	0.0 – 377.2
Canyon live oak	151	3.5	20.2	0.54	189.8	221.7	187.1
		0.1 – 15.2	4.7 – 57.9	0.16 – 0.97	62.2 – 317.1	41.8 – 461.4	26.1 – 453.5
Golden chinkapin	468	4.7	27.6	0.47	146.2	176.7	153.4
		0.1 – 21.1	5.0 – 86.5	0.12 – 0.96	0.0 – 465.7	0.0 – 593.0	0.0 – 626.3
Oregon white oak	18	7.8	33.4	0.41	125.2	119.5	103.3
		1.9 – 20.1	12.0 – 55.8	0.18 – 0.60	5.3 – 292.8	7.2 – 268.5	0.0 – 224.2
Pacific madrone	788	8.0	44.7	0.36	125.0	137.9	123.1
		0.1 – 30.9	4.7 – 99.7	0.04 – 0.96	0.0 – 378.5	0.0 – 515.2	0.0 – 441.8
Red alder	21	3.7	30.1	0.49	226.8	344.5	299.8
		0.1 – 17.4	4.9 – 95.3	0.21 – 0.74	33.6 – 410.3	36.4 – 688.4	60.9 – 677.5
Tanoak	214	3.5	22.7	0.50	225.8	257.0	228.2
		0.1 – 21.2	4.6 – 100.7	0.14 – 0.93	9.9 – 461.3	5.0 – 1,158.9	22.1 – 1,115.5
Willow	95	1.1	13.4	0.46	141.0	118.8	108.3
		0.2 – 3.4	5.5 – 41.9	0.09 – 0.68	78.0 – 286.2	0.0 – 1,332.5	0.0 – 1,327.1

*The crown competition factor for larger-diameter trees is SCCFL for stand-level estimates and PCCFL for point-level estimates. The scaled version of PCCFL takes into account within-stand variation in competition by using the method of Stage and Wycoff (1998).

Table 2. Means and ranges of the tree-level explanatory variables for undamaged and damaged trees (except damage codes 72, 73, 77, 78, and 79).

Species	# Trees	DBH	Height (H)	Crown Ratio (CR)	SCCFL*	Scaled PCCFL*	PCCFL*
Conifers							
Douglas-fir	13,211	13.9 0.1 – 81.3	78.0 4.6 – 251.6	0.45 0.01 –1.00	122.4 0.0 – 534.4	143.5 0.0 – 1,349.1	132.9 0.0 – 1,347.4
Grand/White fir	1,981	12.4 0.1 – 53.2	70.8 4.6 – 202.1	0.48 0.01 – 0.98	115.7 0.0 – 423.4	133.8 0.0 – 816.8	123.7 0.0 – 807.8
Incense-cedar	1,349	9.5 0.1 – 90.0	38.5 4.6 –183.7	0.48 0.05 – 0.98	150.9 0.0 – 485.6	167.6 0.0 – 824.4	160.8 0.0 – 817.7
Pacific yew	40	5.6 0.1 – 19.0	17.3 4.8 – 44.0	0.58 0.21 – 0.93	157.4 2.3 – 279.9	219.2 2.9 – 343.6	193.5 0.0 – 336.7
Ponderosa pine	882	14.6 0.1 – 50.5	78.3 4.6 – 221.8	0.44 0.03 – 0.96	77.9 0.0 – 453.8	86.5 0.0 – 648.1	78.6 0.0 – 634.8
Sugar pine	308	20.4 0.3 – 69.7	86.8 4.9 – 167.6	0.47 0.11 – 0.93	64.5 0.0 – 436.8	68.9 0.0 – 496.4	63.8 0.0 – 502.6
Western hemlock	99	10.1 0.2 – 30.8	58.6 5.2 – 155.8	0.63 0.02 – 0.94	153.3 0.0 – 416.2	178.4 0.0 – 833.5	165.3 0.0 – 841.1
Hardwoods							
Bigleaf maple	85	8.0 0.2 – 28.5	52.9 4.9 – 100.1	0.37 0.10 – 0.73	185.0 1.1 – 342.3	238.6 0.8 – 504.8	194.1 0.0 – 496.7
California black oak	319	10.4 0.1 – 35.6	44.0 4.7 – 114.0	0.34 0.06 – 0.94	141.8 0.0 – 341.4	156.5 0.0 – 458.9	137.2 0.0 – 495.5
Canyon live oak	440	2.7 0.1 – 22.6	17.3 4.7 – 57.9	0.48 0.02 – 0.99	234.7 19.2 – 418.5	273.2 21.0 – 529.7	241.1 7.2 – 529.7
Golden chinkapin	1,026	3.5 0.1 – 28.0	21.6 4.6 – 89.2	0.41 0.03 – 0.96	182.9 0.0 – 506.9	215.7 0.0 – 645.4	193.9 0.0 – 679.0
Oregon white oak	43	6.5 0.2 – 24.5	28.1 5.5 – 55.8	0.35 0.12 – 0.66	149.1 2.4 – 298.3	155.2 1.7 – 339.3	142.3 0.0 – 335.9
Pacific madrone	1,782	8.7 0.1 – 39.7	45.5 4.6 – 105.1	0.33 0.01 – 0.96	133.2 0.0 – 378.5	146.4 0.0 – 624.5	132.6 0.0 – 503.4
Red alder	43	3.3 0.1 – 17.4	27.1 4.9 – 95.3	0.50 0.21 – 0.88	248.0 33.6 – 431.2	355.1 36.4 – 688.4	307.2 60.9 – 677.5
Tanoak	706	2.6 0.1 – 36.8	18.1 4.6 – 108.2	0.48 0.02 – 0.97	242.2 9.9 – 506.8	276.4 5.0 – 1,158.9	253.4 0.0 – 1,115.5
Willow	196	1.4 0.2 – 9.6	16.6 5.5 – 41.9	0.36 0.02 – 0.68	169.9 34.1 – 360.0	216.8 16.0 – 663.8	135.0 21.8 – 488.2

*The crown competition factor for larger-diameter trees is SCCFL for stand-level estimates and PCCFL for point-level estimates. The scaled version of PCCFL takes into account within-stand variation in competition by using the method of Stage and Wycoff (1998).

Table 3. Means and ranges of the plot-level explanatory variables for undamaged trees.

Species	# Plots	Stand Basal Area (SBA)	Site Index (SI)	D_5*	H_5**
Conifers					
Douglas-fir	380	206.9 1.4 – 440.0	99.4 41.5 – 142.7	27.4 2.1 – 67.1	110.0 13.0 – 230.2
Grand/White fir	138	208.2 8.9 – 388.7	100.4 61.6 – 141.1	29.3 5.3 – 62.3	115.3 18.2 – 221.1
Incense-cedar	136	196.5 23.6 – 409.4	96.1 41.5 – 146.9	26.8 5.3 – 63.4	104.5 18.2 – 202.9
Pacific yew	6	261.8 38.8 – 374.1	98.9 88.2 – 107.6	44.0 10.4 – 56.9	142.6 18.2 – 197.4
Ponderosa pine	91	189.4 22.5 – 337.4	95.7 41.5 – 142.7	25.0 5.4 – 47.7	101.6 24.8 – 188.3
Sugar pine	66	211.4 29.1 – 345.2	92.5 54.8 – 129.8	28.4 4.3 – 62.3	110.3 26.8 – 188.9
Western hemlock	14	263.7 119.5 – 374.1	105.1 80.5 – 113.9	36.5 14.5 – 63.3	143.4 67.7 – 214.2
Hardwoods					
Bigleaf maple	15	222.2 68.2 – 388.7	102.8 74.0 – 142.5	36.0 14.0 – 66.5	139.9 55.4 – 230.2
California black oak	36	198.9 29.1 – 302.6	92.6 41.5 – 134.9	25.9 4.3 – 56.4	100.0 26.8 – 174.8
Canyon live oak	41	189.7 29.1 – 365.1	91.5 47.8 – 120.9	26.2 4.3 – 53.1	102.8 26.8 – 183.5
Golden chinkapin	94	189.2 1.4 – 363.9	101.9 64.4 – 135.5	25.0 2.1 – 64.0	100.4 13.0 – 202.9
Oregon white oak	4	168.5 73.8 – 226.2	69.2 41.5 – 95.7	20.6 15.9 – 31.1	86.3 61.3 – 137.8
Pacific madrone	155	193.3 8.9 – 409.4	99.0 41.5 – 142.5	24.4 4.3 – 59.9	99.5 18.2 – 183.5
Red alder	6	266.9 178.7 – 409.4	106.8 77.0 – 138.8	43.2 20.9 – 66.5	150.5 95.6 – 230.2
Tanoak	44	204.3 43.2 – 388.7	101.7 47.2 – 138.8	28.6 5.1 – 64.0	115.2 33.3 – 202.9
Willow	11	120.9 55.9 – 203.4	94.8 66.2 – 113.4	16.0 7.3 – 20.9	71.1 39.8 – 98.4

*D_5 is the average diameter of the five largest-diameter trees per acre.

**H_5 is the average height of the five largest-diameter trees per acre.

Table 4. Means and ranges of the plot-level explanatory variables for undamaged and damaged trees (except damage codes 72, 73, 77, 78, and 79).

Species	# Plots	Stand Basal Area (SBA)	Site Index (SI)	D_5*	H_5**
Conifers					
Douglas-fir	385	205.2 1.4 – 440.0	99.7 41.5 – 146.9	27.2 2.1 – 67.1	109.3 13.0 – 230.2
Grand/White fir	160	207.1 8.9 – 388.7	101.3 61.6 – 146.9	29.0 5.3 – 67.1	115.0 18.2 – 221.1
Incense-cedar	170	201.6 16.0 – 409.4	97.0 41.5 – 146.9	27.3 5.3 – 63.4	106.8 18.2 – 202.9
Pacific yew	14	231.2 38.8 – 374.1	97.9 74.0 – 121.7	37.1 10.4 – 63.4	131.9 18.2 – 202.9
Ponderosa pine	119	187.3 22.5 – 337.4	96.5 41.5 – 146.9	25.7 5.4 – 56.4	102.6 24.8 – 194.2
Sugar pine	117	206.8 23.6 – 345.2	93.4 47.2 – 129.8	28.2 4.3 – 63.4	109.5 26.8 – 202.9
Western hemlock	22	231.1 66.5 – 374.1	106.4 80.5 – 131.1	32.8 7.7 – 63.3	131.4 48.9 – 221.1
Hardwoods					
Bigleaf maple	25	228.2 68.2 – 388.7	104.7 74.0 – 142.5	35.5 14.0 – 66.5	138.6 55.4 – 230.2
California black oak	59	209.1 29.1– 324.6	92.4 41.5 – 134.9	26.8 4.3 – 56.4	105.3 26.8 – 175.5
Canyon live oak	67	189.1 26.9 – 409.4	94.3 47.2 – 138.8	26.2 4.3 – 64.0	102.8 18.2 – 196.3
Golden chinkapin	118	191.5 1.4 – 363.9	101.5 64.4 – 142.7	25.3 2.1 – 64.0	102.2 13.0 – 202.9
Oregon white oak	8	174.9 73.8 – 226.2	71.9 41.5 – 95.9	21.8 15.9 – 34.2	87.5 61.3 – 137.8
Pacific madrone	211	194.8 8.9 – 409.4	99.8 41.5 – 146.9	24.9 4.3 – 63.4	101.9 18.2 – 202.9
Red alder	7	259.0 178.7 – 409.4	107.8 77.0 – 138.8	41.4 20.9 – 66.5	145.9 95.6 – 230.2
Tanoak	65	200.7 26.9 – 388.7	99.9 47.2 – 138.8	28.8 5.1 – 66.5	114.3 24.7 – 230.2
Willow	26	148.2 36.5 – 277.8	102.8 66.2 – 126.9	17.5 7.3 – 28.7	76.9 39.8 – 120.6

*D_5 is the average diameter of the five largest-diameter trees per acre.

**H_5 is the average height of the five largest-diameter trees per acre.

Data Analysis for Undamaged Trees

Our goal was to create equations to predict HCB in the target tree species in southwest Oregon. The HCB equations in this analysis are a modification of the equation used by Ritchie and Hann (1987):

$$HCB = \frac{H}{1.0 + \exp\left[a_0 + a_1 H + a_2 SCCFL + a_3 \ln(SBA) + a_4\left(\frac{DBH}{H}\right) + a_5(SI - 4.5)\right]} \quad [1]$$

where

SCCFL = crown competition factor in larger-diameter trees based on a stand-level estimate

SBA = basal area per acre, or stand density, based on a stand-level estimate

SI = site index, with a base age of 50 (Hann et al. 1987)

a_0 through a_5 = regression coefficients.

The modification of their equation was suggested by an examination of residuals from a fit of Eq. [1] to our undamaged data set, which showed that trees growing in stands with large overstory trees (which we call "older" stands) had longer crowns. This may be caused by different structural conditions in older stands. To account for this difference, we examined a number of alternative variables for their ability to separate older from younger stands. We found that the square of the product of the average height of the five largest-diameter trees per acre (H_5) multiplied by their average diameter (D_5) provided the best separation for these two groups of data. To keep the magnitude about the same as the other variables in the equation, H_5 x D_5 was divided by 10,000 before squaring. Thus, $(H_5 \times D_5/10{,}000)^2$ was added to the Ritchie and Hann equation, yielding:

$$HCB = \frac{H}{1.0 + \exp\left[b_0 + b_1 H + b_2 SCCFL + b_3 \ln(SBA) + b_4\left(\frac{DBH}{H}\right) + b_5(SI - 4.5) + b_6\left(\frac{H_5 \times D_5}{10{,}000}\right)^2\right]} \quad [2]$$

where b_0 through b_6 are the regression coefficients to be estimated by nonlinear regression.

SCCFL is a relative measure of the amount of competition that a tree is experiencing from larger-diameter trees in the stand. To better characterize within-stand variation in competition, Stage and Wyckoff (1998) proposed rescaling a similar measure by multiplying within-stand competition by the ratio of the appropriate plot-level density divided by the appropriate stand level density. For SCCFL, the equivalent rescaling is:

$$Scaled\ PCC\ FL = SCCFL \times \frac{PCCF}{SCCF}$$

where

Scaled PCCFL = crown competition factor in larger-diameter trees based on point-level estimates, taking into account within-stand variation in competition by using the method of Stage and Wycoff (1998)

PCCF = point-level crown competition factor (which relates to point-level density)

SCCF = stand-level crown competition factor (which relates to stand-level density).

The resulting equation for HCB substitutes *Scaled PCCFL* for *SCCFL* in Eq. [2], yielding:

$$HCB = \frac{H}{1.0 + \exp\left[b_0 + b_1 H + b_2 (Scaled\ PCC\ FL) + b_3 \ln(SBA) + b_4\left(\frac{DBH}{H}\right) + b_5(SI - 4.5) + b_6\left(\frac{H_5 \times D_5}{10{,}000}\right)^2\right]} \quad [3]$$

As an alternative to Stage and Wycoff's (1998) approach, the performance of the measured value of PCCFL was also evaluated. Substituting *PCCFL* for *Scaled PCCFL* yields the following equation:

$$HCB = \frac{H}{1.0 + \exp\left[b_0 + b_1 H + b_2 PCCFL + b_3 \ln(SBA) + b_4\left(\frac{DBH}{H}\right) + b_5(SI - 4.5) + b_6\left(\frac{H_5 \times D_5}{10{,}000}\right)^2\right]} \quad [4]$$

where *PCCFL* is the measured value of the crown competition factor for larger-diameter trees based on point-level estimates, without using the re-scaling method of Stage and Wycoff (1998).

Both Ritchie and Hann (1987) and Zumrawi and Hann (1989) found that the variance of the residuals in HCB increased with H. Thus, they used weighted regression with a weight of $(1.0/H)^2$ when estimating the parameters of their equation. Equations [2], [3], and [4] are nonlinear in their parameters. Therefore, in our three equations, we used weighted nonlinear regression with a weight of $(1.0/H)^2$ to estimate the parameters of the equations fit to the undamaged data sets. Each parameter was then tested for statistical significance from 0.0 ($p = 0.05$) using a *t*-test, and, if not significant, it was set to 0.0 and the remaining parameters re-estimated by using weighted nonlinear regression.

Results for Undamaged Trees

Tables 5, 6, and 7 contain parameter estimates (i.e., the values for b_0 through b_6 in Equations [2], [3], and [4]) and associated standard errors from Equations [2], [3], and [4], respectively, fit to the undamaged tree data. The parameter estimates in these tables can be used by researchers in the appropriate HCB prediction equations. These tables also contain the weighted mean square error (MSE) and, for each species, the weighted adjusted coefficient of determination (R_a^2).

Table 5. Parameter estimates and standard errors (in parentheses), along with weighted mean square error (MSE) and weighted adjusted coefficient of determination (R_a^2) for Eq. [2], fit to undamaged trees on untreated plots.

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	MSE	R_a^2
Conifers									
Douglas-fir	1.797136911 (0.10414771)	-0.010188791 (0.00026858)	-0.003346230 (0.00013765)	-0.412217810 (0.02114152)	3.958656001 (0.19586635)	0.008526562 (0.00034201)	0.448909636 (0.02894787)	0.014649	0.5019
Grand/White fir	3.451045887 (0.31906623)	-0.005985239 (0.00080548)	-0.003211194 (0.00056631)	-0.671479750 (0.07198548)	3.931095518 (0.66459098)	0.003115567 (0.00136926)	0.516180892 (0.07127940)	0.018432	0.4482
Incense-cedar	2.428285297 (0.40455399)	-0.006882851 (0.00129005)	-0.002612590 (0.00054930)	-0.572782216 (0.08730740)	2.113378338 (0.52991277)	0.008480754 (0.00141629)	0.506226895 (0.11112775)	0.019542	0.4968
Pacific yew	0.0 (NA)*	0.0 (NA)	0.0 (NA)	0.0 (NA)	2.030940382 (0.39907563)	0.0 (NA)	0.0 (NA)	0.003715	0.4426
Ponderosa pine	1.656364063 (0.27745184)	-0.002755463 (0.00066903)	0.0 (NA)	-0.568302547 (0.05164042)	6.730693919 (0.46768990)	0.001852526 (0.00040456)	0.0 (NA)	0.008770	0.6748
Sugar pine	3.785155749 (0.85196028)	-0.009012547 (0.00201165)	-0.003318574 (0.00117746)	-0.670270058 (0.17335796)	2.758645081 (1.03757329)	0.0 (NA)	0.841525071 (0.26245872)	0.010627	0.4378
Western hemlock	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	4.801329946 (0.64195630)	0.0 (NA)	0.0 (NA)	0.020864	0.1391
Hardwoods									
Bigleaf maple	0.9411395642 (0.25367802)	-0.007486789 (0.00349082)	-0.005476131 (0.00128016)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.015044	0.4452
California black oak	2.601450655 (0.53745352)	0.0 (NA)	-0.002273616 (0.00056622)	-0.554980629 (0.10667406)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.017345	0.2631
Canyon live oak	0.5376600543 (0.11173360)	-0.018632397 (0.00484048)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.024580	0.0868
Golden chinkapin	0.544237656 (0.11112796)	-0.020571754 (0.00176513)	-0.004317523 (0.00042607)	0.0 (NA)	3.132713612 (0.54443256)	0.0 (NA)	0.483748898 (0.12678131)	0.020373	0.4281
Oregon white oak	0.0 (NA)	0.0 (NA)	-0.003330794 (0.00063308)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.008051	0.5038
Pacific madrone	2.955339267 (0.22264570)	0.0 (NA)	0.0 (NA)	-0.798610738 (0.04495648)	3.095269471 (0.37413636)	0.0 (NA)	0.700465646 (0.17133210)	0.018123	0.3320
Tanoak	0.833006499 (0.21645482)	-0.012984204 (0.00316720)	-0.002704717 (0.00070148)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.2491242765 (0.10671054)	0.027645	0.0885
Willow	0.0 (NA)	0.0 (NA)	-0.005666559 (0.00082730)	-0.745540494 (0.08804812)	0.0 (NA)	0.038476613 (0.00309547)	0.0 (NA)	0.005759	0.8392

*NA indicates not applicable.

Table 6. Parameter estimates and standard errors (in parentheses), along with weighted mean square error (MSE) and weighted adjusted coefficient of determination (R_a^2) for Eq. [3], fit to undamaged trees on untreated plots.

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	MSE	R_a^2
Conifers									
Douglas-fir	2.277498056	-0.009178057	-0.002216218	-0.549637362	4.448979001	0.008642331	0.397788750	0.014326	0.5129
	(0.10437754)	(0.00024170)	(0.00008224)	(0.01897781)	(0.17792726)	(0.00033862)	(0.02750244)		
Grand/White fir	3.358996445	-0.005518180	-0.002083065	-0.718643264	4.971192077	0.003691585	0.486723994	0.018871	0.4351
	(0.31617165)	(0.00071273)	(0.00032288)	(0.05834689)	(0.59827868)	(0.00137559)	(0.07135810)		
Incense-cedar	2.717279854	-0.006483005	-0.002403178	-0.602375150	1.893036950	0.007276969	0.493999064	0.018399	0.5110
	(0.36998402)	(0.00106668)	(0.00030684)	(0.06745152)	(0.46268644)	(0.00139149)	(0.10778030)		
Ponderosa pine	1.812888260	-0.003562316	-0.000989380	-0.536956668	5.766751256	0.001825908	0.0	0.008691	0.6777
	(0.28367269)	(0.00074892)	(0.00041585)	(0.05275854)	(0.61440854)	(0.00040276)	(NA)*		
Sugar pine	3.704298306	-0.008578321	-0.002549196	-0.682385522	3.124826066	0.0	0.779124002	0.010624	0.4379
	(0.85199371)	(0.00193043)	(0.00090554)	(0.17137890)	(0.96594015)	(NA)	(0.25253896)		
Hardwoods									
Bigleaf maple	0.9066280756	-0.008156540	-0.003823872	0.0	0.0	0.0	0.0	0.014312	0.4722
	(0.24107067)	(0.00337946)	(0.00085575)	(NA)	(NA)	(NA)	(NA)		
California black oak	2.713416605	0.0	-0.002268069	-0.569789582	0.0	0.0	0.0	0.016454	0.3009
	(0.52261668)	(NA)	(0.00046261)	(0.10256808)	(NA)	(NA)	(NA)		
Golden chinkapin	1.22702741	-0.018812201	-0.003142004	-0.176763995	3.410551576	0.0	0.513479646	0.018695	0.4752
	(0.20051798)	(0.00218977)	(0.00038532)	(0.05537594)	(0.54504711)	(NA)	(0.12692498)		
Oregon white oak	0.0	0.0	-0.003384324	0.0	0.0	0.0	0.0	0.009441	0.4181
	(NA)	(NA)	(0.00072071)	(NA)	(NA)	(NA)	(NA)		
Pacific madrone	2.695463053	-0.007571059	-0.003295097	-0.497895356	0.0	0.0	1.028630922	0.016719	0.3837
	(0.23995356)	(0.00154036)	(0.00028903)	(0.05653451)	(NA)	(NA)	(0.16423611)		
Tanoak	0.4618379349	-0.007986388	-0.001375782	0.0	0.0	0.0	0.2447883935	0.028347	0.0654
	(0.15136587)	(0.00259735)	(0.00043857)	(NA)	(NA)	(NA)	(0.10744467)		

*NA indicates not applicable.

Table 7. Parameter estimates and standard errors (in parentheses), along with weighted mean square error (MSE) and weighted adjusted coefficient of determination (R_a^2) for Eq. [4], fit to undamaged trees on untreated plots.

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	MSE	R_a^2
Conifers									
Douglas-fir	2.35269074	-0.008565012	-0.002318003	-0.569010963	4.304842713	0.008556650	0.363850319	0.014206	0.5170
	(0.10420158)	(0.00023163)	(0.00008214)	(0.01870555)	(0.17763111)	(0.00033745)	(0.02695915)		
Grand/White fir	3.355503977	-0.006928169	-0.003416423	-0.621675907	3.868310111	0.002878164	0.519333875	0.019169	0.4262
	(0.31929664)	(0.00069190)	(0.00033568)	(0.05739376)	(0.60870134)	(0.00138747)	(0.07242257)		
Incense-cedar	2.759003979	-0.005592104	-0.002147610	-0.645009113	2.037199661	0.007902794	0.495191230	0.018737	0.5175
	(0.37427339)	(0.00104683)	(0.00030644)	(0.06733987)	(0.46924456)	(0.00139804)	(0.10855558)		
Ponderosa pine	1.836254592	-0.003427973	-0.001028320	-0.544581798	5.766107159	0.001806782	0.0	0.008665	0.6787
	(0.28401814)	(0.00071332)	(0.00038702)	(0.05189800)	(0.58714024)	(0.00040259)	(NA)*		
Sugar pine	3.751204965	-0.008417167	-0.002155206	-0.717619647	3.580745337	0.0	0.763326918	0.010708	0.4335
	(0.85777316)	(0.00193889)	(0.00082025)	(0.16959454)	(0.91213198)	(NA)	(0.25328588)		
Hardwoods									
Bigleaf maple	0.8616471002	-0.010236617	-0.003999775	0.0	0.0	0.0	0.0	0.015114	0.4426
	(0.24452426)	(0.00342301)	(0.00095282)	(NA)	(NA)	(NA)	(NA)		
California black oak	2.696295291	0.0	-0.002170123	-0.576497818	0.0	0.0	0.0	0.017193	0.2695
	(0.53416404)	(NA)	(0.00053173)	(0.10517683)	(NA)	(NA)	(NA)		
Golden chinkapin	1.161961508	-0.015215108	-0.002884567	-0.199901865	3.148678883	0.0	0.514185679	0.019391	0.4557
	(0.20395411)	(0.00209461)	(0.00041347)	(0.05682670)	(0.59187020)	(NA)	(0.12849936)		
Oregon white oak	0.0	0.0	-0.003950282	0.0	0.0	0.0	0.0	0.009100	0.4392
	(NA)	(NA)	(0.00081887)	(NA)	(NA)	(NA)	(NA)		
Pacific madrone	2.745969728	-0.007406847	-0.003444022	-0.513462537	0.0	0.0	0.952515001	0.016815	0.3802
	(0.24090824)	(0.00154659)	(0.00030610)	(0.05649935)	(NA)	(NA)	(0.16524130)		
Tanoak	0.518265522	-0.008070296	-0.001809563	0.0	0.0	0.0	0.2536480114	0.027304	0.0998
	(0.13273374)	(0.00249941)	(0.00042247)	(NA)	(NA)	(NA)	(0.10602869)		
Willow	0.0	0.0	-0.001056013	-1.105283780	0.0	0.047177525	0.0	0.008763	0.7553
	(NA)	(NA)	(0.00117324)	(0.10990094)	(NA)	(0.00393794)	(NA)		

*NA indicates not applicable.

Data Analysis for Undamaged and Damaged Trees Combined

The impact of damage on predicted HCB was characterized in two analyses. First, by using the same statistical procedures described for undamaged trees alone, Equations [2], [3], and [4] were fit to the data set that included both undamaged and damaged trees, except those with damage codes of 72, 73, 77, 78, and 79 (Table A1). This paralleled the analysis conducted earlier in southwest Oregon by Ritchie and Hann (1987).

The second analysis explored whether the magnitude of impact of damage varied by the type and severity of a damaging agent. For each tree species, corrections to HCB for a particular damage type and severity were calculated as follows:

1. For each species, the regional HCB prediction equations (i.e., Equation [2], [3], or [4] with parameters from Table 5, 6, or 7) were calibrated to each plot containing that species in order to reduce variation caused by between-plot differences in the HCB relationship. This calibration was done by regressing each plot's undamaged-tree HCB on predicted HCB by using the regression model:

   $$CHCB_i = \frac{H}{1.0 + \exp\left(\underline{\beta X} + c_i\right)}$$

   where

   $CHCB_i$ = HCB Equation [2], [3], or [4] calibrated to the i[th] plot

   c_i = undamaged tree plot-level calibration for the i[th] plot estimated by using the weighted nonlinear regression routine of Press et al. (1989)

   $\underline{\beta X}$ = the bracketed portion of Equation [2], [3], or [4] and its respective coefficients from Table 5, 6, or 7.

   Thus:

$$\underline{\beta X} = b_0 + b_1 H + b_2 Z + b_3 \ln(SBA) + b_4\left(\frac{DBH}{H}\right) + b_5(SI - 4.5) + b_6\left(\frac{H_5 \times D_5}{10{,}000}\right)^2$$

   where Z is *SCCFL*, *PCCFL*, or *Scaled PCCFL*, and b_0 through b_6 are the parameters from the table appropriate to the species and the equation under consideration.

   The parameter c_i was set to zero unless there were more than three undamaged trees on the plot and the predicted value was significantly different from zero according to a *t*-test. A *p*-value of 0.1 was used in the *t*-test to make plot-level calibration more frequent.

2. The species specific correction factors (CF) for a damaging agent and its severity were calculated by regressing the measured HCB for all trees with the associated damage to the calibrated predicted HCB:

$$DHCB = \frac{H}{1.0 + \exp\left(\beta \underline{X} + c_i + d_1 + d_2 \times I_s\right)}$$

where

DHCB = predicted HCB for trees of a specified species damaged by a particular agent

d_1 = correction for a particular type of damaging agent, regardless of severity

d_2 = correction for a severe level of the particular type of damaging agent

I_s = 0 if severity of damage is light, and I_s = 1 if the damage is judged to be severe (see Tables A1–A3).

The damaged tree parameters d_1 and d_2 were estimated by using weighted nonlinear regression. Then d_1 and d_2 were tested for significant difference from 0.0 with a *t*-test (p = 0.01). If both parameters were not significant, no CF was reported for the damaging agent. If both parameters were significant, d_1 was reported as the CF for light damage, and $d_1 + d_2$ was reported as the CF for severe damage. If parameter d_1 was significant and parameter d_2 was not, then d_1 was re-estimated by the following equation:

$$DHCB = \frac{H}{1.0 + \exp\left(\beta \underline{X} + c_i + d_1\right)}$$

fit to the combined light and severe damage data by using weighted nonlinear regression. The resulting value of d_1 was reported as the CF for both levels of severity. If parameter d_2 was significant and parameter d_1 was not, then the CF for light damage was set to 0.0, and d_2 was re-estimated by the following equation:

$$DHCB = \frac{H}{1.0 + \exp\left(\beta \underline{X} + c_i + d_2\right)}$$

fit to just the severe damage data by using weighted nonlinear regression. The resulting value of d_2 was reported as the CF for the severe level of damage.

Given the CF for a particular type of damage and its severity, the resulting HCB can be predicted by:

$$DHCB = \frac{H}{1.0 + \exp\left(\beta \underline{X} + CF\right)} \qquad [5]$$

Results for Undamaged and Damaged Trees

For prediction purposes, Tables 8, 9, and 10 contain the parameter estimates (b_0 through b_6) and their standard errors for Equations [2], [3], and [4], respectively, fit to both undamaged and damaged trees, except those with damage codes of 72, 73, 77, 78, and 79. The weighted MSE and weighted R_a^2 for each equation are also reported in these tables.

Tables 11, 12, and 13 contain the damage CFs, and their associated standard errors, for Eq. [5] (i.e., the $\underline{\beta X}$ in Eq. [5] are the values from Equation [2], [3], or [4] using parameter estimates from Table 5, 6, or 7, respectively). These factors differ by type and severity of damage. A negative CF indicates that the HCB of the damaged tree is higher (and therefore the CR is less) than that predicted for an undamaged tree; a positive CF would result in a lower HCB (and a larger CR). Because of the form of Eq. [5], it can be difficult to interpret how a particular level of CF will impact predicted HCB and the resulting CR. Table 14 demonstrates the change in the predicted CR for an undamaged tree that can be expected for a damaged tree with a given level of CF. From this table it can be seen that with a CF of -0.6, an undamaged tree's CR of 0.10 would be reduced to 0.05 in a damaged tree, and an undamaged tree's CR of 0.5 would be reduced to 0.35.

To assess the frequency of occurrence of the damaging agents for a given species on the sample plots used for analysis (i.e., the population represented just by the "modeling" data set), the damaging agents were grouped into the following classes: none, insects, disease, fire, animal, weather, suppression, other (including various top damages), logging, and excessive taper. Next, the percentage of occurrence (though not severity) of each major class of damaging agent, appropriately weighted by the probability of selection, was computed for each plot and then averaged across all of the plots in a sample. The resulting percentages in Table 15 differ from the frequency of damaging agents recorded for the sampled trees themselves (as indicated by the counts of the number of sample trees for each damaging agent in Tables 11, 12, and 13) because of the unequal sampling probabilities used in collecting the data. When examining the frequency of damaging agents, one should remember that while the modeling data set is representative of the stands being modeled, it is not an unbiased inventory of all stands in southwest Oregon.

Discussion

Equations [2], [3], and [4] were developed as tools for predicting HCB. The signs on the coefficients in Equations [2], [3], and [4] indicate how HCB will respond to changes in the predictor variables [H, SBA, DBH/H, SI, $(H_5 \times D_5/10{,}000)^2$, SCCFL, Scaled PCCFL, and PCCFL]. A positive sign indicates that HCB will decrease with an increase in the predictor variable, and a negative sign indicates an increase in HCB. Thus, HCB decreases with increasing values of both site index (SI) and DBH/H (higher DBH/H ratios indicate greater stem taper), and it increases with increasing competition from the overstory (as indicated by SCCFL, Scaled PCCFL, and PCCFL), SBA, and H. For undamaged trees, HCBs are predicted to decrease on trees in stands with older structures.

The equations developed in this study differ from those in previous studies in that they incorporate a predictor variable for distinguishing the structure of older stands from that of younger stands. For undamaged trees, this variable was significant for seven of the species groups. Undamaged trees growing in stands with older characteristics were found to have longer crowns than undamaged trees in younger stands. This may be caused by increased levels of light in the stand resulting from (1) the patchy nature of these stands, (2) the high HCBs for the overstory trees, or (3) reduced crown widths as a result of abrasion caused by wind sway of tall trees.

For nine of the species groups in the undamaged data set, variables Scaled PCCFL or PCCFL (either Eq. [3] or Eq. [4]) did provide a modest improvement in the fit of the equation to the data when compared to SCCFL (Eq. [2]). The number of species groups in which either Scaled PCCFL or PCCFL was an improvement over SCCFL increased to 10 for the combined undamaged and damaged data set. In general, the improvement in fit (as evidenced by the increase in R_a^2) was greater for hardwoods than conifers.

Many of the operational stands in southwest Oregon exhibit variation in density throughout the stand. Characterizing this spatial variability can be important to modeling stand dynamics (Stage and Wykoff 1998) and to understanding the suitability of the stand's structure for wildlife (Dubrasich et al. 1997). Equations [3] and [4] were developed to potentially meet these needs by using Scaled PCCFL or PCCFL, respectively, as predictor variables. Because these equations use point- and not stand-level measurements, application of these equations would require the installation of a grid of sampling points across the stand in order to characterize within-stand variability. Ideally, the sampling unit design at each sample point should be the same as used in this study in order to avoid error introduced by using an alternative design (Hann and Zumrawi 1991).

The presence of some level of damage is quite common in the population represented by this modeling data set, in which only 44% of the conifers and 37% of the hardwoods were found to be undamaged (Table 15). The most common class of damaging agents for conifers was "suppression" followed by "other damage," while the most common class of damage for hardwoods was "other" followed by "suppression." The most common specific damaging agents for conifers within the "other damage" class was "natural mechanical injury" (code 71), followed by "dead or missing top" (code 72) and then "excessive lean" (code 75). For hardwoods, the most common was "excessive lean," followed by "natural mechanical injury" and then "dead or missing top."

With the exception of "excessive forking" (damage code 76), which was significant only for tanoak, all significant damage CFs had negative signs, which indicates an increase in the HCB in damaged trees compared with undamaged trees that have the same tree and stand attributes (Tables 11, 12, and 13). A negative sign indicates that damaged trees have smaller crown ratios than undamaged trees do. The most negative impact on conifers came from "suppression" (damage codes 61 and 62), followed by "dead or missing top" (code 72) and "excessive lean" (code 75); the most negative impact on hardwoods came from "dead or missing top" (code 72), followed by "leaves noticeably sparse" (code 74) and then "suppression" (codes 61 and 62). In general, the negative impact increased with the severity of the damage.

The significant negative impact of suppression indicates that the measures used in Equations [2], [3], and [4] to quantify competitive position within the stand (i.e., SCCFL, Scaled PCCFL, and PCCFL), level of competition (i.e., SBA), and DBH/H were not adequate at characterizing HCB for these trees. Perhaps these trees also suffered from unusually sparse foliage, which resulted in an increased HCB because of the crown compacting method used to define the position of the crown base.

These equations provide new and useful information about tree species growing in the even- and uneven-aged, pure and mixed-species stands of southwest Oregon. To predict unmeasured HCBs when you have not collected data on damaging agents, we recommend Equation [2], [3], or [4] with the undamaged- and damaged-tree parameters from Table 8, 9, or 10. If you noted specific damaging agents and their severity, we recommend the use of Eq. [5], with the appropriate parameters for undamaged trees from Table 5, 6, or 7 and the associated damage CFs from Table 11, 12, or 13.

For predicting change in HCB, we recommend Equation [2], [3], or [4] and the appropriate undamaged parameters from Table 5, 6, or 7. Although static equations are not ideal for predicting changes in HCB, they offer the only available method in the absence of data for developing crown-change equations. A major problem with this use of static equations is that, in some cases, predicted HCB may decrease unrealistically in response to stand-density reductions resulting from thinning and mortality. To ensure that HCB will either remain constant or increase over time, HCB at the end of the growth period can be constrained to be no less than the HCB at the beginning of the growth period. This procedure replicates the behavior described in Oliver and Larsen (1996) in which crown recession ceases after thinning until the stand density and tree height have increased enough to offset the effects of thinning. This method also ignores the possible production of epicormic branches.

Table 8. Parameter estimates and standard errors (in parentheses), along with weighted mean square error (MSE) and weighted adjusted coefficient of determination (R_a^2) for Eq. [2], fit to undamaged trees and damaged trees on untreated plots.

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	MSE	R_a^2
Conifers									
Douglas-fir	1.990155033 (0.08599418)	-0.008180786 (0.00021322)	-0.004696095 (0.00010582)	-0.392033240 (0.01700740)	1.945708371 (0.14196618)	0.007854260 (0.00029991)	0.295593583 (0.02064404)	0.017672	0.4651
Grand/White fir	4.800089990 (0.19909983)	0.0 (NA)*	-0.003268539 (0.00022960)	-0.858744969 (0.03906050)	0.0 (NA)	0.0 (NA)	0.275679490 (0.04704161)	0.024625	0.3868
Incense-cedar	3.127730861 (0.31548617)	-0.004386780 (0.00098384)	-0.003557122 (0.00042659)	-0.637929879 (0.06567674)	0.977816058 (0.33969453)	0.005850321 (0.00111558)	0.257070387 (0.07950652)	0.022646	0.5159
Pacific yew	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	1.225564582 (0.35820146)	0.0 (NA)	0.0 (NA)	0.025300	0.1280
Ponderosa pine	2.024723585 (0.23142306)	-0.001953589 (0.00064380)	-0.001837480 (0.00046602)	-0.568909853 (0.04766200)	4.831886553 (0.46203833)	0.001653030 (0.00034628)	0.0 (NA)	0.011843	0.6231
Sugar pine	3.582314301 (0.57050938)	-0.003256792 (0.00112493)	0.0 (NA)	-0.765250973 (0.10823498)	3.043845568 (0.60556469)	0.0 (NA)	0.0 (NA)	0.016747	0.3135
Western hemlock	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	3.246352823 (0.53372509)	0.0 (NA)	0.0 (NA)	0.041667	0.0196
Hardwoods									
Bigleaf maple	1.000364090 (0.19023390)	-0.010636441 (0.00259688)	-0.005950398 (0.00076501)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.310672769 (0.13004729)	0.012784	0.5167
California black oak	2.672850866 (0.55390277)	0.0 (NA)	-0.001400851 (0.00043988)	-0.605971926 (0.11058076)	0.0 (NA)	0.0 (NA)	0.430988703 (0.20965129)	0.020213	0.1411
Canyon live oak	1.285465907 (0.15183792)	-0.024459278 (0.00359074)	-0.003992574 (0.00048454)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.027834	0.1700
Golden chinkapin	0.387912505 (0.07937631)	-0.015000868 (0.00135873)	-0.004098099 (0.00027157)	0.0 (NA)	2.104871164 (0.36559000)	0.0 (NA)	0.352773356 (0.08761504)	0.021985	0.3147
Oregon white oak	0.0 (NA)	0.0 (NA)	-0.004671430 (0.00046136)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.010084	0.5660
Pacific madrone	3.271130882 (0.16883478)	0.0 (NA)	0.0 (NA)	-0.841331291 (0.03292047)	1.791699815 (0.18359590)	0.0 (NA)	0.927163029 (0.08857987)	0.017964	0.3128
Tanoak	0.4488479442 (0.10845622)	-0.009375810 (0.00182347)	-0.001822050 (0.00034286)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.233233237 (0.05124871)	0.027681	0.0720
Willow	0.0 (NA)	0.0 (NA)	-0.004842962 (0.00083479)	-0.567987126 (0.07683272)	0.0 (NA)	0.0281315332 (0.00264597)	0.0 (NA)	0.012629	0.6378

*NA indicates not applicable.

Table 9. Parameter estimates and standard errors (in parentheses), along with weighted mean square error (MSE) and weighted adjusted coefficient of determination (R_a^2) for Eq. [3], fit to undamaged trees and damaged trees on untreated plots.

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	MSE	R_a^2
Conifers									
Douglas-fir	2.764820027 (0.08761581)	-0.006386063 (0.00019162)	-0.002811791 (0.00006422)	-0.622745097 (0.01574856)	2.754013209 (0.13245144)	0.008097391 (0.00029833)	0.235265576 (0.02009839)	0.017364	0.4745
Grand/White fir	4.529032818 (0.21327434)	-0.001953435 (0.00053843)	-0.003630733 (0.00022674)	-0.767151013 (0.04568159)	0.0 (NA)*	0.0 (NA)	0.293888716 (0.04758201)	0.025156	0.3736
Incense-cedar	3.775223661 (0.29594862)	-0.002740391 (0.00081083)	-0.002469591 (0.00023738)	-0.782793847 (0.05168783)	1.176763365 (0.31092713)	0.004461209 (0.00111600)	0.262183212 (0.07842675)	0.021916	0.5315
Ponderosa pine	2.083628728 (0.23266010)	-0.001830843 (0.00060382)	-0.001536243 (0.00034776)	-0.585867090 (0.04533462)	4.864359312 (0.43485719)	0.001728374 (0.00034074)	0.0 (NA)	0.011791	0.6469
Sugar pine	3.264778818 (0.53687793)	-0.004992924 (0.00110385)	-0.003889436 (0.00047358)	-0.505555582 (0.11252854)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.016083	0.3016
Hardwoods									
Bigleaf maple	0.8144144469 (0.17467229)	-0.008241535 (0.00238226)	-0.003974058 (0.00050881)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.013143	0.5032
California black oak	2.781464383 (0.54587455)	0.0 (NA)	-0.001336456 (0.00037075)	-0.625842640 (0.10789395)	0.0 (NA)	0.0 (NA)	0.474014901 (0.20725887)	0.020017	0.1494
Canyon live oak	0.8869242294 (0.13201759)	-0.021747202 (0.00364674)	-0.002143867 (0.00033455)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.029578	0.1180
Golden chinkapin	1.260117097 (0.16574943)	-0.010669881 (0.00162650)	-0.002131066 (0.00025426)	-0.282035303 (0.04287614)	2.948424008 (0.37164348)	0.0 (NA)	0.494686767 (0.09535939)	0.021525	0.3291
Oregon white oak	0.0 (NA)	0.0 (NA)	-0.004479416 (0.00045652)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.010565	0.5453
Pacific madrone	3.024234372 (0.17962957)	-0.004651232 (0.00102422)	-0.002834117 (0.00019390)	-0.617631113 (0.04130188)	0.0 (NA)	0.0 (NA)	1.117590005 (0.08381950)	0.016738	0.3597
Tanoak	0.3381642619 (0.08450360)	-0.008163917 (0.00168728)	-0.001294201 (0.00022644)	0.0 (NA)	0.0 (NA)	0.0 (NA)	0.2449783995 (0.05119782)	0.027512	0.0777

*NA indicates not applicable.

Table 10. Parameter estimates and standard errors (in parentheses), along with weighted mean square error (MSE) and weighted adjusted coefficient of determination (R_a^2) for Eq. [4], fit to undamaged trees and damaged trees on untreated plots.

Species	b_0	b_1	b_2	b_3	b_4	b_5	b_6	MSE	R_a^2
Conifers									
Douglas-fir	2.863764478	-0.005929962	-0.003055369	-0.634443679	2.493345377	0.007803933	0.218220741	0.016949	0.4870
	(0.08687394)	(0.00018310)	(0.00006452)	(0.01545742)	(0.13130767)	(0.00029525)	(0.01972577)		
Grand/White fir	4.545478377	-0.001749449	-0.003955055	-0.772830346	0.0	0.0	0.292471798	0.024477	0.3905
	(0.20902125)	(0.00050408)	(0.00022393)	(0.04414791)	(NA)*	(NA)	(0.04715934)		
Incense-cedar	3.733773165	-0.002341822	-0.002493699	-0.785370610	1.157586453	0.004790984	0.261882720	0.021827	0.5334
	(0.29587380)	(0.00079092)	(0.00023486)	(0.05123636)	(0.31071461)	(0.00111259)	(0.07831230)		
Ponderosa pine	2.164889464	-0.001760929	-0.001817009	-0.592959116	4.657544958	0.001653607	0.0	0.011651	0.6292
	(0.23299715)	(0.00056805)	(0.00033040)	(0.04405476)	(0.42393767)	(0.00033961)	(NA)		
Sugar pine	3.114845756	-0.005318755	-0.002653561	-0.562500042	1.830749900	0.0	0.0	0.015883	0.3490
	(0.55485466)	(0.00116992)	(0.00053943)	(0.11181126)	(0.65795731)	(NA)	(NA)		
Hardwoods									
Bigleaf maple	0.7320125927	-0.009297762	-0.004152440	0.0	0.0	0.0	0.0	0.013236	0.4969
	(0.16993006)	(0.00239283)	(0.00053797)	(NA)	(NA)	(NA)	(NA)		
California black oak	2.797147773	0.0	-0.001176240	-0.637162966	0.0	0.0	0.450744515	0.020308	0.1370
	(0.55128789)	(NA)	(0.00040322)	(0.10915554)	(NA)	(NA)	(0.20962930)		
Canyon live oak	0.7784332974	-0.020859512	-0.002207000	0.0	0.0	0.0	0.2562966185	0.029195	0.1274
	(0.12572993)	(0.00360292)	(0.00033899)	(NA)	(NA)	(NA)	(0.12780393)		
Golden chinkapin	1.209333223	-0.008955791	-0.002061424	-0.285091592	2.688509986	0.0	0.518797862	0.021711	0.3233
	(0.16752880)	(0.00156982)	(0.00026166)	(0.04358316)	(0.38824904)	(NA)	(0.09527019)		
Oregon white oak	0.0	0.0	-0.004951649	0.0	0.0	0.0	0.0	0.009610	0.5864
	(NA)	(NA)	(0.00047849)	(NA)	(NA)	(NA)	(NA)		
Pacific madrone	3.050103281	-0.004564053	-0.003014098	-0.624812502	0.0	0.0	1.057104981	0.016563	0.3664
	(0.17812855)	(0.00101294)	(0.00019787)	(0.04067147)	(NA)	(NA)	(0.08341462)		
Tanoak	0.3322120057	-0.008073720	-0.001413561	0.0	0.0	0.0	0.2572834703	0.027163	0.0894
	(0.07623225)	(0.00164571)	(0.00021853)	(NA)	(NA)	(NA)	(0.05104345)		
Willow	0.0	0.0	-0.001572444	-0.841115561	0.0	0.0347389429	0.0	0.014303	0.5898
	(NA)	(NA)	(0.00052999)	(0.05974233)	(NA)	(0.00253281)	(NA)		

*NA indicates not applicable.

Table 11. Damage correction factors (CF) for height to crown base predicted by using Eq. [2] and the parameters from Table 5.

Species	Damage code (see Table A1)	# Trees	CF for light damage	Standard error for light damage	CF for severe damage	Standard error for severe damage
Conifers						
Douglas-fir	22	188	-0.2341	0.0387	-0.2341	0.0387
	23	513	NA*	NA	-0.5222	0.0256
	24	236	NA	NA	-0.3803	0.0397
	25	197	-0.2558	0.0406	-0.7821	0.1070
	32	95	-0.6059	0.0620	-0.6056	0.0620
	52	20	0.0000	NA	-0.7170	0.1154
	61	1,227	-0.5282	0.0243	-0.9987	0.0305
	62	153	-0.6973	0.0815	-1.0783	0.0909
	71	1,077	-0.2138	0.0170	-0.5124	0.0534
	72	1,076	-0.3386	0.0241	-0.9040	0.0419
	73	617	-0.2324	0.0223	-0.3780	0.0423
	74	13	0.0000	NA	-0.9098	0.2189
	75	221	NA	NA	-0.5958	0.0480
Grand/White fir	23	30	NA	NA	-0.7164	0.0825
	24	186	NA	NA	-0.4818	0.0384
	32	11	-0.9084	0.1766	-0.9084	0.1766
	61	237	-0.7382	0.0619	-1.5396	0.0953
	62	41	-0.6705	0.1313	-1.5961	0.2102
	71	147	-0.3581	0.0555	-0.3581	0.0555
	72	157	-0.3734	0.0766	-0.8757	0.1146
	73	83	-0.1656	0.0649	-0.1656	0.0649
	75	22	NA	NA	-0.9684	0.1598
Incense-cedar	24	24	NA	NA	-0.3994	0.1367
	25	11	-0.8885	0.1827	-0.8885	0.1827
	32	52	-0.5926	0.0954	-0.5926	0.0954
	61	244	-0.5376	0.0496	-0.9406	0.0738
	62	40	-0.9782	0.1196	-0.9782	0.1196
	71	90	-0.3427	0.0586	-0.3427	0.0586
	72	89	-0.5545	0.0813	-0.9835	0.1012
	73	37	-0.4989	0.1088	-0.4989	0.1088
	75	22	NA	NA	-0.8665	0.1394
Ponderosa pine	61	42	-0.5200	0.1225	-0.5200	0.1225
	62	5	-1.5539	0.1162	-1.5539	0.1162
	72	39	0.0000	NA	-0.8890	0.1155
	73	117	-0.2328	0.0421	-0.2328	0.0421
	74	22	-0.3882	0.0914	-0.3882	0.0914
Sugar pine	21	41	NA	NA	-0.2870	0.0924
	24	25	NA	NA	-0.7177	0.1026
	72	33	-0.7264	0.1142	-0.7264	0.1142
	74	28	-0.5006	0.1416	-0.5006	0.1416
Western hemlock	71	15	-0.4734	0.1511	-0.4734	0.1511

Table 11. (Continued)

Species	Damage code (see Table A1)	# Trees	CF for light damage	Standard error for light damage	CF for severe damage	Standard error for severe damage
Hardwoods						
Bigleaf maple	75	27	NA	NA	-0.5146	0.0949
Canyon live oak	61	21	-0.9576	0.1356	-0.9576	0.1356
	72	28	0.0000	NA	-1.0138	0.2053
	75	218	NA	NA	-0.4563	0.0496
Golden chinkapin	43	69	-0.2501	0.0681	-0.2501	0.0681
	61	20	0.0000	NA	-0.8475	0.1155
	62	20	-0.7718	0.1759	-0.7718	0.1759
	71	82	-0.2683	0.0656	-0.7343	0.2063
	72	20	0.0000	NA	-1.5518	0.3412
	73	21	-0.3493	0.1095	-0.3493	0.1095
	74	13	-1.3342	0.2771	-1.3342	0.2771
	75	206	NA	NA	-0.3279	0.0457
Oregon white oak	75	9	NA	NA	-0.6297	0.1141
Pacific madrone	32	32	0.0000	NA	-0.4898	0.1367
	61	32	0.0000	NA	-0.7353	0.1437
	62	21	-0.3865	0.1258	-1.2376	0.2081
	72	78	0.0000	NA	-1.3317	0.1439
	73	73	-0.2912	0.0610	-0.2912	0.0610
	74	40	-0.6018	0.1232	-0.6018	0.1232
	75	540	NA	NA	-0.2355	0.0246
Red alder	75	20	NA	NA	-0.7566	0.1640
Tanoak	43	19	-0.5710	0.1079	-0.5710	0.1079
	61	76	-0.3690	0.0867	-0.3690	0.0867
	71	50	-0.3276	0.0891	-0.3276	0.0891
	72	27	0.0000	NA	-0.4697	0.1569
	74	11	0.0000	NA	-1.2777	0.2340
	76	12	NA	NA	0.2682	0.0984
Willow	61	19	-1.1728	0.1243	-1.1728	0.1243

*NA indicates not applicable.

Table 12. Damage correction factors (CF) for height to crown base predicted by using Eq. [3] and the parameters from Table 6.

Species	Damage code (see Table A1)	# Trees	CF for light damage	Standard error for light damage	CF for severe damage	Standard error for severe damage
Conifers						
Douglas-fir	22	188	-0.2300	0.0427	-0.501	0.0980
	23	513	NA*	NA	-0.4712	0.0257
	24	236	NA	NA	-0.3708	0.0397
	25	197	-0.2850	0.0427	-0.7667	0.1096
	32	95	-0.5671	0.0631	-0.5671	0.0631
	52	20	0.0000	NA	-0.9745	0.1276
	61	1,227	-0.5955	0.0233	-1.0825	0.0289
	62	153	-0.6650	0.0740	-1.1110	0.0855
	71	1,077	-0.2278	0.0173	-0.5558	0.0538
	72	1,076	-0.3471	0.0238	-0.9184	0.0408
	73	617	-0.2180	0.0224	-0.3701	0.0428
	74	13	0.0000	NA	-0.8154	0.2205
	75	221	NA	NA	-0.6512	0.0474
Grand/White fir	23	30	NA	NA	-0.6937	0.0863
	24	186	NA	NA	-0.4705	0.0393
	32	11	-0.9493	0.2055	-0.9493	0.2055
	61	237	-0.8064	0.0605	-1.6075	0.0983
	62	41	-0.6802	0.1352	-1.5880	0.1924
	71	147	-0.3311	0.0596	-0.6866	0.1213
	72	157	-0.4105	0.0779	-0.9574	0.1197
	73	83	-0.1886	0.0662	-0.1886	0.0662
	75	22	NA	NA	-0.9190	0.1643
Incense-cedar	25	11	-0.8565	0.1960	-0.8565	0.1960
	32	52	-0.4741	0.0937	-0.4741	0.0937
	61	244	-0.5572	0.0508	-0.9625	0.0725
	62	40	-0.8861	0.1145	-0.8861	0.1145
	71	90	-0.3444	0.0586	-0.3444	0.0586
	72	89	-0.5535	0.0823	-0.9672	0.1042
	73	37	-0.4954	0.1125	-0.4954	0.1125
	75	22	NA	NA	-0.8892	0.1518
Ponderosa pine	61	42	-0.5396	0.1256	-0.5396	0.1256
	62	5	-1.5352	0.1203	-1.5352	0.1203
	72	39	0.0000	NA	-0.8271	0.1091
	73	117	-0.2309	0.0425	-0.2309	0.0425
	74	22	-0.0432	0.0878	-0.4032	0.0878
Sugar pine	21	41	NA	NA	-0.2852	0.0960
	24	25	NA	NA	-0.7507	0.1057
	72	33	-0.7341	0.1198	-0.7341	0.1198
	74	28	-0.5266	0.1468	-0.5266	0.1468

Table 12. (Continued)

Species	Damage code (see Table A1)	# Trees	CF for light damage damage	Standard error for light damage	CF for severe severe	Standard error for severe damage
Hardwoods						
Bigleaf maple	75	27	NA	NA	-0.6502	0.0929
Canyon live oak	61	21	-0.8674	0.1395	-0.8674	0.1395
	72	28	0.0000	NA	-0.8256	0.2269
	75	218	NA	NA	-0.3588	0.0478
Golden chinkapin	43	69	-0.4313	0.0737	-0.4313	0.0737
	61	55	-0.5067	0.0931	-0.5067	0.0931
	62	20	-0.8813	0.1701	-0.8813	0.1701
	71	82	-0.3351	0.0712	-0.8523	0.2147
	72	20	0.0000	NA	-1.5868	0.3272
	73	21	-0.5099	0.1239	-0.5099	0.1239
	74	13	-1.4436	0.2792	-1.4436	0.2792
	75	206	NA	NA	-0.4294	0.0491
Oregon white oak	75	9	NA	NA	-0.6349	0.1303
Pacific madrone	61	32	0.0000	NA	-0.7260	0.1419
	62	9	0.0000	NA	-0.8915	0.1665
	71	139	-0.1987	0.0436	-0.1987	0.0436
	72	78	0.0000	NA	-0.9057	0.0968
	74	40	-0.6365	0.1338	-0.6365	0.1338
	75	540	NA	NA	-0.2126	0.0244
Tanoak	43	19	-0.6630	0.1249	-0.6630	0.1249
	61	76	-0.3147	0.0782	-0.3147	0.0782
	71	50	-0.3512	0.0942	-0.3512	0.0942
	72	27	0.0000	NA	-0.4704	0.1591
	74	11	0.0000	NA	-1.3340	0.2272
	76	12	NA	NA	0.3325	0.0555

*NA indicates not applicable.

Table 13. Damage correction factors (CF) for height to crown base predicted by using Eq. [4] and the parameters from Table 7.

Species	Damage code (see Table A1)	# Trees	CF for light damage	Standard error for light damage	CF for severe damage	Standard error for severe damage
Conifers						
Douglas-fir	22	188	-0.2469	0.0378	-0.2469	0.0378
	23	513	NA*	NA	-0.4692	0.0252
	24	236	NA	NA	-0.3614	0.0395
	25	197	-0.2481	0.0417	-0.7482	0.1081
	32	95	-0.5416	0.0617	-0.5416	0.0617
	52	20	0.0000	NA	-0.5448	0.1116
	61	1,227	-0.4809	0.0238	-0.9316	0.0297
	62	153	-0.5916	0.0748	-0.9592	0.0807
	71	1,077	-0.2092	0.0165	-0.4713	0.0519
	72	1,076	-0.3217	0.0232	-0.8738	0.0406
	73	617	-0.2088	0.0218	-0.3554	0.0410
	75	221	NA	NA	-0.5848	0.0467
Grand/White fir	23	30	NA	NA	-0.6124	0.0904
	24	186	NA	NA	-0.4537	0.0390
	32	11	-0.8111	0.1896	-0.8111	0.1896
	61	237	-0.6579	0.0625	-1.3882	0.0907
	62	41	-0.5270	0.1246	-1.4863	0.1793
	71	147	-0.3045	0.0580	-0.6960	0.1325
	72	157	-0.3985	0.0775	-0.9025	0.1159
	73	83	-0.1800	0.0638	-0.1800	0.0638
	75	22	NA	NA	-0.8791	0.1546
Incense-cedar	25	11	-0.8512	0.1897	-0.8512	0.1897
	32	52	-0.6004	0.0965	-0.6004	0.0965
	61	244	-0.4847	0.0520	-0.8590	0.0706
	62	40	-0.8150	0.1131	-0.8150	0.1131
	71	90	-0.2989	0.0593	-0.2989	0.0593
	72	89	-0.5522	0.0840	-0.9865	0.1042
	73	37	-0.4833	0.1099	-0.4833	0.1099
	75	22	NA	NA	-0.9040	0.1463
Ponderosa pine	61	42	-0.5039	0.1264	-0.5039	0.1264
	62	5	-1.4969	0.1218	-1.4969	0.1218
	72	39	0.0000	NA	-0.8102	0.1095
	73	117	-0.2215	0.0423	-0.2215	0.0423
	74	22	-0.3945	0.0872	-0.3945	0.0872
Sugar pine	21	41	NA	NA	-0.2824	0.0941
	24	25	NA	NA	-0.7080	0.1037
	72	33	-0.7319	0.1226	-0.7319	0.1226
	74	28	-0.4872	0.1428	-0.4872	0.1428
Hardwoods						
Bigleaf maple	75	27	NA	NA	-0.2718	0.0877
Canyon live oak	61	21	-0.9886	0.1367	-0.9886	0.1367
	72	28	0.0000	NA	-0.9175	0.2266
	75	218	NA	NA	-0.5003	0.0490

Table 13. (Continued)

Species	Damage code (see Table A1)	# Trees	CF for light damage	Standard error for light damage	CF for severe damage	Standard error for severe damage
Golden chinkapin	43	69	-0.2877	0.0746	-0.2877	0.0746
	61	55	-0.3816	0.0994	-0.3816	0.0994
	62	20	-0.8009	0.1636	-0.8009	0.1636
	71	82	-0.2679	0.0645	-0.7747	0.1961
	72	20	0.0000	NA	-1.4722	0.3234
	73	21	-0.4430	0.1344	-0.4430	0.1344
	74	13	-1.2078	0.2484	-1.2078	0.2484
	75	206	NA	NA	-0.2758	0.0490
Oregon white oak	75	9	NA	NA	-0.4933	0.1475
Pacific madrone	61	32	0.0000	NA	-0.6024	0.1469
	62	9	0.0000	NA	-0.7652	0.1487
	71	139	-0.1250	0.0438	-0.1250	0.0438
	72	78	0.0000	NA	-0.9221	0.1018
	74	40	-0.6195	0.1307	-0.6195	0.1307
	75	540	NA	NA	-0.1506	0.0243
Tanoak	43	19	-0.5537	0.1300	-0.5537	0.1300
	61	76	-0.2149	0.0826	-0.2149	0.0826
	71	50	-0.3810	0.0884	-0.3810	0.0884
	72	27	0.0000	NA	-0.5244	0.1632
	74	11	0.0000	NA	-1.2265	0.2773
	76	12	NA	NA	0.3165	0.0646
Willow	61	19	-1.2640	0.1277	-1.2640	0.1277

*NA indicates not applicable.

Table 14. Predicted damaged tree crown ratios (CR) for each level of damage correction factor (CF).

Damaged tree correction factor (CF)	CR = 0.10	CR = 0.50	CR = 0.90
0.00	0.10	0.50	0.90
-0.20	0.08	0.45	0.88
-0.40	0.06	0.40	0.85
-0.60	0.05	0.35	0.82
-0.80	0.04	0.31	0.80
-1.00	0.03	0.27	0.76
-1.20	0.03	0.23	0.72
-1.40	0.02	0.20	0.69
-1.60	0.02	0.17	0.64
-1.80	0.01	0.14	0.59

Table 15. Percentage, by species, of the modeling population that was affected by various classes of damaging agents.

Species	No damage	Insects	Disease	Fire	Animal	Weather	Suppression	Other	Logging	Excessive taper and off-site
Conifers										
Douglas-fir	44.21	0.02	5.10	0.01	0.73	0.84	29.83	18.91	0.23	0.13
Grand/White fir	40.95	1.48	3.43	0.00	0.90	0.30	31.47	20.79	0.45	0.22
Incense-cedar	48.21	0.00	0.94	0.02	0.86	0.00	33.62	15.33	1.02	0.00
Pacific yew	53.78	0.00	0.85	0.00	0.00	0.00	4.09	39.56	1.71	0.00
Ponderosa pine	46.71	0.92	2.08	0.01	2.70	0.41	25.10	21.92	0.15	0.00
Sugar pine	18.77	0.00	21.87	0.03	10.02	0.84	21.04	27.43	0.00	0.00
Western hemlock	35.24	0.00	5.05	0.01	2.95	2.95	12.17	41.64	0.00	0.00
Hardwoods										
Bigleaf maple	44.97	0.00	0.00	0.00	0.00	0.00	17.24	36.51	0.00	1.27
California black oak	40.87	0.21	1.32	0.00	0.00	0.00	11.47	45.92	0.00	0.21
Canyon live oak	28.56	3.11	1.18	0.00	0.00	0.46	3.53	61.98	0.00	1.18
Golden chinkapin	35.01	9.96	1.35	0.00	9.47	0.01	5.49	38.57	0.00	0.05
Oregon white oak	32.37	0.00	0.00	0.00	0.00	0.00	11.07	56.55	0.00	0.00
Pacific madrone	47.50	0.77	1.62	0.13	0.00	2.10	7.75	39.43	0.00	0.69
Red alder	52.59	0.00	0.00	0.00	0.00	0.00	0.00	47.41	0.00	0.00
Tanoak	27.63	8.78	1.15	0.00	3.39	0.27	11.44	47.20	0.00	0.13
Willow	62.62	0.00	5.81	0.00	0.00	0.15	12.41	18.50	0.00	0.51

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Appendix—Classification of Tree Damage and Its Severity

The following is the actual set of instructions given to field crews in both studies. Presence of damage or pathogen activity was recorded for all living tally trees by using the codes found in Table A1. When a tree was damaged by more than one agent, only the most severe one was recorded.

Damage codes ending in 7, 8, or 9 were always used to indicate living trees that also fell on or near a skidroad or an excavated skidroad. The term "excavated skidroad" indicates at least 2 in. of the top soil was removed (not compacted) during its construction. A tree was defined as being near a skidroad if the crown of the tree extended over the skidroad.

The presence of damage on live tally trees was recorded as being either light or severe. Damage was recorded as severe only when the damage would have (1) prevented the tree from living to maturity or surviving 10 or more years if already mature; (2) prevented the tree from producing marketable products (straight logs of minimum or greater dimensions); or (3) reduced the quality of the tree's products (such as may result from a lightning strike, excessive lean, etc.). Guides for rating the severity of damage can be found in Tables A2 and A3.

Table A1. Damage Codes

Damage	Code
No damaging agent	00
No damaging agent but tree is on a skid road	07
No damaging agent but tree is on an excavated skid road	08
No damaging agent but tree is near a skid road (both types)	09
Insects	
Bark beetles	11
Defoliators	12
Sucking insects	13
Bud- and shoot-deforming insects	14
Tree has insects and is on a skid road	17
Tree has insects and is on an excavated skid road	18
Tree has insects and is near a skid road (both types)	19
Disease	
White pine (and sugar pine) blister rust (always severe)	21
Other rust cankers on main bole	22
Conks on bole, limb, or ground near tree (always severe)	23
Mistletoe (always severe)	24
Other diseases and rot	25
Tree has disease and is on a skid road	27
Tree has disease and is on an excavated skid road	28
Tree has disease and is near a skid road (both types)	29
Fire Damage	
Scorched crown	31
Fire scar on bole	32
Tree has fire damage and is on a skid road	37
Tree has fire damage and is on an excavated skid road	38
Tree has fire damage and is near a skid road (both types)	39
Animal Damage	
Domestic	41
Porcupine	42
Other wildlife	43
Tree has animal damage and is on a skid road	47
Tree has animal damage and is on an excavated skid road	48
Tree has animal damage and is near a skid road (both types)	49
Weather Damage	
Lightning	51
Wind	52
Other	53
Tree has weather damage and is on a skid road	57
Tree has weather damage and is on an excavated skid road	58
Tree has weather damage and is near a skid road (both types)	59
Suppression Damage	
Suppressed seedlings or saplings $\leq$ 6 in. DBH	61
Suppressed pole or sawtimber size tree > 6 in. DBH	62

Table A1. (Continued)

Damage	Code
Tree is suppressed and is on a skid road	67
Tree is suppressed and is on an excavated skid road	68
Tree is suppressed and is near a skid road (both types)	69
Other Damage	
Natural mechanical injury	71
Top out or dead (spike top)	72
Forked top or multiple stem	73
Needles or leaves noticeably short, sparse, or off-color	74
Excessive lean—over 15° from vertical (always severe)	75
Excessive forking—a hardwood tree that forks within the first 8 ft, or a conifer that forks within the first 12 ft, with the main fork then forking again within 8 or 12 ft, respectively (always severe)	76
Tree has other damage and is on a skid road	77
Tree has other damage and is on an excavated skid road	78
Tree has other damage and is near a skid road (both types)	79
Logging and Construction Damage	
Damage by powered equipment	81
Other logging damage	82
Tree has logging damage and is on a skid road	87
Tree has logging damage and is on an excavated skid road	88
Tree has logging damage and is near a skid road (both types)	89
Excessive taper or deformity—will not produce a 12-ft conifer or 8-ft hardwood log	91
Off-site tree	92
Tree has excessive taper and is on a skid road	97
Tree has excessive taper and is on an excavated skid road	98
Tree has excessive taper and is near a skid road (both types)	99

Table A2. Guide for rating severity of damage

Disease Damage

White pine blister rust. This disease attacks all Northwest five-needled pines: white, whitebark, sugar, and limber pines. Record this item as severe when any evidence of the disease is found. Symptoms in infested trees may include discolored bark, the outer edges of the discolorations yellowish to orange; shallow blisters on the bark that may exude a sticky substance or masses of yellow aeciospores; characteristic spindle- or diamond-shaped swelling of the stem or branches accompanied by scaly lesions and black pycnial scars; or copious resin exudation from ruptured bark in areas of infection.

Other rust cankers of the main bole. Record as severe only when cankers deform the bole, cause open wounds, or threaten to girdle the tree. Lodgepole pine is often infected with Peridermium harknessii “hip” cankers, which sometimes kill the tree.

Conk on bole or limb or ground near base of tree. Code as severe whenever any conks are observed.

Mistletoe. This is coded as severe damage.

Table A2. (Continued)

Other diseases and rot. In immature trees, record as severe any disease that appears to threaten the tree's survival to maturity or would reduce its quality at maturity because of topkilling, deformity, or decay of bole or serious reduction of tree vigor. In mature trees, record infections that would seriously jeopardize survival over the next 10 years. Examples of other disease and rot are: Pole Blight of white pine; needle blights, wilts, and rusts; dry rot associated with sunscalds and mechanical damage; needle cast; scabs and leaf galls; and diebacks.

Fire Damage

Crown scorch. In cases where only the foliage has been killed by fire, record fire damage as light unless the fire-killed foliage reaches into the upper one-third of the crown. Ground fires may kill foliage on lower branches without seriously damaging the tree.

Basal scar. In recording fire damage, classify basal scars as light damage unless they have killed the cambium on at least half the bole circumference.

Animal Damage

Record animal damage as severe for trees when at least half the bole circumference has been girdled, or when browsing has so seriously harmed seedlings or saplings that they will probably not develop into sound trees.

Weather Damage

Record as severe when weather damage would prevent immature trees from surviving to maturity or prevent mature trees from surviving 10 years, e.g., loss of 70% of the crown to wind or snowbreak, shattering of the bole by lightning, or partial uprooting by wind.

Suppression Damage

Live, suppressed seedlings or saplings. Suppressed understory trees are common in old-growth stands, but may occur in second-growth timber or even as residual trees after logging. Suppressed seedlings or saplings are usually characterized by extremely short or nonexistent internodes; twisted, gnarled stems; short, flat crowns of live needles forming "umbrella-shaped" trees; or extremely sparse foliage. Such damage should be coded as severe. When in question cut down a sapling that is off the point and count the rings to determine its age. Code as light those seedlings that would probably respond to release.

Other Damage

Natural mechanical injury. Code as severe such things as damage to bole that would reduce the quality of the product at maturity in immature trees or prevent mature trees from living 10 more years. Examples are broken limbs in the crown caused by other trees falling into them, or a bole girdled by at least half by mechanical actions such as rubbing in the wind or boulders rolling against a bole.

Top out or dead (spike top). Code as severe for immature trees. Code as light for mature trees unless more than 10 ft of the top is dead or broken out.

Forked-out or multiple stem. Code as light for small double leaders in tall trees but code as severe all major forks or multiple stems in immature trees. Do not code as severe for mature trees.

Needles or leaves noticeably short, sparse, or off-color. Code as light any minor chlorosis or general "redbelting" of trees caused by frost conditions (when the needle tips of trees in a large area are tinged).

Excessive lean >15° from vertical. Record as severe for all trees, regardless of age or size.

Sound cull-forked tree. Code as severe for a hardwood tree that forks within the first 8-ft log or a conifer that forks within the first 12-ft log, the main fork of which forks again within 8 or 12 ft, respectively.

Table A3. Guide for Rating Severity of Insect Damage

Insect/Host	Light damage	Severe damage
Bark beetles Douglas-fir	Small amount of clear or white pitch on bole.	Current damage. Needles turning yellow or red over most of the tree (tree is dying). Clear or white pitch on bole. Boring dust in bark crevices is conspicuous.
Bark beetles Pines (ponderosa, Jeffrey, lodgepole, sugar, western white)	Copious pitching: pitch tubes large and consist of yellowish to clear masses of pitch. No live insects under bark.	Needles turning yellow to red over most of the tree. Small red pitch tubes (less than 1/4 in. in diameter) common. Reddish boring dust in bark flakes and crevices, or around base of tree. Live insects under bark.
Ips beetles Ponderosa and sugar pines	In a tree beyond conventional rotation age, the top few feet of crown is fading or dead.	Tops killed in seedlings or saplings, or in poletimber and sawtimber trees below rotation age. (In some cases, especially in dense stands of saplings, ips beetles may kill every tree in a small area.)
Defoliators Dominant, co-dominant, and intermediate crown classes		
All species except hemlock and grand fir	Entire crown less than 50% defoliated. Top 10 ft of crown less than 75% defoliated or discolored. Leader normal, but perhaps short. Current foliage with less than 50% of tips discolored or less than 50% of needles missing. A few branches with no shoot growth.	Entire crown more than 50% defoliated. Top 10 ft of crown more than 75% defoliated or discolored. Leader deformed or killed. Current foliage with more than 50% of tips discolored or more than 50% of needles missing. Many branches with no new shoot growth.
Hemlock and grand fir	NA*	All defoliation damage is severe.
Balsam woolly aphid All crown classes of subalpine, Pacific silver, and grand firs	NA	Any degree of balsam woolly aphid infestation on true firs is severe.
Sitka spruce weevil Sitka spruce. Usually attacks trees 8–60 ft tall. Leaders that are currently weeviled begin to droop in August (often turn brown).	Old weevil attacks, causing slight deformity of main stem.	Current weevil infestation with drooping leader; one or more side branches assuming dominance. Mere presence of attack on trees $\geq$20 ft tall reflects significant growth loss. Old damage that has resulted in serious crooks or deformities, if weevil-caused.

*NA indicates not applicable.

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