Research Contribution 39

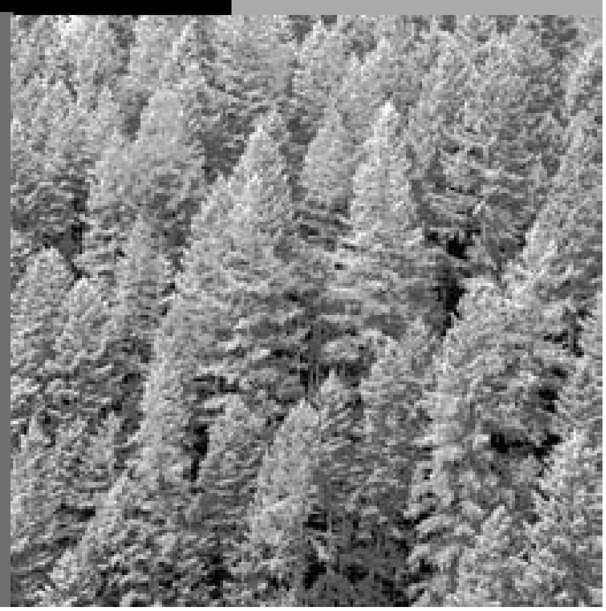
Enhanced Diameter-Growth-Rate Equations for Undamaged and Damaged Trees in Southwest Oregon

by

David W Hann

Mark L Hanus

December 2002



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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

Hann, DW, and ML Hanus. 2002. *Enhanced Diameter-Growth-Rate Equations for Undamaged and Damaged Trees in Southwest Oregon*. Research Contribution 39. Forest Research Laboratory, Oregon State University, Corvallis.

Equations for predicting the 5-yr diameter-growth rate of a tree are presented for eight conifer and nine hardwood tree species from southwest Oregon. Equation parameters for undamaged and damaged trees combined were estimated by weighted nonlinear regression. The resulting equation for Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] explained more than 71% of the variation when validated against an independent data set. These equations are being incorporated into the new edition of ORGANON for southwest Oregon, a model for predicting the development of stands. The equations extend the previous model to older stands and stands with a larger component of hardwood.

We explored the effects of specific damaging agents on the 5-yr diameter-growth rates of the five most frequently encountered species and estimated damage correction factors. Damaging agents can impact 5-yr diameter-growth rate significantly and, as a result, can lead over time to diversification in stand structure. Therefore, full characterization of stand development should include prediction of the presence and frequency of the agents damaging trees within the stand and their impact on tree attributes such as total height, height-to-crown-base, diameter-growth rate, height-growth rate, and mortality rate.

Keywords: ORGANON, growth and yield, untreated stands

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Abbreviations

BAF	Basal area factor
CR	Crown ratio
D	Diameter at breast height
DC	Damage code
ΔD_5	5-yr diameter growth rate
DIST	Horizontal distance from plot center to tree center
EXPAN	Expansion factor
H	Total tree height
HCB	Height to crown base
PBA	Plot basal area
PBAL	Plot basal area in larger trees
SBA	Stand basal area
SBAL	Stand basal area in larger trees
SI	Site index
YCUT	Years since last cut

Conversions

1 acre (ac)	=	4,047 m^2
1 foot (ft)	=	0.305 meter (m)
1 inch (in.)	=	2.34 centimeters (cm)

Introduction

Equations for predicting the diameter-growth rate (ΔD) of trees are an essential component of models that are used to characterize single-tree development and to project the growth of basal area, volume, and other attributes of the stand. Therefore, all single-tree models used to predict stand development over time have included equations for predicting either the basal-area growth rate or ΔD of trees within the stand. One such model is ORGANON (Hann et al. 1997), a single-tree, distance-independent stand development model (Munro 1974) developed for use in three regions of the Pacific Northwest, including southwest Oregon.

The original version of ORGANON for southwest Oregon (SWO-ORGANON) was developed to predict stand development in relatively young conifer stands of the mixed-species and mixed-stand structures found in the area bordered by the North Umpqua River to the north, the California border to the south, the crest of the Cascade Mountains to the east, and the crest of the Coast Range and the Siskiyou Mountains to the west. The targeted conifer species were Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], grand fir [*Abies grandis* (Dougl.) Lindl.] and white fir [*A. concolor* (Gord. & Glend.) Lindl.], incense-cedar (*Calocedrus decurrens* Torr.), ponderosa pine (*Pinus ponderosa* Dougl.), and sugar pine (*P. lambertiana* Dougl.).

The listing of the northern spotted owl (*Strix occidentalis*) as a threatened species under the Endangered Species Act of 1973 has greatly altered the practice of forestry in the Pacific Northwest, including southwest Oregon. In response, research was started in southwest Oregon 1) to identify stand structures and spatial relationships that are utilized effectively by the northern spotted owl and could contribute to the maintenance of a stable population over time, and 2) to develop silvicultural systems and associated mensurational tools needed to implement this knowledge at the stand level. One major mensurational tool needed to manage northern spotted owl habitat was the extension of SWO-ORGANON and its associated diameter-growth-rate equations to include stands with older trees (250 yr or more), a higher component of hardwood species, and more complex spatial structure than were included in the original version.

The first objective of this report, therefore, is to describe the development of equations to predict 5-yr ΔD (ΔD_5) of individual trees for the following species found in southwest Oregon, using both the original and the new, extended data sets: Douglas-fir, grand fir and white fir, incense-cedar, Pacific yew (*Taxus brevifolia* Nutt.), ponderosa pine, sugar pine, western hemlock [*Tsuga heterophylla* (Raf.) Sarg.], bigleaf maple (*Acer macrophyllum* Pursh), California black oak (*Quercus kelloggii* Newb.), canyon live oak (*Q. chrysolepis* Liebm.), golden chinkapin [*Castanopsis chrysophylla* (Dougl.) A. DC.], Oregon white oak (*Q. garryana* Dougl. ex Hook.), Pacific dogwood (*Cornus nuttallii* Aud. ex T. & G.), Pacific madrone (*Arbutus menziesii* Pursh), tanoak [*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.], and willow [*Salix* spp.]. In concordance with the analysis of Hann and Larsen (1991), we developed these equations using data from both undamaged and damaged trees. They will be used in a revision of SWO-ORGANON.

Previous analyses with the data sets used in this study found that damaging agents significantly impacted both the height/diameter relationship (Hanus et al. 1999) and the height-to-crown-base (Hanus et al. 2000) of trees in the study area. Therefore, the second objective of this report is to examine whether or not damaging agents significantly affected ΔD_5 of trees in the study area.

Data Description

Study Area

Data for this analysis were obtained in southwest Oregon, in the Pacific Northwest of the United States. Because of the unique combination of weather conditions and geologic features in the Pacific Northwest, its forests represent some of the more productive (site indices up to 150 ft at a breast height age of 50 yr) and ecologically complex coniferous forests in the world.

Forests in southwest Oregon grow in the widest range of soil and climatic conditions of any region within the Pacific Northwest (Franklin and Dyrness 1973). In addition, several floras converge in southwest Oregon. As a result, the forests of southwest Oregon are probably the most complex of the Pacific Northwest (Franklin and Dyrness 1973). Twenty-seven coniferous species and over 17 hardwood species are found in southwest Oregon (Burns and Honkala 1990a,b), often growing in mixed-species stands with a variety of stand structures.

The modeling data were collected in 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. 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 mi west of Glendale (123°50'W). Elevation of the sample plots ranged from 900 to 5100 ft. Selection was limited to stands <120 yr old with 80% of the basal area in conifer species. The second study covered the same general location, but extended the selection criteria to include stands with trees >250 yr old and to 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.

In total, 30 tree species were found on these 529 plots. The most common conifer was Douglas-fir (527 plots), followed by 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 was Pacific madrone (270 plots), followed by golden chinkapin (156 plots), California black oak (88 plots), canyon live oak (82 plots), Pacific dogwood (81 plots), and tanoak (75 plots). The number of species on a plot ranged from 1 to 12 and averaged almost 5 species.

Stand structures in the sample area ranged from even-aged stands of one or two stories to uneven-aged stands. Of the 529 stands, 363 were classified as even-aged and 166 were classified as uneven-aged.

Sampling Design

In both studies, each stand was sampled with a plot composed of 4–25 sample points spaced 150 ft apart. The sampling grid was established so that all sample points were at least 100 ft from the edge of the stand. At each sample point, trees were sampled with a nested subplot design composed of four subplots: trees ≤4.0 in. in diameter at breast height (D) were selected on a circular subplot with radius of 7.78 ft; trees with D = 4.1–8.0 in. were selected on a circular subplot with radius of 15.56 ft; trees with D = 8.1–36.0 in. were selected on a 20-BAF variable-radius subplot; and trees with D >36.0 in. were selected on a 60-BAF variable-radius subplot.

Tree Measurements

Tree measurements taken at the end of the previous 5-yr growth period (as indicated by a subscript of 2 on the variables) included a mortality indicator of whether the tree died in the past 5 yr, the type and severity of any damage, D_2, total tree height (H_2), height-to-crown-base (HCB_2), and horizontal distance from point location to tree center (*DIST*). In addition, radial growth and height growth over the past 5 yr were measured on subsamples of the trees.

Mortality dating was based on physical features of the dead tree as described by the USDA Forest Service (1978) and Cline et. al. (1980). The type and severity of any damage on each tree were noted according to the procedures and codes described in Hanus et al. (1999, 2000). Although not required to do so, some of the field crews also noted additional damage codes in the remarks column of the field forms for trees damaged by multiple agents; these codes were also entered into the data base. The damage codes (DCs) are briefly described in Table 1.

D_2 was measured to the last whole 0.1 in. 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 by the pole-tangent method (Larsen et al. 1987). When tops were broken or dead, H_2 was measured to the top of the live crown. For trees with uneven crown length, lower branches on the longer side of the crown were

Table 1. Description of the damage codes (DCs).

DC	Cause of damage
0	No damaging agent
11	Bark beetles
12	Defoliators
13	Sucking insects
14	Bud- and shoot-deforming insects
21	White pine and sugar pine blister rust
22	Other rust and cankers on main bole
23	Conks on bole, limb, or ground near tree caused by heart rot, root disease, etc.
24	Mistletoe
25	Other diseases and rot*
31	Scorched crown
32	Fire scar on bole
41	Domestic animals
42	Porcupine
43	Other wildlife
51	Lightning
52	Wind
53	Other weather (e.g., snow or ice bending or breakage)
61	Suppressed seedlings or sapling, D ≤6 in.
62	Suppressed pole or sawtimber size tree, D >6 in.
71	Natural mechanical injury to bole or crown**
72	Top out or dead (spike top)
73	Forked top or multiple stem
74	Needles or leaves noticeably short, sparse, or off-color
75	Excessive lean (>15° from vertical)
76	Excessive forking†
81	Power equipment
82	Other logging
91	Excessive taper or deformity‡
92	Off-site tree

* e.g., abiotic diseases, needle diseases, diebacks, scales, leaf galls, pole blight

mentally transferred to fill in the missing portion of the shorter side of the crown in order to generate a "full, even" crown. HCB_2 was then measured to this mentally generated position on the bole (epicormic and short internodal branches were ignored).

Procedures for measuring the 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 the lean was ≤15° from vertical, H_2 and HCB_2 were measured directly to the leaning tip and crown base (i.e., the lean was ignored). If the lean was >15° from vertical, 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.

Accurately and precisely determining H_2 and HCB_2 for dead trees at the time they died was sometimes difficult, especially if the tree had been dead for several years and was missing foliage or part of the top at the time of measurement. Therefore, we compared the measured H_2 and HCB_2 for the dead trees to predicted H_2 and HCB_2 for severely damaged, but living, trees with the same class of damage to determine if the dead tree values were biased and, if biased, to develop adjustments for the bias. [The procedures are described in Hann and Hanus (2001).] The measured H_2 for dead trees did not differ significantly from the predicted H_2 for severely damaged, living trees with the same class of damage, but the HCB_2 for dead trees did differ significantly from the predicted HCB_2. Hanus et al. (2000) found that HCB_2 values of severely damaged trees often were higher than those predicted for undamaged trees. In all cases of this study, the HCB_2 for dead trees was even higher, on average, than the predicted HCB_2. This difference was judged to result from measurement error caused by the difficulty in identifying *HCB* on dead trees in which some or all of the foliage and branches were missing. The HCB_2 of dead trees therefore was adjusted down to the values expected for severely damaged live trees, and the adjusted values of HCB_2 were used in all subsequent analyses.

DIST was determined by adding 0.5 (D_2) to the horizontal distance from point location to tree face. Past radial growth at breast height was measured by coring every live tree capable of admitting an increment borer. The increment core was taken at the point on the tree facing plot center in order to avoid selection bias. Five-year height growth was measured on a subsample of Douglas-fir, grand fir, white fir, ponderosa pine, sugar pine, and incense-cedar trees on each plot. Trees were rejected from the selection process if they had experienced top damage in the previous five full growth periods or if they had any other type of severe damage. (Trees with light damage were acceptable.) Current growth was ignored on trees measured during the growing season. For all trees <25–45 ft (based on the size of the telescoping pole used to measure H_2 and HCB_2) that met the selection criteria, 5-yr height growth was measured directly with the pole if the five full internodes at the top of the tree were clearly visible. For trees taller than the telescoping pole, a subsample of up to six trees on each plot were felled and sectioned at the first and sixth whorls. The ages at these whorls were determined to ensure a true 5-yr growth period, and the distance between the two whorls was measured to determine 5-yr height growth.

Table 1 continued

** Caused by falling trees, abrasion between trees, rolling rocks or logs, etc.

† A hardwood tree forking within the first 8 ft, or a conifer forking within the first 12 ft, the main fork then forking again within 8 or 12 ft, respectively

‡ Will not produce a 12-ft conifer or 8-ft hardwood log

The expansion factor ($EXPAN_2$), or number of trees per acre, for a sampled tree alive at the end of the growth period was assigned by the following rules, which are based on the sampling design used to collect the data:

- If $D_2 \leq 4.0$ in., $EXPAN_2 = 229.18$ trees/ac
- If 4.0 in. $< D_2 \leq 8.0$ in., $EXPAN_2 = 57.30$ trees/ac
- If 8.0 in. $< D_2 \leq 36.0$ in., $EXPAN_2 = 3666.93(D_2)^{-2}$
- If $D_2 > 36.0$ in., $EXPAN_2 = 11,000.79(D_2)^{-2}$.

Point and Plot Measurements

Aspect and slope were measured at each sampling point. Information obtained 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), number of previous cuts made in the stand, and the number of years since the last cut (*YCUT*). The last two items were determined by field visits to the offices of the managing agencies. One of the stand selection criteria was that the stand could not have been treated within the past 5 yr. Therefore, 6 yr was the smallest value possible for *YCUT*.

Backdating of Tree Attributes

Because the objective of the project was to predict future, rather than past, ΔD_5, we had to backdate all of the measurements for each sample tree in order to estimate their values at the start of the previous 5-yr growth period, as indicated by a subscript of 1 on the variables (i.e., D_1, H_1, HCB_1, and $EXPAN_1$). Procedures used in backdating each variable are described by Hann and Hanus (2001).

Derivation of Additional Tree and Stand Attributes

After the basic tree variables had been backdated, several tree and stand variables previously used by other researchers in modeling diameter growth rate were calculated. ΔD_5 was calculated by subtracting D_1 from D_2 for all trees with a radial growth measurement. Crown ratio, a measure of tree vigor previously used by Hann and Larsen (1991), Zumrawi and Hann (1993), and many others to model ΔD, was determined at the start of the growth period (CR_1) for each tree:

$$CR_1 = 1.0 - (HCB_1)/(H_1)$$

Plant-to-plant interactions have been separated into two parts (e.g., Weiner 1986, 1990; Vanclay 1994): 1) two-sided competition, resulting from competition for below-ground resources, such as nutrients and moisture, and 2) one-sided competition, resulting from competition for light. Stand basal area per acre (SBA_1) was chosen to quantify the two-sided competition that a tree was experiencing at the start of the growth period. SBA_1

has been used previously in tree ΔD equations (e.g., Hann and Larsen 1991; Zumrawi and Hann 1993).

Stand basal area per acre in larger trees ($SBAL_1$) was used to quantify the one-sided competition that a tree was experiencing at the start of the growth period. $SBAL_1$, which has been previously used in tree ΔD equations (e.g., Hann and Larsen 1991; Zumrawi and Hann 1993), is the sum of the basal area in trees with DBH_1 larger than that of the subject tree. Therefore, the $SBAL_1$ of the largest diameter tree in the stand would be 0, while that of the smallest diameter tree would be near, but somewhat less than, SBA. If D_1 and H_1 in a stand are strongly and positively correlated, such that trees with the largest D_1's in the stand also have the largest H_1's, $SBAL_1$ is also an indirect indicator of the vertical position of a tree's top in the stand.

In order to better characterize within-stand variation in competition, Stage and Wykoff (1998) proposed rescaling $SBAL_1$ by multiplying it by the ratio of the appropriate point basal area per acre (PBA_1) to SBA_1:

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

Another measure of within-stand variability is the direct calculation of basal area per acre 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 for the stand included Douglas-fir site index (SI) from Hann and Scrivani (1987) and an indicator variable (I_{Data}) of whether the data were collected in the original study (I_{Data} = 0) or the new study (I_{Data} = 1). The I_{Data} variable is used to assess whether there were significant differences in ΔD_5 between the two periods in which the data sets were collected that might be attributable to fluctuations in weather (Peterson and Heath 1990; Wensel and Turnblom 1998; Yeh and Wensel 2000), endemic levels of insect attack (Edmonds et al. 2000), endemic levels of disease (Edmonds et al. 2000), and so forth.

The following five indicator variables were defined to determine how long the impact of cutting (if it existed) lasted:

IC_1 = 1.0 if $6 \leq YCUT \leq 10$
= 0.0 otherwise

IC_2 = 1.0 if $11 \leq YCUT \leq 15$
= 0.0 otherwise

IC_3 = 1.0 if $16 \leq YCUT \leq 20$
= 0.0 otherwise

IC_4 = 1.0 if $21 \leq YCUT \leq 25$
= 0.0 otherwise

IC_5 = 1.0 if $YCUT \geq 26$
= 0.0 otherwise

Stand-level variables that were used in developing the individual-tree ΔD_5 equations are summarized in Table 2; tree-level variables are summarized in Table 3. For a given species or species group, plots with significant *YCUT* indicator variables were eliminated from the final modeling data sets. This resulted in the loss of 3,028 Douglas-fir, 945 grand/white fir and 497 ponderosa pine trees for modeling purposes. The data summaries in Tables 2 and 3 are for the final modeling data sets.

Validation Data

Data from the untreated plots on two research installations in the study area were used to validate the final ΔD_5 equation for Douglas-fir. These data were collected as part of the work that developed a new version of ORGANON for the Stand Management Co-operative (SMC) located at the University of Washington (Chappell and Osawa 1991). This modeling data set was composed of data collected by the SMC and data collected by other sources.

The first set of untreated plots was from the Stampede Creek Levels of Growing Stock (LOGS) installation (Curtis 1992). This LOGS installation was established in 1968 in a 25-yr-old (at breast height), naturally established stand of even-aged Douglas-fir. Based on the measured tree heights in 1993, when the stand was 50-yr-old at breast height, the Hann and Scrivani (1987) *SI* for the stand was 112.0 ft. The three untreated plots on the installation are 0.2 ac; they have been remeasured every 5 yr since establishment. Because the 1998 remeasurement was the most recent made on the installation, data were available from six 5-yr growth periods for the validation analysis. Tree attributes recorded at each measurement included species and *D* of every tree with $D \geq 1.6$ in., and *H* for a small subsample of the trees. Starting at the first remeasurement (1973), *HCB* was also measured on a small subsample of the trees according to the same procedure used in this study.

The second set of untreated plots was from the Fawn Saddle SMC Type II installation. This installation was established in 1986 in a 16-yr-old (at breast height) plantation of Douglas-fir. Based on the measured tree heights in 1998, when the stand was 28 yr old at breast height, the Hann and Scrivani (1987) site index for the stand was 149.7 ft. The one control plot and four treatment plots on the installation are 0.5 ac; they have been remeasured every 4 yr since establishment (two of the plots were also remeasured in 1996). Remeasurements through 1998 were obtained by this project; therefore, data were available from three 4-yr growth periods for the validation analysis. None of the five plots had been treated at the time of the last remeasurement.

Tree attributes measured and recorded at each measurement in these plots included species and *D* of every tree with $D \geq 1.6$ in., and the *H* and *HCB* for a subsample of approximately 40 of the trees on each plot. For the Fawn Saddle SMC data, crown base was defined as the lowest whorl that had live branches around at least three-quarters of the stem circumference. *HCB* was then measured as the distance between the ground and this whorl. Because this method of defining *HCB* ($HCB_{3/4}$) produces a greater *HCB*

Table 2. Sample size and summary statistics, expressed as the mean and the range (in parentheses), for the stand-level ΔD_5 data.

Species	Plots	*SI*	SBA_1
		Conifers	
Douglas-fir	407	99.6 (41.5–146.9)	186.6 (0.1–542.0)
Grand/white firs	169	101.3 (61.6–146.9)	196.8 (10.1–542.0)
Incense-cedar	217	96.5 (41.5–146.9)	183.6 (10.1–402.8)
Pacific yew	20	92.2 (66.2–113.7)	193.7 (37.9–358.5)
Ponderosa pine	130	96.9 (41.5–146.9)	179.1 (7.8–348.6)
Sugar pine	168	92.5 (47.2–138.8)	178.9 (11.1–342.7)
Western hemlock	36	105.2 (74.0–135.6)	172.4 (20.1–349.7)
		Hardwoods	
Bigleaf maple	27	104.9 (74.0–142.5)	216.6 (39.8–401.6)
California black oak	80	89.7 (41.5–134.9)	189.2 (48.6–304.7)
Canyon live oak	48	93.5 (52.0–138.8)	190.5 (16.0–402.8)
Chinkapin	120	100.6 (64.4–131.1)	181.6 (20.8–393.3)
Oregon white oak	8	69.1 (41.5–95.9)	173.1 (121.4–220.8)
Pacific dogwood/willow	26	100.8 (76.5–125.2)	171.1 (29.4–337.7)
Pacific madrone	240	98.5 (41.5–146.9)	178.1 (7.8–402.8)
Tanoak	40	102.0 (47.2–138.8)	207.1 (21.4–401.6)

Table 3. Sample size and summary statistics, expressed as the mean and the range (in parentheses), for the tree-level ΔD_5 data, including both damaged and undamaged trees.

Species	Trees	D_1	ΔD_5	CR_1	$SBAL_1$	$PBAL_1$	Scaled $PBAL_1$
				Conifers			
Douglas-fir	12,403	16.1 (0.1–80.8)	0.8 (0.1–4.2)	0.46 (0.05–1.0)	110.1 (0.0–516.0)	110.2 (0.0–700.0)	118.4 (0.0–688.1)
Grand/white fir	1,951	13.5 (0.6–51.1)	0.8 (0.1–4.3)	0.50 (0.05–1.0)	141.1 (0.0–539.1)	143.4 (0.0–720.0)	153.9 (0.0–715.4)
Incense-cedar	1,276	13.2 (0.2–83.5)	0.6 (0.1–4.7)	0.50 (0.06–1.0)	124.6 (0.0–396.0)	125.5 (0.0–510.9)	133.1 (0.0–522.8)
Pacific yew	44	8.8 (2.9–22.5)	0.2 (0.1–0.6)	0.60 (0.25–0.94)	157.9 (0.0–355.9)	169.6 (0.0–420.0)	178.5 (0.0–441.3)
Ponderosa pine	1,007	15.9 (0.1–59.6)	0.7 (0.1–5.1)	0.45 (0.05–1.0)	84.4 (0.0–272.0)	83.7 (0.0–460.0)	92.4 (0.0–359.2)
Sugar pine	413	20.1 (1.1–69.6)	1.1 (0.6–4.9)	0.49 (0.07–1.0)	63.7 (0.0–288.0)	67.4 (0.0–360.0)	70.9 (0.0–393.1)
Western hemlock	139	10.2 (1.4–30.0)	0.7 (0.1–3.0)	0.66 (0.05–1.0)	127.5 (0.0–341.2)	141.9 (0.0–452.0)	145.0 (0.0–452.0)
				Hardwoods			
Bigleaf maple	86	8.6 (1.4–28.4)	0.4 (0.1–2.1)	0.39 (0.05–0.88)	181.3 (2.0–375.0)	156.9 (0.0–400.0)	175.2 (1.0–389.2)
California black oak	427	12.5 (1.6–42.3)	0.3 (0.1–1.5)	0.38 (0.05–1.0)	104.6 (0.0–294.7)	98.7 (0.0–400.0)	107.3 (0.0–404.5)
Canyon live oak	188	5.0 (2.1–22.4)	0.3 (0.1–1.0)	0.47 (0.05–0.93)	170.0 (0.0–377.9)	160.4 (0.0–580.0)	173.3 (0.0–570.8)
Chinkapin	535	6.9 (1.1–27.6)	0.4 (0.1–1.8)	0.44 (0.06–1.0)	133.3 (0.0–390.0)	137.0 (0.0–420.0)	148.2 (0.0–436.3)
Oregon white oak	37	8.1 (2.0–24.4)	0.2 (0.1–0.3)	0.38 (0.13–0.64)	92.5 (3.3–214.6)	94.7 (0.0–187.6)	94.2 (2.0–182.0)
Pacific dogwood/willow	55	3.6 (2.0–8.7)	0.4 (0.1–1.1)	0.42 (0.05–0.79)	160.0 (20.8–335.0)	152.9 (53.7–331.5)	137.1 (11.3–347.3)
Pacific madrone	1,924	9.5 (1.2–44.5)	0.4 (0.1–2.7)	0.35 (0.05–0.97)	117.5 (0.0–365.0)	116.0 (0.0–560.0)	127.6 (0.0–551.3)
Tanoak	216	6.8 (1.3–36.4)	0.4 (0.1–1.2)	0.48 (0.06–0.94)	175.5 (8.0–393.9)	179.6 (0.0–557.2)	187.7 (3.3–525.3)

than the method used to collect *HCB* data in both the current study and at the Stampede Creek LOGS installation (Maguire and Hann 1987), we used the conversion equation described in the Appendix to transform $HCB_{3/4}$ to *HCB*.

D_1, H_1, HCB_1, and $EXPAN_1$ were defined to be the tree values at the start of each growth period for each untreated plot. The 5-yr remeasurement cycle made the definition of D_1, H_1, HCB_1, $EXPAN_1$, D_2, H_2, HCB_2, and $EXPAN_2$ straightforward for the Stampede Creek installation. Because of the use of 4-yr (and sometimes 2-yr) growth periods, the Fawn Saddle data required interpolation and extrapolation to define D_2, H_2, and HCB_2. The 5-yr growth periods were defined such that actual measurement values (instead of interpolated or extrapolated values) were used for D_1, H_1, HCB_1, and $EXPAN_1$ in order to avoid problems with measurement error. As a result, the 5-yr growth period data created from the Fawn Saddle data set used the 1986 measurement data and the 1994 remeasurement data as the start of the two growth periods. Interpolation was used to estimate the values of D_2, H_2, and HCB_2 values in 1991, and extrapolation was used to estimate the values in 1999. These procedures are described in the Appendix.

Several additional attributes were then calculated for each plot and installation combination. ΔD_5 was determined by subtracting D_1 from D_2. $SBAL_1$ was computed for each growth period from D_1 and $EXPAN_1$ of all trees alive at the start of the growth period. CR_1 was calculated for those trees with actual measurements of H_1 and HCB_1. Only trees with a value of CR_1 were included in the validation data set. A summary of the resulting validation data can be found in Table 4.

Table 4. Sample size and summary statistics, expressed as the mean and the range (in parentheses), for the ΔD_5 validation data set.

Location	Trees	D_1	ΔD_5	*CR*	$SBAL_1$	SBA_1
Stampede Creek	248	9.8 (3.2–21.8)	0.7 (-0.1–1.9)	0.43 (0.05–0.70)	102.4 (0.0–242.7)	200.2 (138.3–247.0)
Fawn Saddle	388	10.0 (3.2–18.4)	1.5 (0.0–3.4)	0.71 (0.43–1.00)	65.7 (0.0–177.3)	129.4 (81.6–177.9)

Data Analysis

ΔD_5 of Undamaged and Damaged Trees Combined

In the first step of the analysis to develop new ΔD_5 equations for ORGANON, the following ΔD_5 model form, which had been previously used for southwest Oregon by Hann and Larsen (1991), was fit to the Douglas-fir data set that included both undamaged and damaged trees (the largest data set available for modeling; Table 3):

$$\Delta D_5 = e^{\sum_{i=0}^{7} a_i X_i} + \varepsilon$$

where [1]

X_0 = 1.0

X_1 = $\ln(D_1 + 1)$

X_2 = D_1^2

X_3 = $\ln[(CR_1 + 0.2)/1.2]$

X_4 = $\ln(SI - 4.5)$

X_5 = $SBAL_1^2/[\ln(D_1 + 5)]$

X_6 = SBA_1

X_7 = I_{Data}

a_i = regression parameters

ε = random error

Applying the procedures described in Kmenta (1986) and Hann and Larsen (1991), we estimated the parameters by weighted nonlinear regression with a weight of the reciprocal of predicted ΔD_5 ($Pred\Delta D_5$). To check the equation, we examined both the weighted and the unweighted residuals for systematic trends across $Pred\Delta D_5$ and the independent variables. This analysis was done by 1) dividing the range of $Pred\Delta D_5$ and the independent variables into classes, 2) computing the mean weighted or unweighted residual and the standard deviation of the residuals in each class, and 3) visually examining the resulting data for systematic trends that might indicate lack of fit. This examination indicated that Eq. [1] did not fit the data well for small D_1s, for very large D_1s associated with the "older" stands, and for large BAL_1s. After examining a number of alternative model forms, we found that the following fit the Douglas-fir data better:

$$\Delta D_5 = e^{\sum_{i=0}^{7} b_{1,i} X_{1,i}} + \varepsilon \qquad [2.1]$$

where

$X_{1,0}$ = 1.0

$X_{1,1}$ = $\ln(D_I + 5)/10$

$X_{1,2}$ = $D_I/100$

$X_{1,3}$ = $\ln[(CR_I + 0.2)/1.2]$

$X_{1,4}$ = $\ln(SI - 4.5)/10$

$X_{1,5}$ = $SBAL_I/[(1000)\ln(D_I + 2.7)]$

$X_{1,6}$ = $SBA/100$

$X_{1,7}$ = $I_{Data}/10$

$b_{v,i}$ = regression parameter for the v^{th} variation (v = 1,...,3) of Equation [2.v] and the i^{th} independent variable (i = 0,...,7)

v = 1 in Eq. [2.1]

The modeling data set contained data from both even- and uneven-aged stands. Uneven-aged structures can result in smaller, often younger, trees shaded by larger, often older, trees. This is particularly true in "all-aged" stands in which trees of all sizes and ages are uniformly mixed throughout the stand. Understory trees often have slower height- growth rates than overstory trees (e.g., Ritchie and Hann 1986; Wensel et al. 1987; Dolph 1988; Hann and Ritchie 1988; Ritchie and Hann 1990). Therefore, trees growing in uneven-aged stands may never achieve the same dominant heights as trees growing on the same sites in even-aged stands. As a result, estimation of *SI* in uneven-aged stands may systematically underestimate the true site quality of the site. For this reason, modelers such as Wykoff and Monserud (1988), Wykoff (1990), and Monserud and Sterba (1996) have advocated not using *SI* when the data set contains uneven-aged stands.

The following approach was applied to both the Douglas-fir data set (the largest data set composed of trees with intermediate shade tolerance) and the ponderosa pine data set (a shade-intolerant species) to evaluate whether or not the *SI* measured in uneven-aged stands significantly altered $Pred\Delta D_5$:

1) The following uneven-aged stand indicator variable was defined:

I_{UE} = 1.0 if the stand is uneven-aged

= 0.0 otherwise

2) The following equation was then fit to each data set by weighted, nonlinear regression:

$$\Delta D_5 = e^{\sum_{i=0}^{3} b_{1,i} X_{1,i} + b_{1,4} X_{1,4}^{*} + \sum_{i=5}^{7} b_{1,i} X_{1,i}} + \varepsilon$$

where

$$X_{1,4}^{*} = \ln[(SI - 4.5) + \gamma\, I_{UE}\,(SI - 4.5)]/10$$

If SI in uneven-aged stands is systematically underestimated, γ should be significantly >0.

3. The value of γ was tested to determine if it was significantly >0 by the 1-sided *t*-test with P = 0.05.

The value of γ was -0.0086 for Douglas-fir and -0.2072 for ponderosa pine, with standard errors of 0.0110 and 0.0501, respectively. Therefore, the value of γ for both species was not significantly >0, indicating that the SI estimates in uneven-aged stands were not significantly smaller than those from even-aged stands. As a result, Eq. [2.1] was judged adequate for characterizing the ΔD_5 in both stand structures.

Eq. [2.1] was therefore fit to each of the ΔD_5 data sets with weighted nonlinear regression. The signs of the parameters should be positive for $b_{v,1}$, $b_{v,3}$, and $b_{v,4}$ and negative for $b_{v,2}$, $b_{v,5}$, and $b_{v,6}$ (Hann and Larsen 1991; Zumrawi and Hann 1993). Therefore, the parameters were examined to determine if they were of the correct sign and if they were significantly different from 0 at P = 0.05. Parameters not significantly different from 0 were set to 0 and the remaining parameters re-estimated.

As another check of parameters for Eq. [2.1], predicted maximum ΔD_5 was determined by setting CR_1 = 1, $SBAL_1$ (or *Scaled* $PBAL_1$ or $PBAL_1$) = 0, and SBA_1 = the basal area of the tree, and graphing the maximum values over D_1 for three levels of SI (60, 100, and 140 ft). These graphs were then compared to the largest Ds reported by Jensen et al. (1994) and Hardin et al. (2001) for each species in the study to ascertain whether or not predicted maximum ΔD_5 was near 0 when D_1 was near its maximum.

Reasonably behaved and significant parameter estimates for Eq. [2.1] were obtained for Douglas-fir, grand fir, white fir, ponderosa pine, sugar pine, incense-cedar, California black oak, and Oregon white oak. In accordance with the precedent set by Hann and Larsen (1991), grand and white firs were fit as a combination. Because of small sample sizes, Hann and Larsen (1991) combined Oregon white oak and California black oak and used an intercept indicator variable for Oregon white oak to characterize the differences between the two species. The resulting parameters were used for both Oregon white oak and California black oak (i.e., all parameters, except the intercept, were identical for the two species). The enhanced data set used in this analysis provided enough additional measurements of California black oak to allow a fit to that data set alone. The Oregon white oak data set, however, was still very weak. Therefore, we again applied the approach of Hann and Larsen (1991) to the combined data set in order to estimate parameters for Oregon white oak. This resulted in an intercept parameter that was significantly different (P = 0.01) from California black oak; the remaining parameters were only slightly different because of the combining of the two data sets.

The parameters of the remaining species exhibited numerous problems, including too many parameters having incorrect sign or not differing significantly from 0, or yielding predictions that did not behave as expected. This led to the recognition of the following features that would result in a minimally acceptable ΔD_5 model form and its parameters:

- The equation must include both D_1 terms with parameters of the correct signs and magnitudes in order to provide the expected peaking over D_1, and the maximum ΔD_5 predicted from the equation must be near 0 for the maximum D_1 for the species. On the basis of the results of the successful fits to Eq. [2.1], we expected that the ΔD_5 should peak at roughly 0.1 to 0.15 of the maximum D_1 for the species.

- The equation must include a *BAL* or *BA* term, or both, with parameter(s) of correct sign(s) and magnitude(s) in order to provide a potential response to density and density manipulation.

The following model forms were used to guarantee this behavior:

$$\Delta D_5 = e^{\sum_{i=0}^{6} c_{1,i} X_{2,i}} + \varepsilon \qquad [3.1]$$

where

$X_{2,0}$ = 1.0

$X_{2,1}$ = $[k_1 \ln(D_1 + k_2)/10] - [k_3 (D_1/100)^{k_4}]$

$X_{2,2}$ = $\ln[(CR_1 + 0.2)/1.2]$

$X_{2,3}$ = $\ln(SI - 4.5)/10$

$X_{2,4}$ = $SBAL_1 / [(1000)\ln(D_1 + 2.7)]$

$X_{2,5}$ = $SBA_1^{1/2}/100$

$X_{2,6}$ = $I_{Data}/10$

$c_{v,i}$ = regression parameter for the v^{th} variation (v = 1,...,3) of Equation [3.v] and the i^{th} independent variable (i = 0,...,6)

v = 1 in Eq. [3.1]

k_j = fixed constants, j = 1,...,4

The k values were determined by trial and error in order to meet the first expected feature of a minimally acceptable fit. The following bounds were placed on the $c_{1,i}$ parameters estimated in the weighted nonlinear regression fits in order to meet both the second expected feature of a minimally acceptable fit and other expected behaviors:

1) $c_{1,1} \geq 1.0$

2) $c_{1,2} \geq 0.0$

3) $c_{1,3} \geq 0.0$

4) $c_{1,4} \leq 0.0$

5) if $c_{1,4} < 0.0$, $c_{1,5} \leq 0.0$

6) if $c_{1,4} = 0.0$, $c_{1,5} \leq -2.0$

The data sets available to fit Eqs. [2.1] and [3.1] included stands that had been previously cut. Hann et al. (in press) found that the ΔD_5 equations developed for unthinned stands underpredicted the ΔD_5 of thinned stands; the underprediction varied by the amount of *BA* removed in the thinning and the time since thinning. Although the previously cut stands in this study did include *YCUT*, no data were available on the amount of *BA* removed in the previous cutting. Therefore, we applied the following approach to the data set for each species to evaluate the impact of operational cuttings on predicted ΔD_5 and to eliminate the data showing a statistically significant impact:

1) The following equations were fit to the appropriate species data sets by using the *YCUT* indicator variables (IC_1, IC_2 ,..., IC_5):

$$\Delta D_5 = e^{\sum_{i=0}^{7} b_{1,i} X_{1,i} + \sum_{j=1}^{5} d_j IC_j} + \varepsilon$$

$$\Delta D_5 = e^{\sum_{i=0}^{6} c_{1,i} X_{2,i} + \sum_{j=1}^{5} d_j IC_j} + \varepsilon$$

2) The parameters of the cutting indicator variables (i.e., the d_js) were tested for significant difference from 0 by the *t*-test. In this case, $P = 0.01$ was used in order to reduce the data removed in the next step.

3) If d_1 was significantly different from 0, those data were removed from the modeling data set. If d_2 was also significantly different from 0, those data also 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 had been 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 variations of the equations that included the *Scaled PBAL*$_1$ and the *PBAL*$_1$ variables were formed for Eq. [2]:

$$\Delta D_5 = e^{\sum_{i=0}^{7} b_{2,i} X_{2,i}} + \varepsilon \qquad [2.2]$$

where $X_{1,5} = [\textit{Scaled PBAL}_1]/[(1000)\ln(D_1 + 2.7)]$;

and

$$\Delta D_5 = e^{\sum_{i=0}^{7} + b_{3,i} X_{1,i}} + \varepsilon \qquad [2.3]$$

where $X_{1,5} = PBAL_1/[(1000)\ln(D_1 + 2.7)]$;

Two other base equations were similarly formed for Eq. [3]:

$$\Delta D_5 = e^{\sum_{i=0}^{6} c_{2,i} X_{2,i}} + \varepsilon \qquad [3.2]$$

where $X_{2,4} = [\textit{Scaled } PBAL_1]/[(1000)\ln(D_1 + 2.7)]$;

and

$$\Delta D_5 = e^{\sum_{i=0}^{6} c_{3,i} X_{2,i}} + \varepsilon \qquad [3.3]$$

where $X_{2,4} = PBAL_1/[(1000)\ln(D_1 + 2.7)]$

Eqs. [2.1], [2.2], and [2.3] were then fit to the final modeling data sets for Douglas-fir, grand/white firs, ponderosa pine, sugar pine, incense-cedar, California black oak, and Oregon white oak, and Eqs. [3.1], [3.2], and [3.3] were fit to the final modeling data sets for the remaining species. Parameters not significantly different from 0 at $P = 0.05$ or providing unreasonable predictive behavior were removed and the reduced equation was fit again to the final modeling data.

The predictive behaviors of Eqs. [2.1] and [3.1] for Douglas-fir, grand/white firs, ponderosa pine, incense-cedar, Pacific madrone, and golden chinkapin were then evaluated against the ΔD_5 equations of Hann and Larsen (1991). For a given species, ΔD_5s from both sets of equations were computed for each tree of that species in the modeling data set. $Pred\Delta D_5$ from Hann and Larsen (1991) was then subtracted from the $Pred\Delta D_5$ of Eqs. [2.1] or [3.1] and the differences were plotted across D_1, CR_1, SI, $SBAL_1$ and SBA_1. To allow better examination of the differences caused by the interaction of D_1 and $SBAL_1$, the data set for each species was divided into six $SBAL_1$ classes ($SBAL_1 = 0.0$, $0.0 < SBAL_1 \leq 50.0$, $50.0 < SBAL_1 \leq 100.0$, $100.0 < SBAL_1 \leq 200.0$, $200.0 < SBAL_1 \leq 300.0$, and $SBAL_1 > 300.0$) and the differences for each class were plotted across D_1.

Finally, the predictive ability of Eq. [2.1] for Douglas-fir was evaluated with the validation data set described in Table 4. $Pred\Delta D_5$ was computed for each tree in the validation data set and the difference, δ_i, between actual ΔD_5 and $Pred\Delta D_5$ was calculated. We then computed the following validation statistics, using $Pred\Delta D_5$ with $I_{Data} = 0$ and $Pred\Delta D_5$ with $I_{Data} = 1$:

$$\bar{\delta} = \sum_{i=1}^{m} \frac{\delta_i}{m}$$

$$MSE = \sum_{i=1}^{m} \frac{\delta_i^2}{m}$$

with bias $R_a^2 = 1.0 - \dfrac{MSE}{Var(\Delta D_5)}$

without bias $R_a^2 = 1.0 - \frac{[m/(m-1)][MSE - \bar{\delta}^2]}{Var(\Delta D_5)}$

where

$\bar{\delta}$ = mean difference

MSE = mean square error

R_a^2 = adjusted coefficient of determination

m = number of observations in the validation data set

$Var(\Delta D_5)$= estimated variance of actual $\Delta D_{5,i}$

$$= \frac{\sum_{i=1}^{m} \Delta D_{5,i}^2 - m(\overline{\Delta D_5})^2}{(m-1)}$$

where

$\overline{\Delta D_5}$ = mean of actual $\Delta D_{5,i}$

$$= \frac{\sum_{i=1}^{m} \Delta D_{5,i}}{m}$$

$\bar{\delta}$ is a measure of bias, and MSE is a measure of precision. It is desirable to have both values as near to 0 as possible. Both values of R_a^2 provide a measure of how well the regression equation fits the data. They measure the proportion of the variance about the mean of the dependent variable that is explained by the regression equation. A value = 1 for R_a^2 that includes possible bias would indicate both that the regression equation is unbiased and that it explains all of the variation in the validation data set. A value = 1 for R_a^2 that has possible bias removed indicates that the regression equation would explain all of the variation in the validation data set if the possible bias were removed. A negative value for either value of R_a^2 indicates that a mean ΔD_5 predicts better than the regression equation. It should be noted that if $\bar{\delta}$ were zero for a data set, R_a^2 with bias would be somewhat larger than R_a^2 without bias because the equation for the latter includes $m/(m-1)$, which is always >1. The validation statistics were computed for each of the five growth periods and for the combined data.

Impact of Damage on ΔD_5

The following process was used to examine whether or not damaging agents significantly change ΔD_5 of trees in the study area:

1) ΔD_5 equations were developed for those species combinations with adequate data from undamaged trees: Douglas-fir, grand/white firs, ponderosa pine, incense-cedar,

and Pacific madrone. Eqs. [2.1], [2.2], and [2.3] were fit to Douglas-fir, grand/white firs, ponderosa pine, and incense-cedar, and Eqs. [3.1], [3.2], and [3.3] were fit to Pacific madrone by weighted nonlinear regression.

2) For each species, $Pred\Delta D_5$ from the equations developed in the first step of the analysis was calibrated to each plot containing undamaged trees of that species in order to reduce variation caused by between-plot differences in the ΔD_5 relationship. This calibration was done by regressing each plot's undamaged ΔD_5 on $Pred\Delta D_5$. The regression model was

$$CPred\Delta D_{5,i,j} = \kappa_j(Pred\Delta D_{5,i})$$

where

$CPred\Delta D_{5,i,j}$ = $Pred\Delta D_{5,i}$ calibrated to the j^{th} plot,

i = 1 for Eqs. [2.1] and [3.1]

i = 2 for Eqs. [2.2] and [3.2]

i = 3 for Eqs. [2.3] and [3.3]

κ_j = undamaged tree plot-level calibration for the j^{th} plot, estimated by using weighted linear regression and the reciprocal of $Pred\Delta D_{5,i}$ as the weight.

The parameter κ_j was set = 1 unless there were more than three undamaged trees on the plot and the parameter was significantly different from 1 according to a *t*-test. In order to make plot-level calibration more frequent, $P = 0.10$ was used in the *t*-test.

3) The species-specific correction factors (CF) for a damaging agent and its severity were calculated by regressing the measured ΔD_5 for all trees with the damage to $CPred\Delta D_5$:

$$\Delta D_5 = \lambda_1(CPred\Delta D_5) + \lambda_2 I_s(CPred\Delta D_5)$$

where

ΔD_5= ΔD_5 for trees of a specified species that were damaged by a particular agent

λ_1 = CF for a particular type of damaging agent, regardless of severity

λ_2 = CF for a severe level of the particular type of damaging agent

I_s = 0 if damage is slight, or

= 1 if damage is severe.

The damaged-tree parameters λ_1 and λ_2 were estimated by using weighted linear regression with a weight of the reciprocal of $CPred\Delta D_5$. Then λ_1 and λ_2 were tested for significant differences from 1.0 and 0.0, respectively, with a *t*-test (P = 0.05). If both parameters were not significant, no *CF* was reported for the damaging agent. If both parameters were significant, λ_1 was reported as the *CF* for light damage, and $\lambda_1 + \lambda_2$ was reported as the *CF* for severe damage. If the parameter λ_1 was significant and parameter λ_2 was not, λ_1 was re-estimated by

$$D\Delta D_5 = \lambda_1 (CPred\Delta D_5)$$

fit to the combined light and severe damage data by using weighted linear regression. The resulting value for λ_1 was reported as the *CF* for both levels of severity. If λ_2 was significant and λ_1 was not, then the *CF* for light damage was set = 1.0 and λ_2 was re-estimated by

$$D\Delta D_5 = \lambda_2 (CPred\Delta D_5)$$

fit to just the severe damage data by using weighted linear regression. The resulting value λ_2 was reported as the *CF* for the severe level of damage.

RESULTS

ΔD_5 OF UNDAMAGED AND DAMAGED TREES COMBINED

Tables 5, 6, and 7 contain parameter estimates and associated standard errors for those tree species that were fit to Eqs. [2.1], [2.2], and [2.3], respectively, with data from undamaged and damaged trees combined. Tables 8, 9, and 10 contain parameter estimates and associated standard errors for those tree species that were fit to Eqs. [3.1], [3.2], and [3.3], respectively, using data from both undamaged and damaged trees. These tables also contain Furnival's (1961) index of fit (FIF) for each combination of species and type of equation. Because the fits to the equations used $Pred\Delta D_5$ as a weight, the resulting weighted MSEs are not comparable between equations or species. FIF adjusts for the differences in weights between equations and species; it is equal to MSE for unweighted fits (Furnival 1961). As with MSE, the smaller the FIF, the better is the fit to the data, with FIF = 0 indicating a perfect fit.

Seven of the 15 species or species groups had significant $SBAL_1$ parameters in Eqs. [2.1] or [3.1] (Table 5 or 8). For all seven, use of either $PBAL_1$ or scaled $PBAL_1$ did reduce FIF slightly when compared with use of $SBAL_1$. The reduction averaged 1.29% for the seven species groups, ranging from 0.12% (golden chinkapin) to 2.64% (sugar pine). For six of the seven (Douglas-fir, grand/white firs, ponderosa pine, sugar pine, golden chinkapin, and Pacific madrone), Eq. [2.3] or [3.3] with $PBAL_1$ was superior to Eq. [2.2] or [3.2] with *Scaled PBAL*$_1$, and Eq. [2.1] or [3.1] with *SBAL*$_1$ was superior to Eq. [2.2] or [3.2] with *Scaled PBAL*$_1$. Incense-cedar was the only species for which Eq. [2.3] with *PBAL*$_1$ did not provide the lowest FIF. In this case, Eq. [2.2] with *Scaled PBAL*$_1$ was superior to Eq. [2.3] with *PBAL*$_1$ and both of these were superior to Eq. [2.1] with *SBAL*$_1$.

If the *BAL*$_1$ parameter in Eqs. [2.1], [2.2], [2.3], [3.1], [3.2], or [3.3] was not significantly different from 0, the statistics for the species group are reported only for Eqs. [2.1] and [3.1] in Tables 5 and 8, respectively. The signs of the statistically significant parameters reported in Tables 5–10 met the expectations defined in the Data Analysis section.

The parameters for the data set indicator variable (i.e., $b_{1,7}$, $b_{2,7}$, $b_{3,7}$, $c_{1,6}$, $c_{2,6}$, and $c_{3,6}$) were significantly different from 0 at $P = 0.05$ for 7 of the 15 species groups (Douglas-fir, grand/white firs, sugar pine, California black oak, Oregon white oak, golden chinkapin, and Pacific madrone). In all cases, the ΔD_5 in the second measurement period was lower than that in the first, the reductions ranging from a little under 11% (Douglas-fir) to over 27% (golden chinkapin). Table 11 presents the validation statistics resulting from the use of Eq. [2.1] to predict the ΔD_5 of Douglas-fir trees in the validation data set.

Eq. [2.1] for Douglas-fir explained from 54% ($I_{Data} = 0$) to 71% ($I_{Data} = 1$) of the variation in the overall validation data. Eq. [2.1] also overpredicted ΔD_5 for both validation data sets, with the bias being larger when $I_{Data} = 0$ (as indicated by the larger negative values of $\hat{\delta}$. The validation statistics also indicate that setting $I_{Data} = 1$ produced predictions with greater precision (as indicated by small values of MSE) than setting it = 0. If the

Table 5. Parameter values, standard errors (in parentheses), and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [2.1], incorporating *SBAL*$_1$, to both damaged and undamaged trees.

Species	Parameters								FIF
	$b_{1,0}$	$b_{1,1}$	$b_{1,2}$	$b_{1,3}$	$b_{1,4}$	$b_{1,5}$	$b_{1,6}$	$b_{1,7}$	
Douglas-fir	-5.35558894 (0.1366281)	8.40528547 (0.3006902)	-4.27481848 (0.1385603)	1.15950313 (0.0210740)	9.54711126 (0.2459915)	-8.94779670 (0.2073946)	0.0 (NA)	-1.12227771 (0.1079423)	0.3356748
Grand/white fir	-5.84904111 (0.4225825)	16.68196109 (1.1101671)	-8.53271265 (0.5924395)	1.21222176 (0.0496326)	6.79346647 (0.7818602)	-8.09965733 (0.4927958)	0.0 (NA)	-1.36680538 (0.3040955)	0.3602551
Incense-cedar	-2.08551255 (0.4455922)	5.96043703 (1.04531814)	-2.15223077 (0.4138047)	1.02734556 (0.0706498)	3.83450822 (0.8061402)	-4.89046624 (1.0269417)	-6.09024782 (0.9989924)	0.0 (NA)	0.2897407
Ponderosa pine	-4.51958940 (0.5703402)	8.13998712 (1.5987874)	-4.93858858 (0.7074554)	1.10249641 (0.0856985)	8.79440023 (0.8845515)	-10.8521667 (1.2223842)	-3.33706948 (0.9708745)	0.0 (NA)	0.3201356
Sugar pine	-4.12342552 (0.7602989)	7.34988422 (1.9214983)	-4.25469735 (0.8415319)	1.05942163 (0.1131301)	8.08656390 (1.2987004)	-10.7837565 (1.5204740)	0.0 (NA)	-2.35340267 (0.7152572)	0.4763056
Black oak	-4.43438109 (0.8977771)	9.30930363 (3.1336642)	-4.65947242 (1.7351527)	0.0 (NA)	5.10717175 (1.2503912)	0.0 (NA)	-6.88832423 (1.3520610)	-2.62567955 (0.6874838)	0.1762429
White oak	-4.89465257 (0.8649736)	9.38718628 (2.9676617)	-4.73653133 (1.6517410)	0.0 (NA)	5.01587960 (1.1904031)	0.0 (NA)	-6.75936521 (1.3054874)	-2.73319673 (0.6555301)	0.1285795

NA: not applicable.

Table 6. Parameter estimates, standard errors (in parentheses), and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [2.2], incorporating *Scaled PBAL*$_1$, to both damaged and undamaged trees.

	Parameters								
Species	$b_{2,0}$	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	$b_{2,4}$	$b_{2,5}$	$b_{2,6}$	$b_{2,7}$	FIF
Douglas-fir	-5.26485430 (0.1349726)	8.14183086 (0.2978215)	-4.20015544 (0.1371996)	1.10729561 (0.0210867)	9.44636624 (0.2431232)	-8.59663252 (0.1882458)	0.0 (NA)	-1.23615817 (0.1061808)	0.3555496
Grand/white fir	-5.69855384 (0.4254606)	15.95012526 (1.1099103)	-8.15834097 (0.5887600)	1.22064868 (0.0493722)	6.76943567 (0.7856259)	-6.96451737 (0.4273319)	0.0 (NA)	-1.64373229 (0.2937536)	0.3597567
Incense-cedar	-1.99721314 (0.436728061)	5.74141749 (0.9299737)	-2.22687898 (0.4051642)	0.94279877 (0.0702515)	3.79210144 (0.7934265)	-5.76758383 (0.7337959)	-5.99456800 (0.7649484)	0.0 (NA)	0.2834671
Ponderosa pine	-4.76091177 (0.5591602)	9.32929837 (1.5328182)	-5.14463895 (0.7036230)	1.05925022 (0.0859506)	8.90584970 (0.8766881)	-8.62116345 (0.9508967)	-4.80490111 (0.8644790)	0.0 (NA)	0.3390921
Sugar pine	-4.24582940 (0.731527279)	7.90801893 (1.83018532)	-4.63750461 (0.8114541)	0.98324378 (0.1113381)	8.07271090 (1.2630020)	-11.2431331 (1.3617692)	0.0 (NA)	-1.67522477 (0.7099491)	0.4948463

NA: not applicable.

Table 7. Parameter estimates, standard errors (in parentheses), and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [2.3], incorporating *PBAL*$_1$, to both damaged and undamaged trees.

	Parameters								
Species	$b_{3,0}$	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	$b_{3,4}$	$b_{3,5}$	$b_{3,6}$	$b_{3,7}$	FIF
Douglas-fir	-5.38452018 (0.1352387)	8.49425833 (0.2982016)	-4.20210756 (0.1378741)	1.14881471 (0.0207993)	9.44672422 (0.2442046)	-8.12984627 (0.1815869)	0.0 (NA)	-1.38050581 (0.1063332)	0.3323374
Grand/white fir	-5.72778485 (0.4257523)	15.70118842 (1.1093881)	-7.93268245 (0.5861268)	1.22971456 (0.0487405)	6.87644884 (0.7888977)	-6.97785870 (0.4160757)	0.0 (NA)	-1.80475489 (0.2878256)	0.3589099
Incense-cedar	-2.18503419 (0.4368046)	6.36524409 (0.9053131)	-2.29341609 (0.4060259)	0.95300532 (0.07014670)	3.93172818 (0.7986180)	-5.27639705 (0.6731553)	-6.56646959 (0.7200358)	0.0 (NA)	0.2843044
Ponderosa pine	-4.74246220 (0.5575444)	9.49976221 (1.5164771)	-4.97595018 (0.6992749)	1.06746631 (0.0854926)	8.77381993 (0.8757971)	-8.39759128 (0.8940172)	-5.30678211 (0.8334569)	0.0 (NA)	0.3163858
Sugar pine	-4.21849640 (0.7386664)	7.94147160 (1.8460437)	-4.49262347 (0.8164860)	1.00709403 (0.1101728)	7.91320302 (1.2771148)	-10.4703947 (1.2842310)	0.0 (NA)	-2.20030363 (0.6912150)	0.4637272

NA: not applicable.

Table 8. Parameter estimates, standard errors (in parentheses), constants, and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [3.1], incorporating $SBAL_1$, to both damaged and undamaged trees.

Species	Parameters							Constants				FIF
	$c_{1,0}$	$c_{1,1}$	$c_{1,2}$	$c_{1,3}$	$c_{1,4}$	$c_{1,5}$	$c_{1,6}$	k_1	k_2	k_3	k_4	
Conifers												
Pacific yew	-9.15835863	1.0	1.16688474	0.0	0.0	-2.0	0.0	10.0	4000.0	35.0	4.0	0.396195
	(0.1898428)	(NA)	(0.4449597)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	
Western hemlock	-5.70052255	4.32543518	1.10859727	9.77332597	0.0	-5.26263229	0.0	2.0	5.0	1.0	1.0	0.387716
	(2.0183147)	(2.7143461)	(0.2471648)	(3.3603995)	(NA)	(1.2624650)	(NA)	(NA)	(NA)	(NA)	(NA)	
Hardwoods												
Bigleaf maple	-3.41449922	1.0	0.0	3.24349277	0.0	-9.89519477	0.0	10.0	10.0	5.0	1.0	0.309679
	(2.1824708)	(NA)	(NA)	(4.9718779)	(NA)	(2.5905360)	(NA)	(NA)	(NA)	(NA)	(NA)	
Canyon live oak	-3.59333060	1.0	0.51637418	0.0	0.0	-2.0	0.0	12.0	10.0	7.0	1.0	0.173958
	(0.1043920)	(NA)	(0.1612613)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	
Golden chinkapin	-7.78451344	1.0	0.0	10.1436101	-8.34323811	0.0	-3.20305926	12.0	10.0	7.0	1.0	0.238611
	(0.6788611)	(NA)	(NA)	(1.4899285)	(0.7142811)	(NA)	(0.5709665)	(NA)	(NA)	(NA)	(NA)	
Pacific madrone	-8.84531757	1.0	0.51225596	4.18129153	-3.55254593	-3.21315389	-2.32164709	15.0	110.0	6.0	2.0	0.212897
	(0.3318567)	(NA)	(0.0551296)	(0.7069547)	(0.5575168)	(0.6175323)	(0.2930116)	(NA)	(NA)	(NA)	(NA)	
Pacific dogwood/willow	-8.08352683	1.0	0.31176647	0.0	0.0	-7.30788052	0.0	10.0	4000.0	35.0	4.0	0.245972
	(0.5034763)	(NA)	(0.2910236)	(NA)	(NA)	(3.3203804)	(NA)	(NA)	(NA)	(NA)	(NA)	
Tanoak	-3.36821750	1.0	0.0	0.0	0.0	-3.39813575	0.0	12.0	10.0	7.0	1.0	0.232091
	(0.2140591)	(NA)	(NA)	(NA)	(NA)	(1.4731256)	(NA)	(NA)	(NA)	(NA)	(NA)	

NA: not applicable.

Table 9. Parameter estimates, standard errors (in parentheses), constants, and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [3.2], incorporating *Scaled* $PBAL_1$, to both damaged and undamaged trees.

	Parameters							Constants				
Species	$c_{2,0}$	$c_{2,1}$	$c_{2,2}$	$c_{2,3}$	$c_{2,4}$	$c_{2,5}$	$c_{2,6}$	k_1	k_2	k_3	k_4	FIF
Golden chinkapin	-7.87271938	1.0	0.0	10.3011451	-7.20566346	0.0	-3.44034747	12.0	10.0	7.0	1.0	0.2546330
	(0.6793686)	(NA)	(NA)	(1.4921861)	(0.6225582)	(NA)	(0.5702440)	(NA)	(NA)	(NA)	(NA)	
Pacific madrone	-8.85223157	1.0	0.46008161	4.20371443	-4.13211556	-3.23929225	-2.31021361	15.0	110.0	6.0	2.0	0.2184012
	(0.3279535)	(NA)	(0.0553826)	(0.6998883)	(0.4727882)	(0.5758516)	(0.2901171)	(NA)	(NA)	(NA)	(NA)	

NA: not applicable.

Table 10. Parameter estimates, standard errors (in parentheses), constants, and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [3.3], incorporating $PBAL_1$, to both damaged and undamaged trees.

	Parameters							Constants				
Species	$c_{3,0}$	$c_{3,1}$	$c_{3,2}$	$c_{3,3}$	$c_{3,4}$	$c_{3,5}$	$c_{3,6}$	k_1	k_2	k_3	k_4	FIF
Golden chinkapin	-8.00791772	1.0	0.0	10.47527082	-6.79924060	0.0	-3.51935769	12.0	10.0	7.0	1.0	0.2383327
	(0.6841590)	(NA)	(NA)	(1.5043207)	(0.6146045)	(NA)	(0.3256356)	(NA)	(NA)	(NA)	(NA)	
Pacific madrone	-8.84245390	1.0	0.44604911	4.18477592	-4.36175830	-3.39590383	-2.33606215	15.0	110.0	6.0	2.0	0.2094597
	(0.3272007)	(NA)	(0.0553998)	(0.6989219)	(0.4619868)	(0.5610190)	(0.2889857)	(NA)	(NA)	(NA)	(NA)	

NA: not applicable.

Table 11. Validation statistics for Douglas-fir Eq. [2.1], incorporating $SBAL_1$.

Data set	Growth period	m*	$\bar{\delta}$	MSE	R_a^2 With bias	R_a^2 Without bias
I_{Data} = 0.0						
Stampede Creek	All	248	-0.20	0.0934	0.6504	0.7940
	1973–1977	29	-0.26	0.0943	0.6904	0.9200
	1978–1982	60	-0.26	0.1204	0.6334	0.8385
	1983–1987	59	-0.26	0.1113	0.5462	0.8316
	1988–1992	54	-0.15	0.0600	0.7218	0.8288
	1993–1997	46	-0.03	0.0739	0.6771	0.6819
Fawn Saddle	All	388	-0.47	0.3819	0.2434	0.6881
	1987–1991	196	-0.24	0.1663	0.5065	0.6818
	1995–1999	192	-0.71	0.6020	-1.3071	0.6215
All	All	636	-0.37	0.2694	0.5358	0.7655
I_{Data} = 1.0						
Stampede Creek	All	248	-0.10	0.0687	0.7429	0.7812
	1973–1977	29	-0.14	0.0514	0.8312	0.8943
	1978–1982	60	-0.15	0.0855	0.7397	0.8117
	1983–1987	59	-0.17	0.0712	0.7097	0.8240
	1988–1992	54	-0.07	0.0471	0.7816	0.8052
	1993–1997	46	0.04	0.0798	0.6513	0.6589
Fawn Saddle	All	388	-0.26	0.2366	0.5313	0.6653
	1987–1991	196	-0.01	0.1109	0.6708	0.6709
	1995–1999	192	-0.52	0.3649	-0.3984	0.6354
All	All	636	-0.20	0.1711	0.7051	0.7724

* Number of observations in the validation data set.

bias could be removed, the amount of explained variation in the overall data set would increase to 77% for both values of I_{Data}.

Eq. [2.1] predicted ΔD_5 substantially better for the Stampede Creek LOGS data than for the Fawn Saddle SMC data. The average bias for each installation's overall data set was twice as large at Fawn Saddle than at Stampede Creek, and Eq. [2.1] explained only 24% of the variation, including bias, at Fawn Saddle, but 65% of the variation, including bias, at Stampede Creek.

The differences in Equation [2.1] caused by I_{Data} may indicate that the average growing conditions for the periods in the second data set better represent the average conditions for the 27 yr of data found in the validation data set than do the average growing conditions for the periods in the first data set. To explore this further, we also calculated the validation statistics for each of the five growth periods at Stampede Creek and the two growth periods at Fawn Saddle (Table 11). For the modeling data set, 51% of the first data set fell in Stampede Creek's 1978–1982 growth period, 27% of the second data set fell in Stampede Creek's 1988–1992 growth period, and 21% of the second data set fell in Fawn Saddle's 1987–1991 growth period. A total of 92% of the first modeling data set and 85% of the second modeling data set had at least 4 yr of their ΔD_5 from these three growth periods.

Impact of Damage on ΔD_5

Tables 12, 13, and 14 contain parameter estimates and associated standard errors for Douglas-fir, grand/white firs, ponderosa pine and incense-cedar fit to Eqs. [2.1], [2.2], and [2.3], respectively, using data from undamaged trees only. Table 15 contains parameter estimates and associated standard errors for Pacific madrone fit to Eqs. [3.1], [3.2], and [3.3], using data from undamaged trees only. These tables also contain FIF for each combination of species and type of equation.

Equations fit to undamaged trees resulted in parameter estimates that differed from those produced by fitting both undamaged and damaged trees to the same model forms. The following expansion of Eq. [2.1] was used to examine whether these differences were statistically significant for the largest data set (i.e., Douglas-fir):

$$\Delta D_5 = e^{b_{1,0}+\sum_{i=1}^{7} b_{1,i}X_{1,i}+\sum_{j=0}^{7} \varsigma_{1,j}X_{1,j+8}} + \varepsilon$$

where

$X_{1,8} = I_{Damage}$

I_{Damage} = 1 if the tree is damaged

= 0 otherwise

$X_{1,9} = (I_{Damage})(\ln(D_1 + 5)/10)$

$X_{1,10} = (I_{Damage})(D_1/100)$

$X_{1,11} = (I_{Damage})(\ln[(CR_1 + 0.2)/1.2])$

$X_{1,12} = (I_{Damage})(\ln(SI + 4.5)/10)$

$X_{1,13} = (I_{Damage})(SBAL_1/[(1000)\ln(D_1 + 2.7)])$

$X_{1,14} = (I_{Damage})(SBA_1^{1/2}/100)$

$X_{1,15} = (I_{Damage})(I_{Data}/10)$

The equation was fit to the combined undamaged and damaged data set with weighted nonlinear regression. The "ς" parameters are damaged-tree adjustments to the *b* parameters in the equation. If damaged trees have the same parameters as undamaged trees, then the "ς" parameters should be 0. They were, therefore, tested for significance from 0 by using a *t*-test and $P = 0.05$. The intercept adjustment parameter ($\varsigma_{1,0}$) and the adjustment pa-

Table 12. Parameter estimates, standard errors (in parentheses), and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [2.1], incorporating $SBAL_1$, to undamaged trees of the selected species.

Species	Parameters								FIF
	$b_{1,0}$	$b_{1,1}$	$b_{1,2}$	$b_{1,3}$	$b_{1,4}$	$b_{1,5}$	$b_{1,6}$	$b_{1,7}$	
Douglas-fir	-5.04273981 (0.1593252)	7.22746379 (0.3760587)	-3.63543901 (0.1854310)	1.07263875 (0.0246059)	9.33671721 (0.2774658)	-7.92066893 (0.2413612)	0.0 (NA)	-1.16622114 (0.1216995)	0.3494685
Grand/white firs	-5.58507554 (0.5339163)	15.08039139 (1.4744919)	-7.76716930 (0.8164566)	1.10457081 (0.0656161)	7.03585531 (0.9644012)	-8.15769829 (0.6392642)	0.0 (NA)	-0.86664435 (0.4270987)	0.3997447
Incense-cedar	-2.35540362 (0.5782756)	7.01289996 (1.4918842)	-2.90735613 (0.6962984)	0.85931315 (0.0940943)	3.91932262 (0.9799442)	-4.84181294 (1.3310519)	-5.93427999 (1.3490382)	0.0 (NA)	0.3341809
Ponderosa pine	-3.70319952 (0.6903080)	5.47350326 (2.0019894)	-3.95738031 (0.9617768)	1.12800757 (0.1145348)	8.23091566 (1.0428280)	-11.20443057 (1.6078674)	-2.20695372 (1.2087937)	0.0 (NA)	0.3302911

NA: not applicable.

Table 13. Parameter estimates, standard errors (in parentheses), and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [2.2], incorporating *Scaled* $PBAL_1$, to undamaged trees of the selected species.

Species	Parameters								FIF
	$b_{2,0}$	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	$b_{2,4}$	$b_{2,5}$	$b_{2,6}$	$b_{2,7}$	
Douglas-fir	-4.99424247 (0.1568618)	7.04136635 (0.3719445)	-3.61603751 (0.1835344)	1.01640267 (0.0246536)	9.30377640 (0.2734511)	-7.77346806 (0.2196864)	0.0 (NA)	-1.26120495 (0.1195958)	0.3670135
Grand/ white firs	-5.48607536 (0.5376146)	14.66700204 (1.4743724)	-7.56798075 (0.8153161)	1.10864458 (0.0661971)	6.99509072 (0.9700034)	-7.24858213 (0.5886500)	0.0 (NA)	-1.23247041 (0.4161622)	0.4017508
Incense-cedar	-2.45718895 (0.5664531)	7.08826180 (1.3492256)	-3.05073031 (0.6882958)	0.77398430 (0.0942312)	4.17819312 (0.9686206)	-5.45712341 (0.9253571)	-6.08039293 (0.9904196)	0.0 (NA)	0.3272917
Ponderosa pine	-3.87089026 (0.6832188)	6.33362804 (1.9506757)	-4.17221353 (0.9639399)	1.01643375 (0.1171273)	8.31952879 (1.0340411)	-9.51604363 (1.2842887)	-3.54701306 (1.0702113)	0.00.3519911 (NA)	

NA: not applicable.

Table 14. Parameter estimates, standard errors (in parentheses), and the Furnival's index of fit (FIF) for the nonlinear fits of Eq. [2.3], incorporating $PBAL_1$, to undamaged trees of the selected species.

Species	Parameters								FIF
	$b_{3,0}$	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	$b_{3,4}$	$b_{3,5}$	$b_{3,6}$	$b_{3,7}$	
Douglas-fir	-5.14542435 (0.1575401)	7.35982666 (0.3739219)	-3.60048451 (0.1847973)	1.06533619 (0.0243797)	9.39286662 (0.2755475)	-7.22576553 (0.2132954)	0.0 (NA)	-1.38754788 (0.1201922)	0.3469055
Grand/white firs	-5.52196638 (0.5371900)	14.06993056 (1.4721937)	-7.12946048 (0.8083090)	1.12193828 (0.0652024)	7.26505238 (0.9723398)	-7.28393988 (0.5767864)	0.0 (NA)	-1.42044227 (0.4059395)	0.4001395
Incense-cedar	-2.59486512 (0.5681082)	7.67414317 (1.3282828)	-2.99277976 (0.6878135)	0.78754247 (0.0943768)	4.25346500 (0.9758607)	-4.67609900 (0.8475819)	-6.94650528 (0.9190335)	0.0 (NA)	0.3284210
Ponderosa pine	-3.76731187 (0.6846605)	6.39766539 (1.9432111)	-3.82540531 (0.957726)	1.06742413 (0.1142291)	8.06405269 (1.0339032)	-8.94454686 (1.1883816)	-4.20176743 (1.0254675)	0.0 (NA)	0.3257620

NA: not applicable.

Table 15. Parameter estimates, standard errors (in parentheses), constants, and the Furnival's index of fit (FIF) for the non-linear fits of Eq. [3.1], incorporating $SBAL_1$; Eq. [3.2], incorporating *Scaled* $PBAL_1$; and Eq. [3.3], incorporating $PBAL_1$, to undamaged trees of Pacific madrone.

Equation	Parameters							Constants				FIF
	$c_{i,0}$	$c_{i,1}$	$c_{i,2}$	$c_{i,3}$	$c_{i,4}$	$c_{i,5}$	$c_{i,6}$	k_1	k_2	k_3	k_4	
[3.1], *i* = 1	-8.62445504	1.0	0.43302999	4.07933009	-1.85125546	-5.70730440	-1.72607868	15.0	110.0	6.0	2.0	0.2228891
	(0.5194669)	(NA)	(0.0898700)	(1.0958687)	(0.9216532)	(0.9464021)	(0.4463149)	(NA)	(NA)	(NA)	(NA)	
[3.2], *i* = 2	-8.61651605	1.0	0.41580853	4.09830833	-1.53753983	-5.99346455	-1.71675566	15.0	110.0	6.0	2.0	0.2262077
	(0.5200778)	(NA)	(0.0288100)	(1.0976832)	(0.7604133)	(0.8834421)	(0.4468369)	(NA)	(NA)	(NA)	(NA)	
[3.3], *i* = 3	-8.61254012	1.0	0.40261179	4.07111048	-2.00453165	-5.90092949	-1.75683410	15.0	110.0	6.0	2.0	0.2228232
	(0.5196914)	(NA)	(0.0913992)	(1.0977833)	(0.7460027)	(0.8644074)	(0.4468375)	(NA)	(NA)	(NA)	(NA)	

NA: not applicable.

rameter on the $SBAL_1/\ln(DBH_1 + 2.7)$ variable ($\varsigma_{1,5}$) for damaged trees were significantly different from 0. Therefore, inclusion of damaged trees in the modeling data set does significantly affect the estimated parameters of the resulting ΔD_5 equation.

Table 16 presents the number of sample trees observed with a given type and severity of damage for Douglas-fir, grand/white firs, ponderosa pine, incense-cedar, and Pacific madrone. Tables 17, 18, and 19 display the damage *CF*s for the equations containing $SBAL_1$ (Eqs. [2.1] and [3.1]), *Scaled* $PBAL_1$ (Eqs. [2.2] and [3.2]), and $PBAL_1$ (Eqs. [2.3] and [3.3]), respectively, that were significantly different from 1 (P = 0.05) for these species. The *CF* values for those type and severity-of-damage codes found in Table 16 but not in Tables 17, 18, and 19 were not significantly different from 1. For a tree with a particular *DC* and severity, ΔD_5 is predicted by multiplying the appropriate *CF* by ΔD_5 for an undamaged tree as predicted by Eqs. [2.1], [2.2], [2.3], [3.1], [3.2], or [3.3] and the parameters in Tables 12, 13, 14, or 15.

Fourteen damaging agents had a statistically significant impact on the ΔD_5 of one or more tree species (Tables 17, 18, and 19). Many of these damaging agents occurred relatively infrequently in both the sample trees (calculated excluding the trees' $EXPAN_1$) and in the sampled population (calculated including the trees' $EXPAN_1$) for the stands selected in the study (Table 20). Exceptions to this were suppression damage in small conifer trees (DC 61), which affected more than 7% of the ponderosa pine to nearly 24% of the incense-cedar in the sampled population, and severe lean (DC 75) in Pacific madrone, which affected nearly 29% of the sampled population.

For the conifer species examined, the damaging agents always reduced ΔD_5, whereas some of the significant damaging agents increased ΔD_5 for the one hardwood species examined. For severely damaged trees, the size of the reduction ranged from 6.34% for Pacific madrone with excessive lean (DC 75) to 67.06% for Douglas-fir with sparse or off-color needles (DC 74). Only one damaging agent, a dead or missing top (DC 72), caused a reduction in all species. Five of the damaging agents (DCs 61, 62, 71, 73, 75) were common to four of the species groups, and another four of the damaging agents (DCs 23, 24, 25, 32) were common to three of the species.

Of the common significant damaging agents, suppression (DCs 61 and 62) produced a reduction in ΔD_5 that was one of the largest for the conifer species, with average reductions >35% for small trees and >46% for large ones. With the exception of ponderosa pine, the reductions for severely damaged trees were greater for the larger trees (DC 62) than the smaller (DC 61). The most common damaging agent, a dead or missing top (DC 72), caused reductions for severely damaged trees that ranged from nearly 15% for Pacific madrone to more than 35% for grand/white firs.

Discussion

ΔD_5 of Undamaged and Damaged Trees Combined

In developing the original ΔD_5 equations, Hann and Larsen (1991) recognized the potential problem of using *SI* as a measure of productivity in uneven-aged stands. They therefore explored several alternative productivity variables, but found, contrary to Wykoff and Monserud (1988), that none of them were as useful as *SI*. Because of limiting computer hardware and software, however, they were not able to test directly whether *SI* was systematically underestimated in uneven-aged stands. Current computer technology has removed these limitations.

The results of this analysis indicate that, contrary to the concerns of Wykoff and Monserud (1988) and Monserud and Sterba (1996), reasonable *SI* measurements can be obtained in the uneven-aged stands of southwest Oregon. Our suggested method for determining *SI* in the even- and uneven-aged stands of southwest Oregon is described in the Appendix. We can think of three explanations for this result:

- These stands rarely exhibit a true "all-aged" structure. Instead, the stands are often composed of

Table 16. Number of trees damaged, by damage code (DC) and severity, for each major species.

DC	Severity*	Douglas-fir	Grand/white firs	Incense-cedar	Ponderosa pine	Pacific madrone
11	1	14	0	0	10	0
	2	4	4	0	3	0
22	1	130	13	4	0	1
	2	29	17	0	0	2
23	2	553	30	4	9	0
24	2	256	181	28	7	0
25	1	97	13	7	13	11
	2	26	18	4	0	8
31	1	0	0	1	0	0
	2	0	0	2	0	0
32	1	59	4	32	12	22
	2	42	9	25	2	39
42	1	0	0	0	11	0
	2	0	0	0	9	0
43	1	8	0	0	0	0
	2	2	0	0	2	0
51	1	0	1	0	1	0
	2	2	1	0	1	0
52	1	3	0	0	0	0
	2	10	0	0	0	0
53	1	36	28	0	4	3
	2	16	4	0	3	0
61	1	372	104	108	3	22
	2	193	55	29	15	21
62	1	90	32	40	2	12
	2	57	12	12	5	9
71	1	771	96	62	53	112
	2	123	27	15	7	30
72	1	576	82	48	62	22
	2	457	76	49	51	71
73	1	433	52	30	79	83
	2	178	28	9	53	11
74	1	28	3	4	14	19
	2	15	2	2	10	20
75	2	140	18	17	26	563
76	2	2	0	0	0	44
81	1	57	15	8	4	4
	2	7	3	1	0	1
82	1	24	7	9	0	4
	2	9	3	0	2	4
91	1	1	0	0	0	0
	2	3	0	0	3	7

* 1 = light damage; 2 = severe damage.

Table 17. Damage correction factors and standard errors (in parentheses), by damage code (DC), for Eqs. [2.1] and [3.1], both incorporating $SBAL_1$.

		Damage level	
Species	DC	Light	Severe
Douglas-fir	23	NA (NA)	0.8087 (0.0192)
	24	NA (NA)	0.8281 (0.0320)
	25	0.9007 (0.0416)	0.6930 (0.0960)
	32	0.8075 (0.0492)	0.8075 (0.0492)
	61	0.6499 (0.0193)	0.6499 (0.0193)
	62	0.6273 (0.0462)	0.4715 (0.0350)
	71	1.0000 (NA)	0.8052 (0.0465)
	72	0.8361 (0.0177)	0.6841 (0.0251)
	73	0.8474 (0.0166)	0.8474 (0.0166)
	74	1.0000 (NA)	0.3294 (0.0614)
	75	NA (NA)	0.7967 (0.0494)
Grand/white fir	23	NA (NA)	0.7613 (0.0966)
	24	NA (NA)	0.7890 (0.0300)
	32	0.5658 (0.0691)	0.5658 (0.0691)
	53	0.8368 (0.0778)	0.8368 (0.0778)
	61	0.6969 (0.0368)	0.6969 (0.0368)
	62	0.4589 (0.0359)	0.4589 (0.0359)
	71	1.0000 (NA)	0.7542 (0.1093)
	72	0.8543 (0.0461)	0.6468 (0.0574)
	73	1.0000 (NA)	0.8458 (0.0703)
	75	NA (NA)	0.5939 (0.1430)
Incense-cedar	61	0.6984 (0.0421)	0.6984 (0.0421)
	62	0.5639 (0.0696)	0.5639 (0.0696)
	71	1.0000 (NA)	0.7037 (0.0894)
	72	0.7617 (0.0433)	0.7617 (0.0433)
Ponderosa pine	23	NA (NA)	0.6275 (0.1436)
	24	NA (NA)	0.5720 (0.1370)
	25	0.7843 (0.0821)	0.7843 (0.0821)
	32	0.6916 (0.1009)	0.6916 (0.1009)
	42	0.7631 (0.0862)	0.7631 (0.0862)
	61	0.5413 (0.0716)	0.5413 (0.0716)
	62	0.6150 (0.1206)	0.6150 (0.1206)
	72	1.0000 (NA)	0.8339 (0.0670)
	73	1.0000 (NA)	0.8372 (0.0480)
	75	NA (NA)	0.7358 (0.1102)
Pacific madrone	25	0.7573 (0.0940)	0.7573 (0.0940)
	71	1.1540 (0.0575)	1.1540 (0.5750)
	72	0.8533 (0.0574)	0.8533 (0.0574)
	73	1.1724 (0.0509)	1.1724 (0.0509)
	74	0.7788 (0.0857)	0.7788 (0.0857)
	75	NA (NA)	0.9366 (0.0241)
	76	NA (NA)	1.2893 (0.1303)

NA: Not applicable.

Table 18. Damage correction factors and standard errors (in parentheses), by damage code (DC), for Eqs. [2.2] and [3.2], both incorporating *Scaled* $PBAL_1$.

		Damage level	
Species	DC	Light	Severe
Douglas-fir	23	NA (NA)	0.8225 (0.0197)
	24	NA (NA)	0.8408 (0.0310)
	25	0.9092 (0.0398)	0.7041 (0.0952)
	32	0.8120 (0.0509)	0.8120 (0.0509)
	61	0.6629 (0.0194)	0.6629 (0.0194)
	62	0.6454 (0.0470)	0.4925 (0.0355)
	71	1.0000 (NA)	0.8150 (0.0482)
	72	0.8400 (0.0177)	0.6830 (0.0251)
	73	0.8742 (0.0197)	0.7887 (0.0304)
	74	1.0000 (NA)	0.3369 (0.0687)
	75	NA (NA)	0.7992 (0.0492)
Grand/white fir	24	NA (NA)	0.7766 (0.0293)
	32	0.6207 (0.0720)	0.6207 (0.0720)
	61	0.7122 (0.0403)	0.7122 (0.0403)
	62	0.4994 (0.0468)	0.4994 (0.0468)
	71	1.0000 (NA)	0.7516 (0.1072)
	72	0.8649 (0.0470)	0.6365 (0.0584)
	73	1.0000 (NA)	0.8441 (0.0688)
	75	NA (NA)	0.5860 (0.1350)
Incense-cedar	61	0.7288 (0.0451)	0.7288 (0.0451)
	62	0.5769 (0.0711)	0.5769 (0.0711)
	71	1.0000 (NA)	0.6599 (0.0860)
	72	0.7444 (0.0428)	0.7444 (0.0428)
Ponderosa pine	23	NA (NA)	0.6091 (0.1509)
	24	NA (NA)	0.5518 (0.1283)
	25	0.7912 (0.0816)	0.7912 (0.0816)
	32	0.6943 (0.1052)	0.6943 (0.1052)
	42	0.7800 (0.0845)	0.7800 (0.0845)
	61	0.5309 (0.0754)	0.5309 (0.0754)
	62	0.5438 (0.1468)	0.5438 (0.1468)
	72	1.0000 (NA)	0.8142 (0.0625)
	73	1.0000 (NA)	0.8032 (0.0451)
	74	0.7937 (0.0977)	0.7937 (0.0977)
	75	NA (NA)	0.6732 (0.0970)
Pacific madrone	25	0.7503 (0.0926)	0.7503 (0.0926)
	71	1.1484 (0.0566)	1.1484 (0.0566)
	72	0.8499 (0.0565)	0.8499 (0.0565)
	73	1.1717 (0.0508)	1.1717 (0.0508)
	74	0.7795 (0.0845)	0.7795 (0.0845)
	75	NA (NA)	0.9353 (0.0240)
	76	NA (NA)	1.2850 (0.1262)

NA: Not applicable.

Table 19. Damage correction factors and standard errors (in parentheses), by damage code (DC), for Eqs. [2.3] and [3.3], both incorporating $PBAL_1$.

Species	DC	Damage level	
		Light	Severe
Douglas-fir	23	NA (NA)	0.8515 (0.0202)
	24	NA (NA)	0.8585 (0.0315)
	25	0.8803 (0.0379)	0.8803 (0.0379)
	32	0.8610 (0.0509)	0.8610 (0.0509)
	61	0.6631 (0.0193)	0.6631 (0.0193)
	62	0.6533 (0.0472)	0.4960 (0.0360)
	71	1.0000 (NA)	0.8183 (0.0475)
	72	0.8401 (0.0176)	0.6878 (0.0255)
	73	0.8798 (0.0200)	0.8033 (0.0309)
	74	1.0000 (NA)	0.3596 (0.0747)
	75	NA (NA)	0.7876 (0.0480)
Grand/white fir	24	NA (NA)	0.8713 (0.0345)
	32	0.6627 (0.0862)	0.6627 (0.0862)
	61	0.7390 (0.0440)	0.7390 (0.0440)
	62	0.5056 (0.0458)	0.5056 (0.0458)
	72	0.8902 (0.0490)	0.6496 (0.0601)
	73	1.0000 (NA)	0.8494 (0.0661)
	75	NA (NA)	0.6213 (0.1522)
Incense-cedar	61	0.7305 (0.0448)	0.7305 (0.0448)
	62	0.5910 (0.0713)	0.5910 (0.0713)
	71	1.0000 (NA)	0.6658 (0.0869)
	72	0.7459 (0.0413)	0.7459 (0.0413)
Ponderosa pine	24	NA (NA)	0.5702 (0.1121)
	32	0.6965 (0.1114)	0.6965 (0.1114)
	42	0.7665 (0.0872)	0.7665 (0.0872)
	61	0.5442 (0.0822)	0.5442 (0.0822)
	72	1.0000 (NA)	0.8370 (0.0679)
	73	1.0000 (NA)	0.8078 (0.0446)
	74	0.7762 (0.0958)	0.7762 (0.0958)
	75	NA (NA)	0.6628 (0.1038)
Pacific madrone	25	0.7550 (0.0923)	0.7550 (0.0923)
	71	1.1482 (0.0564)	1.1482 (0.0564)
	72	0.8587 (0.0564)	0.8587 (0.0564)
	73	1.1668 (0.0498)	1.1668 (0.0498)
	74	0.7789 (0.0841)	0.7789 (0.0841)
	75	NA (NA)	0.9424 (0.0241)
	76	NA (NA)	1.2767 (0.1254)

NA: Not applicable.

Table 20. Percentage of significant damage codes (DCs) in the sample trees and in the sampled population.

Species	DC	% of	
		Sample trees	Sampled population
Douglas-fir	0	60.25	57.36
	23	4.46	1.07
	24	2.06	0.86
	25	0.99	1.39
	32	0.81	0.14
	61	4.56	12.99
	62	1.19	1.36
	71	7.21	7.82
	72	8.33	6.94
	73	4.93	3.56
	74	0.35	0.49
	75	1.13	2.27
Grand/white fir	0	49.80	49.36
	23	1.54	0.34
	24	9.27	1.62
	32	0.67	0.11
	53	1.64	0.90
	61	8.15	20.79
	62	2.25	2.68
	71	6.30	6.96
	72	8.09	8.94
	73	4.10	2.32
	75	0.92	1.25
Incense-cedar	0	54.86	54.69
	61	10.74	23.92
	62	4.08	2.99
	71	6.03	4.56
	72	7.60	5.65
Ponderosa pine	0	51.74	52.79
	23	0.89	0.20
	24	0.70	0.67
	25	1.29	1.01
	32	1.39	0.17
	42	1.99	3.02
	61	1.79	7.10
	62	0.70	1.14
	72	11.22	8.32
	73	13.11	8.28
	75	2.58	3.68
Pacific madrone	0	39.24	44.22
	25	0.99	0.75
	71	7.38	7.17
	72	4.83	5.48
	73	4.89	2.69
	74	2.03	2.44
	75	29.26	28.64
	76	2.29	1.93

small, even-aged clumps or groups (particularly of ponderosa pine), which may allow height growth in the trees within the group similar to that in even-aged stands.

- The criteria that Hann and Scrivani (1987) used for selecting "site quality" trees included inspection of the increment core from the tree to detect irregular radial growth patterns caused by previous suppression or damage. Monserud (1984, 1988) thought that this type of criterion would help to minimize the measurement of inappropriate *SI* trees in "irregular" stands.

- Even with inspection of the increment cores before felling, Hann (1998) found that the height growth pattern for dominant, older (150–450 yr old or more at breast height) Douglas-fir trees showed that many had experienced early suppression of height growth. However, these trees also had substantially accelerated their height growth rate once freed from suppression. As a result, they were able to recover the height lost from that early suppression and, therefore, to exhibit increasing *SI* over time.

Our analysis of the effects of cutting indicates that, of the 15 data sets yielding a significant ΔD_5 equation, only three species or species-groups had significant *YCUT* indicator variables: Douglas-fir, grand/white firs, and ponderosa pine. When significant, the signs of the parameters were always positive, indicating that trees from recently cut stands had larger ΔD_5 than would be expected for trees from uncut stands with the same tree and stand attributes. The increase in ΔD_5 in cut stands was largest in the first 5-yr period after cutting, and the size of the increase declined as time since cutting increased. Total duration of the cutting impact was 15 yr for the three species or species groups. These findings agree with those of Hann et al. (in press).

In general, the larger sample produced by adding the hardwood and older-stand data from the second data collection resulted in more species with significant ΔD_5 models and more significant parameters for each species than were available to Hann and Larsen (1991). Equations are now available for Pacific yew, Pacific dogwood, and willow. Therefore, it may be possible to extend SWO-ORGANON to include these species.

Hann and Larsen (1991) reported that the parameter for *SI* was not significantly different from 0 for incense-cedar, Pacific madrone, and bigleaf maple. In the new equations, the *SI* parameter is now significant for these species. Two species, canyon live oak and tanoak, that had an *SI* parameter in the equations of Hann and Larsen (1991) no longer have one in the new equations. In the original fits, both of these species had been combined with other species that exhibited much stronger *SI* effects. As a result of these changes, only four species groups do not have a *SI* term in the new equations: canyon live oak, tanoak, Pacific yew, and Pacific dogwood/willow.

The expanded data set also made it possible to fit more species-specific equations. In the equations of Hann and Larsen (1991), tanoak was combined with golden chinkapin, and California black oak, Oregon white oak, and canyon live oak had common parameters except for the intercept. In the new equations, separate equations were fit for golden chinkapin, tanoak, California black oak, and canyon live oak. Oregon white oak was again fit by using an intercept correction to a combined California black oak and Oregon white oak data set.

The initial basal area per acre in larger trees (BAL_1) variables (i.e., $SBAL_1$, $PBAL_1$, and *Scaled* $PBAL_1$) are measures of the amount of one-sided competition for light, and the SBA_1 variable is a measure of two-sided competition for water and nutrients. Therefore, the relative size of the parameters for the BAL_1 variables and SBA_1 indicates how much each may be limiting ΔD. Species groups that include just a BAL_1 variable (Douglas-fir, grand/white firs, sugar pine, and golden chinkapin) are directly responding only to competition from larger trees. Species groups that include just SBA_1 (western hemlock, Pacific yew, California black oak, Oregon white oak, big leaf maple, canyon live oak, tanoak, and Pacific-dogwood/willow) are directly responding to competition from all trees, regardless of their position in the stand. Finally, species groups that include both a BAL_1 variable and SBA_1 (ponderosa pine, incense-cedar, and Pacific madrone) are directly responding most strongly to competition from larger trees and less strongly to competition from smaller trees in the stand.

This interpretation of the direct response to competition is tempered by the response of *CR* to type of competition. In the revised SWO-ORGANON, change in *CR* will be predicted from the *HCB* equations for undamaged trees given by Hanus et al. (2000). Many of the species group equations in Hanus et al. (2000) include crown competition factor in larger trees (*CCFL*), basal area per acre (*BA*), or both. *CCFL* is another measure of one-sided competition, and including *CCFL*, *BA*, or both in these equations increases *HCB* as either one increases, which reduces *CR*.

The *HCB* equations for 7 of the 10 species groups that include *CR* in their ΔD_5 equations incorporate *CCFL*, *BA*, or both. Equations for Douglas-fir, grand/white firs, incense-cedar, sugar pine, and Pacific dogwood/willow included both variables; ponderosa pine and Pacific madrone included only *BA*. Therefore, inclusion of *BA* in the *HCB* equations for Douglas-fir, grand/white firs, and sugar pine will result in an indirect ΔD_5 response to competition from smaller trees, and the inclusion of *CCFL* in the *HCB* equation for Pacific-dogwood/willow will result in an indirect ΔD_5 response to competition from larger trees. The two species that include only *BA* in their *HCB* equations will show an enhanced ΔD_5 response, both direct and indirect, to the level of two-sided competition in the stand.

The significant differences we found in ΔD_5 between the two measurement periods (as indicated by I_{Data}) might be due in part to fluctuations in climate between the measurement periods. Wensel and Turnblom (1998) and Yeh and Wensel (2000) have shown that variation in growth rates of Douglas-fir, white fir, red fir, ponderosa pine, sugar pine, and incense-cedar over time in northern California are related to variations in precipitation and temperature. These differences also may be caused by variations in the level of endemic insect or disease attacks (Edmonds et al. 2000) or other factors.

Eqs. [2.1], [2.2], [2.3], [3.1], [3.2], and [3.3] produce predictions of ΔD_5 that behave quite differently from the equations of Hann and Larsen (1991). For example, the maximum ΔD_5 for all species from Eqs. [2.1] and [3.1] (with $I_{Data} = 0$) occurs at substantially smaller D_1s than do the peaks from the Hann and Larsen (1991) equation, and the maximum ΔD_5s are substantially smaller for all species except Oregon white oak and California black oak (Table 21). These examples of the peak and size differences in maximum ΔD_5 were calculated by setting $SI = 100$, $CR_1 = 1$, $SBAL_1 = 0$, and SBA_1 = the tree's basal area (i.e., $0.005454154[D_1^2]$).

The major differences between the new equations and those of Hann and Larsen (1991) are in the form of the variables incorporating D_1 and the three expressions of BAL_1. A more detailed comparison of the predictions from Eqs. [2.1] and [3.1] to those from the equations in Hann and Larsen (1991) indicated that the largest differences in predictions were usually caused by these changes. The following is a general description of how using the new equations affects $Pred\Delta D_5$ for the species examined:

- for Douglas-fir, grand fir, and white fir:
  - $Pred\Delta D_5$ of trees with large $SBAL_1$ ($\geq$200 ft²/ac) is larger, regardless of the size of D_1.
  - $Pred\Delta D_5$ of trees with small $SBAL_1$ ($\leq$50 ft²/ac) is larger if D_1 is either small ($\leq$10 in.) or large ($\geq$50 in.).

Table 21. Comparison of the predicted maximum ΔD_5 from Eqs [2.1] and [3.1], both incorporating $SBAL_1$, to the predicted maximum ΔD_5 from the equations of Hann and Larsen (1991). Predicted maximum ΔD_5 was computed by setting $SI = 100$, $CR_1 = 1.0$, $SBAL_1 = 0.0$, and $SBA_1 = 0.005454154D_1^2$.

	Maximum ΔD_5		D where ΔD_5 peaks	
Species	1991	Eqs. [2.1] and [3.1]	1991	Eqs. [2.1] and [3.1]
		Conifers		
Douglas-fir	2.58	2.14	21.8	14.7
Grand/white fir	2.27	2.29	18.7	14.6
Incense-cedar	2.97	2.86	31.4	22.7
Ponderosa pine	5.97	3.24	27.1	11.5
Sugar pine	3.77	2.46	26.4	12.3
Western hemlock	1.82	2.26	23.0	15.0
		Hardwoods		
Bigleaf maple	1.89	1.63	13.7	10.0
California black oak	0.38	0.70	22.0	15.0
Canyon live oak	0.47	0.50	22.0	7.1
Golden chinkapin	0.74	0.57	13.1	7.1
Oregon white oak	0.27	0.43	22.0	14.8
Pacific madrone	1.16	0.93	15.5	10.4
Tanoak	0.74	0.62	13.1	7.1

- for ponderosa pine:
  - $Pred\Delta D_5$ of trees with large $SBAL_1$ ($\geq$200 ft^2/ac) is smaller, regardless of the size of D_1.
  - $Pred\Delta D_5$ of trees with small $SBAL_1$ ($\leq$50 ft^2/ac) is larger if D_1 is small ($\leq$5 in.) and smaller if D_1 is large ($\geq$20 in.).
- for incense-cedar:
  - $Pred\Delta D_5$ of trees with large $SBAL_1$ ($\geq$200 ft^2/ac) is smaller if D_1 is small ($\leq$6 in.).
  - $Pred\Delta D_5$ of trees with small $SBAL_1$ ($\leq$50 ft^2/ac) is larger if D_1 is small or medium ($\leq$40 in.).
- for Pacific madrone:
  - $Pred\Delta D_5$ of trees with large D_1 ($\geq$20 in.) is smaller, regardless of $SBAL_1$.
  - $Pred\Delta D_5$ of trees with large $SBAL_1$ ($\geq$200 ft^2/ac) is smaller, regardless of the size of D_1.
- for golden chinkapin:
  - $Pred\Delta D_5$ of trees with large $SBAL_1$ ($\geq$200 ft^2/ac) is larger, regardless of the size of D_1.
  - $Pred\Delta D_5$ is larger in trees with a short CR_1 ($\leq$0.25) and smaller in trees with a long CR_1 ($\geq$0.75).

Part of the overprediction for the Fawn Saddle validation data may be due to the difficulty in estimating *SI* in young plantations (Hann et al., in press). In our experience, *SI* estimates are often overpredicted in very young plantations, with the predictions declining as the plantation ages. The estimated *SI* at Fawn Saddle was higher than in any of the plots measured in this study (Table 2). *SI* in 1990 was estimated to be 153.6 ft, dropping in 1998 to 149.7 ft.

If the I_{Data} relationship found in the modeling data set is also manifest in the validation data, Eq. [2.1] should perform better on the Stampede Creek 1978–1982 data with I_{Data} = 0, and Eq. [2.1] with I_{Data} = 1 should perform better on both the 1988–1992 data from Stampede Creek and 1987–1991 data from Fawn Saddle. This is true for both of the latter cases, but it is not true for the 1978–1982 data from Stampede Creek. Furthermore, the period-by-period validation statistics indicate that it was only in one growth period (1993–1997 at Stampede Creek) that setting I_{Data} = 0 produced a smaller bias and a higher level of precision than setting I_{Data} = 1. Therefore, the differences in the two components of the modeling data, as indicated by I_{Data}, are not found in the validation data. Given these findings, we recommend that the ΔD_5 equations reported in this study be used with I_{Data} = 1. The resulting projections of future ΔD_5 will be lowered and, therefore, conservative.

Based on the *YCUT* analysis, the ΔD_5 equations for incense-cedar, Pacific yew, sugar pine, western hemlock, and all hardwood species can be applied to unthinned stands and to all thinned stands, regardless of the amount of time since thinning. The ΔD_5 equations for Douglas-fir, grand fir, white fir, and ponderosa pine can be applied to unthinned stands and to stands thinned more than 15 yr in the past. Estimates of ΔD_5 for Douglas-fir trees in more recently thinned stands can be obtained by applying the thinning modifier developed for Douglas-fir by Hann et al. (in press) to the Douglas-fir equations produced in this study. An examination of the parameter estimates and associated standard errors on the *YCUT* indicator variables (IC_1, IC_2 ,..., IC_5) for the four species indicates that grand fir, white fir, and ponderosa pine responded to cutting similarly to Douglas-fir. Therefore, we recommend using the Douglas-fir thinning modifier of Hann et al. (in press) for grand fir, white fir, and ponderosa pine as well.

Impact of Damage on ΔD_5

Trees affected by many of the damaging agents had significantly different *H* (Hanus et al. 1999) and *HCB* (Hanus et al. 2000) from that of undamaged trees. Table 22 summarizes the effect on *H* and *HCB* of those damaging agents found to affect ΔD_5 significantly for the five species groups examined in this study. All of the damaging agents either increased or did not affect *HCB*, and most of the damaging agents either reduced or did not affect *H*.

In three of the species groups (Douglas-fir, incense-cedar, and ponderosa pine), *H* was larger in trees with DC 61. Because *CR* is a function of *H* and *HCB*, changes in these values can change *CR*. *CR* will decrease in all situations in which there is an increase in *HCB*, a reduction in *H*, or both. Where *H* increases, *CR* may increase or decrease, depending on the size of the relative increase in *H* versus the size of the relative increase in *HCB*. Therefore, the fact that many of these damaging agents were significant in this study indicates that the ΔD_5 reduction is attributable to more than a possible change in CR_1.

Reductions in ΔD_5 can be caused by several alterations resulting from damage, including loss of

- vertical position within the stand, leading to increased shading
- photosynthetically efficient crown
- xylem, phloem, cambium, or all three, needed for conducting moisture, mineral salts and photosynthate
- nutrients and moisture to parasites.

The damaging agents that significantly reduced D_5 in the five species examined can be related to one or more of these losses.

Loss of Vertical Position Within the Stand

The vertical position of the tree top within the stand can affect the intensity of light striking the crown and, therefore, the amount of photosynthate produced by the crown.

Table 22. Effects of selected damaging agents on *H* (Hanus et al. 1999) and *HCB* (Hanus et al. 2000). The damaging agents selected were those affecting ΔD_5 for the species. A ranking of 1 indicates the largest reduction or increase.

		H		*HCB*	
Species	Damage code	Effect	Rank of effect	Effect	Rank of effect
Douglas-fir	23	Reduction	6	Increase	8
	24	Reduction	4	Increase	10
	25	No change	NA	Increase	5
	32	Reduction	2	Increase	6
	61	Increase	1	Increase	2
	62	No change	NA	Increase	1
	71	Reduction	5	Increase	9
	72	Reduction	1	Increase	4
	73	Reduction	3	Increase	11
	74	No change	NA	Increase	3
	75	No change	NA	Increase	7
Grand/white fir	23	No change	NA	Increase	6
	24	Reduction	6	Increase	7
	32	Reduction	1	Increase	4
	53	No change	NA	No change	NA
	61	No change	NA	Increase	2
	62	No change	NA	Increase	1
	71	Reduction	4	Increase	8
	72	Reduction	2	Increase	5
	73	Reduction	5	Increase	9
Incense-cedar	61	Increase	1	Increase	3
	62	No change	NA	Increase	2
	71	No change	NA	Increase	4
	72	Reduction	1	Increase	1
Ponderosa pine	23	No change	NA	No change	NA
	24	No change	NA	No change	NA
	25	No change	NA	No change	NA
	32	No change	NA	No change	NA
	42	Reduction	2	No change	NA
	61	Increase	1	Increase	3
	62	No change	NA	Increase	1
	72	Reduction	1	Increase	2
	73	Reduction	3	Increase	4
	75	No change	NA	No change	NA
Pacific madrone	25	No change	NA	No change	NA
	71	No change	NA	No change	NA
	72	Reduction	1	Increase	1
	73	Reduction	3	Increase	3
	74	No change	NA	Increase	2
	75	Reduction	4	Increase	4
	76	Reduction	2	No change	NA

NA: Not applicable.

By definition, trees in the suppressed crown class are shorter than trees in the dominant crown class (Oliver and Larson 1996). Therefore, trees classed as having suppression damage (DCs 61, 62) should also have an inferior vertical position within the stand. Similarly, a dead or missing top (DC 72) or a severe lean (DC 53 or 75) will cause the top of the tree to be in an inferior vertical position. In conifers, forking (DCs 73, 76) results from past height damage and would, therefore, also place a top in an inferior vertical position. When measurement crews indicated multiple damage codes, over two-thirds of the trees with conks (DC 23) as their primary damage also had a secondary DC of 72, 73, or 76, indicating that loss of vertical position may partially explain the reduction in ΔD_5 for trees with conks.

In a hardwood species, forking may indicate that the tree has a broader crown than usual for its *CR.* A broad crown can result in greater leaf area and, therefore, a larger than expected ΔD_5 for the *CR.*

Loss of Photosynthetically Efficient Crown

Because of the reported photosynthetic inefficiency for the lower portions of the crown (Labyak and Schumacher 1954; Stein 1955; Staebler 1963; Barrett 1968; Woodman 1971), the loss of the top of the crown (DC 72) would result in lower production of photosynthate than in an undamaged tree with the same *H* and *HCB*. Frosts (DC 53), which can cause problems in southwest Oregon (Stein 1981, 1986), can kill young needles and shoots (Miller 1993), the most photosynthetically efficient leaves at any vertical position within the crown (Mitchell 1975). Short, sparse, or off-color leaves (DCs 61, 62, 74) are indicators of reduced photosynthetic efficiency of the crown. Dwarf mistletoes can kill branches and tops within the crown (Edmonds et al. 2000). Finally, several needle diseases (DC 25), such as needle blights, rusts, and casts, can kill needles, and annual cankers (DC 25) can result in dieback of the tips of twigs and branches (Scharpf 1993; Bega and Scharpf 1993; Smith and Scharpf 1993; Edmonds et al. 2000).

Loss of Xylem, Phloem and/or Cambium

Direct loss of xylem, phloem, cambium, or all three, can be caused by fire scarring (DC 32), porcupines (DC 42), and rolling rocks and logs and abrasion between trees (DC 71). Root diseases (DC 23) can also cause the loss of conductive tissue (Smith 1993; Edmonds et al. 2000).

Loss of Nutrients and Moisture to Parasites

Numerous species of dwarf mistletoe infect tree species found in southwest Oregon, causing growth reductions, mortality, and loss in wood quality (Scharpf and Hawksworth 1993). Growth reduction can be substantial and is caused by the parasitic nature of dwarf mistletoes (Scharpf and Hawksworth 1993).

These factors probably do not express all of the mechanisms by which damaging agents affect the ΔD of trees. Each damage code used in this study often included many damaging agents, and some of the damage codes have vague definitions.

An example of the latter are the suppression damage codes (61 and 62). Not all trees given a crown classification of "suppressed" by the field crews also received a suppression damage code, and not all trees given a suppression damage code had crown classifications of "suppressed" (Table 23). Suppression damage is usually characterized by extremely short or nonexistent internodes; twisted, gnarled stems; short, flat crowns of live needles forming "umbrella-shaped" trees; or an extreme sparseness of foliage (Hanus et al. 2000). Therefore, suppression damage may indicate something more than just loss of vertical position, as indicated by the suppressed crown class, or sparse foliage. The application of the suppression damage codes may be the field crews' way of saying "This is a very poor quality tree with many problems, including suppression."

This analysis indicates that damaging agents can significantly impact ΔD_5. As a result, damaging agents can lead to diversification in stand structure. The presence and frequency of trees affected by damaging agents are expected to vary by stand structure (primarily species mix) and to vary geographically and chronologically for a given stand structure. Many of the significant damaging agents were encountered relatively infrequently, but the number of different damaging agents encountered was relatively large (i.e., Table 21 indicates that the percentage of undamaged trees in the sampled population ranged from 44% for Pacific madrone to 57% for Douglas-fir), and the long duration of most stands increases the exposure to damaging agents.

We believe that a full characterization of stand development should include the prediction of the presence and frequency of the various damaging agents within the stand (including severity of damage) and their subsequent impact on tree attributes such as *H*, *HCB*, ΔD, height growth rate, and mortality rate. Unfortunately, the long-term data on the characterization and dynamics of damaging agents that are needed to develop such prediction equations are not now available. We recommend, therefore, that a determined effort be given to the collection of such data.

Table 23. Percentage of the trees with damage codes 61 or 62 falling in various crown classes for the sample trees and for the sampled population.

		Crown class			
Species	Attribute	Dominant	Codominant	Intermediate	Suppressed
Douglas-fir	Sample trees	0.0	0.7	25.6	73.7
	Sampled population	0.0	0.3	23.2	76.5
Grand/white fir	Sample trees	0.0	0.5	10.8	88.7
	Sampled population	0.0	0.3	6.5	93.2
Incense-cedar	Sample trees	0.0	0.0	14.8	85.2
	Sampled population	0.0	0.0	8.8	91.2
Ponderosa pine	Sample trees	0.0	0.0	20.0	80.0
	Sampled population	0.0	0.0	17.2	82.8
Pacific madrone	Sample trees	1.6	1.6	28.1	68.7
	Sampled population	1.2	1.2	31.2	66.3

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Appendix

Conversion Equation: $HCB_{3/4}$ to HCB

Two methods of measuring *HCB* have been used extensively in the Pacific Northwest:

1) In trees of uneven crown length, the lower branches on the longer side of the crown are mentally transferred to fill in the missing portion of the shorter side. The objective of this method is to generate a "full, even" crown. *HCB* is then measured to this mentally generated position on the bole. Epicormic and short internodal branches are ignored.

2) Crown base is defined as the lowest whorl with live branches in at least three quadrants around the stem circumference. Again, epicormic branches and whorls not continuous with the main crown are ignored. *HCB* by this method ($HCB_{3/4}$) is the distance from the ground to the whorl defining this crown base. Maguire and Hann (1987) showed that $HCB_{3/4}$ was greater than or equal to *HCB*.

Because *HCB* is used in the ΔD_5 equations developed in this study, an equation for converting $HCB_{3/4}$ to *HCB* would be useful to organizations that routinely measure $HCB_{3/4}$. Data to develop the conversion equation were available from a subset of the trees felled for this study. On these trees, *HCB* was measured according to the procedures described under Data Description immediately before the tree was felled. After felling, the whorl meeting the "3/4" rule defined above was determined and $HCB_{3/4}$ was measured with a tape. The data are summarized in Table A1.

After examining a number of alternatives, we chose the following model form as best characterizing the relationship between *HCB* and $HCB_{3/4}$:

$$HCB = HCB_{3/4} - \Phi_0[1.0 - e^{-(HCB_{3/4}/100)^{\Phi_1}}] \qquad \text{[A1]}$$

Weighted nonlinear regression, with a weight of $(HCB_{3/4})^{-2}$ to homogenize the variance of the residuals, was used to estimate the parameters of the equation for each species. The Φ_0 parameter for Eq. [A1] was not significantly different from 0 (P = 0.05) for grand/white firs, sugar pine, and incense-cedar, indicating that no correction was necessary for those species. The Φ_1 parameter for Eq. [A1] could not be estimated for ponderosa pine and, as a result, was set to 3.5 (the value of Φ_1 for Douglas-fir, rounded to the nearest tenth) in order to estimate Φ_0 for that species. The resulting parameter estimates, their standard errors, and the weighted MSE for each species are found in Table A2.

Table A1. Description of the height-to-crown-base (*HCB*) adjustment data set, expressed as mean and range (in parentheses).

Species	Trees	$HCB_{3/4}$	*HCB*	*DBH*	Height
Douglas-fir	582	49.8 (1.9–171.2)	46.2 (1.2–168.5)	15.5 (0.9–72.1)	87.0 (10.1–252.3)
Grand/white fir	100	29.3 (4.1–82.0)	29.3 (4.0–76.0)	10.2 (1.3–24.7)	65.6 (10.9–143.3)
Incense-cedar	34	15.6 (0.0–47.9)	16.0 (2.3–58.5)	8.3 (0.8–30.1)	36.7 (9.1–111.8)
Ponderosa pine	56	50.6 (7.1–108.5)	47.7 (7.0–94.1)	14.5 (1.3–35.3)	81.9 (14.4–169.3)
Sugar pine	31	43.3 (3.6–94.5)	38.9 (2.5–87.5)	16.5 (1.9–36.2)	78.4 (15.6–132.3)

Table A2. Regression coefficients, standard error (in parentheses), and associated MSE for the height-to-crown-base (*HCB*) adjustment Eq. [A1].

	Parameters		
Species	Φ_0	Φ_1	MSE
Douglas-fir	21.74982462 (4.09880340)	3.51526731 (0.75313533)	0.0682
Grand/white fir	0.0 (NA)	3.5 (NA)	0.0271
Incense-cedar	0.0 (NA)	3.5 (NA)	0.0915
Ponderosa pine	16.15925801 (7.98204356)	3.5 (NA)	0.0315
Sugar pine	0.0 (NA)	3.5 (NA)	0.0611

NA: Not applicable.

Interpolation and Extrapolation Procedures

The Fawn Saddle validation data required either interpolation or extrapolation to compute D_2, H_2, and HCB_2 at the end of 5-yr growth periods from each tree's measurements of those attributes. The ending values and all subsequent values for trees dying during a growth period were set to the values at the start of the growth period. The following general procedure was used for each of the three attributes of those trees that were alive for at least one remeasurement:

1) For each tree with actual values from the first measurement and at least two remeasurements, simple linear regression was used to fit the following:

$$\ln(Y_X - Y_0) = a + b\ln(X)$$

where Y_X = the remeasurement of the attribute (*D, H,* or *HCB*) to be interpolated or extrapolated, taken X years from the first measurement

Y_0 = the first measurement of the attribute to be interpolated or extrapolated

X = the number of years from the first measurement to the remeasurement of interest for the attribute to be interpolated or extrapolated. At Fawn Saddle, X had values of 4, 8, and 12 on all plots and an additional value of 10 on two of the plots.

The b parameter was restricted to be >0.

2) For the first 5-yr growth period, the following interpolation procedures were used to calculate Y_5:

   a) if the tree had two or more remeasurements,

   $$Y_5 = Y_4 + (Y_8 - Y_4)[(5^b - 4^b)/(8^b - 4^b)]$$

   Interpolation is linear if $b = 1.0$.

   b) if the tree had only one remeasurement,

   $$Y_5 = Y_0 + (Y_4 - Y_0)(5/4)$$

3) For the second 5-yr growth period, the following extrapolation procedure was used to calculate Y_{13} for all trees alive at the last remeasurement:

   a) for plots with a remeasurement at $X = 10$,

   $$Y_{13} = Y_{10} + (Y_{12} - Y_{10})[(13^b - 10^b)/(12^b - 10^b)]$$

   b) for plots with a remeasurement at $X = 12$ but not $X = 10$,

   $$Y_{13} = Y_8 + (Y_{12} - Y_8)[(13^b - 8^b)/(12^b - 8^b)]$$

Extrapolation is linear if $b = 1.0$.

Estimation of Site Index in Even- and Uneven-aged Stands

The use of *SI* as a measure of productivity was developed for application in even-aged stands, and the method first used measures of average stand age and average dominant height as predictors of *SI* (e.g., McArdle and Meyer 1930; Dunning and Reineke 1933; King 1966). Probably because of the difficulty of measuring tree heights, the trees used in calculating the average height were usually selected from the largest-diameter, rather than the tallest, trees in the stand. The use of average stand attributes makes it more difficult to apply these measures of *SI* to uneven-aged stands.

More recent approaches have used the age and height of individual dominant trees in the stand as predictors of *SI* (e.g., Curtis et al. 1974; Monserud 1984; Biging 1985; Hann and Scrivani 1987). How these individual tree measurements are combined to form an estimate of the stand's *SI* varies from study to study. As examples,

1) Monserud (1984) recommended a) determining the number of *SI* tree measurements needed to meet a target precision for a given plot size, b) measuring the heights and ages on each of the SI-quality trees needed to fulfill the required sample size, c) calculating *SI* for each SI-quality tree, and d) averaging across all SI-quality trees to estimate the stand *SI*;

2) Barrett (1978) recommended a) measuring the heights and ages on each of the three tallest SI-quality trees falling on a 0.2-ac plot, b) averaging the three ages, and c) calculating the stand *SI* from the average age and the height of the tallest tree;

3) Cochran (1979) recommended a) measuring the heights and ages on each of the three to five tallest SI-quality trees falling on a 0.2-ac plot, b) calculating *SI* for each SI-quality tree, and c) assigning the largest tree *SI* value as the stand's *SI*.

All three methods required collection and examination of an increment core from the tree for evidence of suppression. Trees that had been suppressed were rejected as SI-quality trees. Monserud (1984) thought that trees from uneven-aged stands that met the definition of a SI-quality tree could be used to estimate *SI* in that type of stand structure.

Hann (1998), however, found that dominant Douglas-fir trees from uneven-aged stands that had been suppressed in their early years often did not evidence that suppression in their annual rings. Therefore, the use of the tallest tree and largest tree *SI* from a small fixed-area plot in the studies of Barrett (1978) and Cochran (1979) led to the following method for estimating *SI* in either even- or uneven-aged stands in southwest Oregon:

1) Measure at least 10 heights and ages on the tallest site-quality Douglas-fir or ponderosa pine trees in the stand. The trees should be spread throughout the stand. Trees that had been suppressed, as evidenced by the increment core, should be rejected as SI-quality trees. If there are not enough trees on the sampling grid to satisfy the requirement, additional measurements should be taken from trees not on the sampling grid. Our experience and those of Dunning and Reineke (1933) and Biging (1985) indicate that dominant white fir, grand fir, and sugar pine exhibit the same height-growth pattern as dominant Douglas-fir when growing in the same stand. Therefore, heights and ages from these species can be grouped with Douglas-fir to determine the "Douglas-fir" *SI* of the stand. Because ponderosa pine exhibits a different dominant

height from Douglas-fir when they are growing together (Hann and Scrivani 1987), stands with a mixture of these species should have at least ten *SI* trees measured on each species.

2) Using the dominant height-growth equations and the iterative solution method described in Hann and Scrivani (1987), calculate each tree's *SI* and rank the resulting values, largest to smallest, for each of the two species groups (i.e., "Douglas-fir" and ponderosa pine).

3) The species group *SI* for the stand is the average of the *SI* values for a subsample of the *SI* trees for that species group. This subsample is composed of the two trees from the same species group with the largest and second largest *SI* values plus all additional *SI* trees from that species group that are within 6% of the largest *SI* value.

This procedure does differ from that recommended in Hann and Scrivani (1987). However, their definitions of a site-quality tree (p. 2), a stand (p. 5), and how to handle the calculation of a weighted *SI* for management units composed of several stands (p. 6) are still appropriate. Also appropriate is their recommendation not to apply their equations to trees <15–20 yr old at breast height. The equations of Hann and Scrivani (1987) will extrapolate accurately to trees ≥250 yr old at breast height (Hann 1998).

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