Research Contribution 41

ENHANCED HEIGHT-GROWTH-RATE EQUATIONS FOR UNDAMAGED AND DAMAGED TREES IN SOUTHWEST OREGON

by

David W Hann

Mark L Hanus

December 2002

OREGON STATE
UNIVERSITY
COLLEGE OF
FORESTRY

Forest Research Laboratory

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ACKNOWLEDGMENTS

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

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ABSTRACT

Hann, DW, and ML Hanus. 2002. *Enhanced Height-Growth-Rate Equations for Undamaged and Damaged Trees in Southwest Oregon.* Research Contribution 41. Forest Research Laboratory, Oregon State University, Corvallis.

Equations for predicting the 5-yr height growth rate of a tree are presented for six conifer species from southwest Oregon. Equations for the combination of undamaged and damaged trees were estimated with weighted nonlinear regression techniques. These equations are being incorporated into the new southwest Oregon version of ORGANON, a model for predicting the development of stands. The equations extend the previous model to older stands and to stands with a heavier component of hardwood tree species.

The effects of specific damaging agents on the 5-yr height growth rate were explored for Douglas-fir, the most frequently encountered species, and damage correction factors were estimated. The findings of this analysis indicated that damaging agents can have a significant impact upon 5-yr height growth rate, and as a result, they can lead, over time, to diversification in within-stand structure. Therefore, a full characterization of stand development should include the prediction of the presence and frequency of the various damaging agents affecting trees within the stand and their subsequent impact upon tree attributes such as total height, height to crown base, diameter growth rate, height growth rate, and mortality rate.

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INTRODUCTION

Equations for predicting the height growth rate (ΔH) of trees are an essential component of models used to characterize single-tree development and to project the growth of volume and other attributes of the stand over time. 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 southwest Oregon version (SWO-ORGANON) predicted stand development in fairly young conifer stands of mixed species and mixed stand structures. These stands typically are found in an area bordered by the North Umpqua river to the north and the California border to the south, and the crest of the Cascade Mountains to the east and the crest of the Coast Range/Siskiyou Mountains to the west. The targeted conifer species for this work were Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], grand fir [*Abies grandis* (Dougl.) Lindl.], white fir [*Abies concolor* (Gord. & Glend.) Lindl.], ponderosa pine [*Pinus ponderosa* Dougl.], sugar pine [*Pinus lambertiana* Dougl.] and incense-cedar [*Calocedrus decurrens* Torr.].

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

'The first objective of this report, therefore, is to describe the development of equations for predicting 5-yr ΔH (ΔH_5) of individual Douglas-fir, grand fir, white fir, ponderosa pine, sugar pine, and incense-cedar trees in southwest Oregon, using both the original and the new extended data sets. In concordance with the analysis conducted earlier in southwest Oregon by Ritchie and Hann (1990), both undamaged and damaged trees were included in the development of these equations, which are being incorporated into a revision of SWO-ORGANON.

Previous analyses of the data sets used in this study found that damaging agents had a significant impact upon the height/diameter relationship (Hanus et al. 1999), the height to crown base (Hanus et al. 2000), and the diameter growth rate (Hann and Hanus

2002) of trees in the study area. Therefore, the second objective of this report is to examine whether or not damaging agents have a significant impact upon ΔH_5 of Douglas-fir trees in the study area.

DATA DESCRIPTION

STUDY AREA

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

The modeling data are from two studies associated with the development of the southwest Oregon version of ORGANON (Hann et al. 1997). The first set was collected during 1981, 1982, and 1983, as part of the southwest Oregon Forestry Intensified Research (FIR) Growth and Yield Project. That study included 391 plots in an area extending from near the California border (42°E10'N) in the south, to Cow Creek (43°E00'N) in the north, and from the Cascade crest (122°E15'W) on the east to approximately 15 miles west of Glendale, Oregon (123°E50'W). Elevation of the sample plots ranged from 900 to 5,100 ft. Sampling was limited to stands under 120 yr with at least 80% basal area in conifer species. The second study covered about the same area, but extended the selection criteria to include stands with coniferous trees over 250 yr, as well as younger stands with a greater component of hardwoods. An additional 138 plots were measured between 1992 and 1996 in this study. Stands treated in the past 5 yr were not sampled in either study.

Thirty tree species were identified on these 529 plots in the two studies. The most common conifers were Douglas-fir (527 plots), incense-cedar (244 plots), grand fir (235 plots), ponderosa pine (191 plots), sugar pine (191 plots), and white fir (161 plots). The most common hardwood species were Pacific madrone (270 plots), golden chinkapin (156 plots), California black oak (88 plots), canyon live oak (82 plots), Pacific dogwood (81 plots), and tanoak (75 plots). The number of species found on a plot ranged from 1 to 12, with an average of nearly 5 species.

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

SAMPLING DESIGN

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

Table 1. Description of the damage codes.

Code	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 due to heart rot, root disease, etc.
24	Mistletoe
25	Other diseases and rot such as abiotic diseases, needle diseases, diebacks, scales, leaf galls, pole blight, etc.
31	Scorched crown
32	Fire scar on bole
41	Domestic animals
42	Porcupine
43	Other wildlife
51	Lightning
52	Wind
53	Other weather such as snow or ice bending or breakage
61	Suppressed seedlings or sapling ≤ 6" DBH
62	Suppressed pole or sawtimber size tree > 6" DBH
71	Natural mechanical injury to bole or crown caused by falling trees, abrasion between trees, rolling rocks or logs, etc.
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—over 15 degrees from vertical
76	Excessive forking—a hardwood tree that forks within the first 8 feet, or a conifer that forks within the first 12 feet, the main fork then forking again within 8 or 12 feet, respectively.
81	Damage by powered equipment
82	Other logging
91	Excessive taper or deformity—will not produce a 12-ft conifer or 8-ft hardwood log
92	Off-site tree

TREE MEASUREMENTS

The measurements recorded at the end of the previous 5-yr growth period (indicated by a subscript of 2 on the variables) included an indicator of individual tree mortality over the past 5 yr, the type and severity of any damage, D_2, total tree height (H_2), height to live-crown base (HCB_2), and horizontal distance from point location to tree center ($DIST$). In addition, the previous 5-yr radial and height growths were measured on subsamples of trees.

The dating of mortality was based upon 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 recorded according to the procedures and codes described in Hanus et al. (1999) and (2000). Some of the field crews recorded additional damage codes in the remarks column of the field forms for trees damaged by multiple agents. These additional codes, although they were not a measurement requirement, were also entered into the database. Table 1 describes the damage codes.

D_2 was recorded to the last whole tenth of an inch with a diameter tape. H_2 and HCB_2 were measured to the nearest 0.1 ft on all trees, either directly with a 25- to 45-ft telescoping fiberglass pole or, for taller trees, indirectly, via the pole-tangent method (Larsen et al. 1987). For trees with broken or dead tops, H_2 was measured to the top of the live crown. To determine the HCB_2 for trees of uneven crown length, the lower branches on the longer side of the crown were mentally transferred to fill in the missing portion of the shorter side of the crown. Epicormic and short internodal branches were ignored in this process. HCB_2 was then measured to this mentally generated position on the bole. Procedures for measuring H_2 and HCB_2 for leaning trees depended on the severity of the lean, with all measurements taken at right angles to the direction of the lean. If lean was ≤15°E, it was ignored and H_2 and HCB_2 were measured directly to the leaning tip and crown base. If lean was >15°E, the tree tip and crown base were mentally swung to a vertical position, and H_2 and HCB_2 were measured to those imaginary points.

It can be difficult to accurately and precisely determine a tree's H_2 and HCB_2 at the time of death, especially if the tree has been dead for several years and, as a result, is missing foliage or part of the top at the time of measurement. Therefore, measured H_2 and HCB_2 for dead trees were compared with predicted H_2 and HCB_2 for severely damaged but living trees with the same class of damage. It could then be determined if the values for the dead trees were biased and, if so, adjustments could be developed for the bias. These procedures are described in Hann and Hanus (2001).

This comparison revealed that 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. However, the measured HCB_2 for dead trees did differ significantly from the predicted HCB_2 for severely damaged, living trees with the same class of damage. Hanus et al. (2000) found that severely damaged trees often had higher HCB_2 values than those predicted for undamaged trees. In Hann and Hanus (2001), the HCB_2 for dead trees always was higher, on average, than the predicted HCB_2 for severely damaged, living trees with the same class of damage. This difference was deemed a result of measurement error related to the difficulty in identifying *HCB* on dead trees in which some or all of the foliage and branches is missing. Therefore, the HCB_2 for dead trees was adjusted downwards to values expected for severely damaged, living trees, and the adjusted values were used in all subsequent analyses.

DIST, used in backdating the temporary plots, was determined by adding one-half the value of D_2 to the horizontal distance from point location to tree face. Past 5-yr radial growth at breast height was measured with an increment borer on all trees having a large enough D_2 (approximately 2 in. or larger) and at least 5 yr of growth since achieving breast height. The increment core was taken at the point on the tree facing plot center, to avoid selection bias. ΔH_5 was measured on subsamples 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. Current growth was ignored on trees measured during the growing season.

For all trees under 25 to 45 ft (based upon the size of the telescoping pole used to measure H_2 and HCB_2) that met the selection criteria, ΔH_5 was measured directly with the pole, if the five full internode lengths at the top of the tree were clearly visible. For trees taller than the telescoping pole, a subsample (up to six trees on each plot) was felled in order to measure ΔH_5. The target six trees included the two dominant trees with largest diameters on the plot, the two intermediate trees with smallest diameters on the plot, and two co-dominant trees with D_2 closest to the mid-range between the dominant and intermediate trees. Each felled tree was sectioned at the first and sixth whorls (at just the fifth whorl for trees measured during the dormant season). The ages at these whorls were determined to ensure a true 5-yr growth period. If the ring count at the sixth whorl was not 5 (ignoring the current year's partial ring), then additional cuts were made at lower or higher whorls until the whorl with a ring count of 5 was found. Finally, the distance between the two whorls was measured for ΔH_5.

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

1. $D_2 \leq 4.0$ in., $EXPAN_2 = 229.18$ tpa;
2. $D_2 > 4.0$ in. but ≤ 8.0 in., $EXPAN_2 = 57.30$ tpa;
3. $D_2 > 8.0$ in. but ≤ 36.0 in., $EXPAN_2 = 3{,}666.93\,(D_2)^{-2}$;
4. $D_2 > 36.0$ in., $EXPAN_2 = 11{,}000.79\,(D_2)^{-2}$.

POINT AND PLOT MEASUREMENTS

Aspect and slope were measured at each sampling point. Measurements for the plot or stand included ownership of the stand, elevation at the center of the stand (from USGS topographic maps), area of the stand (from aerial photographs), number of previous cuts on the stand, and number of years since the last cut ($YCUT$). The last two items were obtained from the appropriate managing agencies. One of the selection criteria was that the stand could not have been treated within the past 5 yr. Therefore, 6 yr was the smallest value possible for $YCUT$.

BACKDATING OF TREE ATTRIBUTES

Because the objective was to predict future rather than past ΔH_5, it was necessary to backdate all measurements for each sample tree on the plot. Values could then be estimated for the start of the previous 5-yr growth period, as indicated by a subscript of '1'. Procedures used in backdating each variable are described in Hann and Hanus (2001).

DERIVATION OF ADDITIONAL TREE AND STAND ATTRIBUTES

After the basic tree measurements had been backdated, several tree and stand variables used previously in modeling ΔH (Hann and Ritchie, 1988; Ritchie and Hann, 1990) were calculated. Crown ratio, a measure of tree vigor previously used by Hann and Ritchie (1988), Ritchie and Hann (1990), and others to model ΔH, was determined at the start of the growth period (CR_I) for each tree:

$CR_I = 1.0 - (HCB_I)/(H_I)$

Our experience, along with the past experiences of Dunning and Reineke (1933) and Biging (1985), indicates that dominant white fir, grand fir, and sugar pine exhibit the same height growth pattern as dominant Douglas-fir when they grow in the same stand. Therefore, the equations of Hann and Scrivani (1987) were used to group these species with Douglas-fir to determine the Douglas-fir site index (SI_{DF}). However, Hann and Scrivani (1987) found that the ponderosa pine site index (SI_{PP}) was 0.941 of the SI_{DF} for the same site, and that the shape of the dominant height growth for ponderosa pine differed from that of Douglas-fir. Thus, they developed separate equations for ponderosa pine. Finally, our experience indicates that the incense-cedar site index (SI_{IC}) was approximately 0.7 of the SI_{DF} for the same site. The incense-cedar dominant height growth equations of Dolph (1983) predicted that the shape of the dominant height growth of incense-cedar was very similar to that of Douglas-fir for the same value of SI.

Given the SI for a species in a stand (SI_{SP1}; $SP1 = DF$ for Douglas-fir, white fir, grand fir, and sugar pine; $SP1 = PP$ for ponderosa pine; $SP1 = IC$ for incense-cedar), potential ΔH_5 ($P\Delta H_5$) was calculated from the dominant height growth equations in Hann and Scriviani (1987). The ponderosa pine equation was used for that species; the Douglas-fir equation was used for all other species. Hann (1998) found that the Douglas-fir dominant height growth equation could be accurately extrapolated into stands with trees ≥250 yr old. $P\Delta H_5$ for was determined from these equations in the following manner:

$$P\Delta H_5 = f_{SP2}[SI_{SP1}, (GEA + 5.0)] - H_1$$

$$GEA = f_{SP2}^{-1}[SI_{SP1}, H_1]$$

where

f_{SP2} = The dominant height growth rate function from Hann and Scrivani (1987) for species $SP2$; $SP2 = DF$ for Douglas-fir, white fir, grand fir, sugar pine, and incense-cedar trees; $SP2 = PP$ for ponderosa pine trees.

GEA = The calculated growth effective age for the tree.

GEA is the age of a dominant tree with the same H_I and on the same SI_{SPI} as the tree of interest (Hann and Ritchie 1988). It is determined by solving the dominant height growth equation to express GEA as a function of H_I and SI_{SPI}.

The percentage of crown closure at H_I for the start of the growth period (CCH_I) was used to quantify tree position across a stand ($SCCH_I$) or at one of the sample points within the stand ($PCCH_I$). To calculate $SCCH_I$ or $PCCH_I$ for a particular tree, H_I of that tree was used to define a reference height (RH_I). Crown widths for the start of the growth period (CW_l) at RH_l for all other trees in the stand or on the sample point were estimated with the equations described in Hann (1999) and Hann and Hanus (2001). If the RH_l fell above H_l for another tree, CW_l for that tree was '0'; if it fell below HCB_l for another tree, then CW_l at HCB_l was used for that tree. CW_l for each tree was converted to crown area (CA_l) by the formula for the area of a circle. The CA_l for each tree was then multiplied by $EXPAN_l \div NP$ (for estimating $SCCH_l$ of the tree) or by $EXPAN_l$ (for estimating $PCCH_l$ of the tree) and summed across all sample trees in the stand or on the sample point and expressed as a percentage of acreage covered. This procedure was repeated to calculate $SCCH_l$ and $PCCH_l$ for all trees in the stand or on the sample point.

To better characterize within-stand variation in competition, Stage and Wykoff (1998) proposed using a rescaled stand level position variable rather than a point level position variable. In our application, this approach can be translated into rescaling $SCCH_l$ by multiplying it with the ratio of the point crown closure (PCC_l) divided by stand crown closure (SCC_l), where crown closure is calculated by the equations of Hann (1997). The resulting equation for calculating scaled $PCCH_l$ is:

$$Scaled\ PCCH_l = SCCH_l x\ \frac{PCC_l}{SCC_l}$$

Table 2. Mean and range for the plot-level ΔH_5 data from damaged and undamaged trees.

Species	Number of plots	SCC_1	SI_{SP1}
Douglas-fir	408	163.8 (1.2 - 389.2)	98.6 (41.5 - 146.9)
Grand & white firs	196	144.7 (32.0 - 370.4)	99.0 (61.6 - 145.0)
Incense cedar	115	155.9 (12.5 - 367.3)	64.7 (40.5 - 97.0)
Ponderosa pine	109	136.8 (2.5 - 389.2)	90.8 (49.5 - 138.2)
Sugar pine	84	156.8 (20.0 - 389.2)	91.0 (52.0 - 128.2)

Table 3. Mean and range for the plot-level ΔH_5 data from undamaged trees.

Species	Number of plots	SCC_1	SI_{SP1}
Douglas-fir	364	161.0 (9.9 - 389.2)	99.1 (47.2 - 146.9)
Grand & white firs	169	142.5 (32.0 - 370.4)	99.2 (61.6 - 145.0)
Incense cedar	110	154.2 (12.5 - 367.3)	64.5 (40.5 - 97.0)
Ponderosa pine	104	134.7 (2.5 - 389.2)	90.8 (49.5 - 138.2)
Sugar pine	68	164.7 (51.0 - 389.2)	90.4 (52.8 - 128.2)

Wensel et al. (1987), Wensel and Robards (1989), and Yeh and Wensel (1999) used a different reference height to define the tree position for their model of ΔH_5 in the mixed conifer stands of northern California. They set the reference height to $0.66(H_l)$ for each tree, then calculated crown closure at that point ($SCC66_l$), with the same procedures described above for the calculation of $SCCH_l$.

Summaries of the plot-level variables used to develop the individual tree ΔH_5 equations are presented in Table 2 for the combination of damaged and undamaged trees and in Table 3 for undamaged trees alone. Summaries of the tree-level variables are presented in Table 4 for the combination of damaged and undamaged trees and in Table 5 for undamaged trees alone. Excluded from these tables are data from those plots found to have a significant cutting effect (described in the Data Analysis section).

VALIDATION DATA

Data from control plots on two research installations located in the study area were used to validate the final ΔH_5 equation for Douglas-fir. These data were collected as part of the

Table 4. Mean and range for the tree-level ΔH_5 data from damaged and undamaged trees.

Species	Number of trees	D_1	H_1	CR_1	$SCCH_1$	Scaled $PCCH_1$	$PCCH_1$	$SCC66_1$	ΔH_5
Douglas-fir	2,436	6.1 (0.1 - 43.8)	39.0 (4.6 - 203.2)	0.56 (0.05 - 1.0)	73.6 (0.0 - 336.0)	93.2 (0.0 - 873.8)	80.3 (0.0 - 905.4)	108.0 (0.3 - 362.6)	5.1 (0.1 - 17.5)
Grand & white firs	699	5.8 (0.1 - 33.5)	37.2 (4.6 - 167.4)	0.56 (0.05 - 1.0)	75.3 (0.0 - 332.9)	98.7 (0.0 - 939.8)	83.7 (0.0 - 932.8)	101.3 (1.9 - 362.3)	4.6 (0.1 - 18.2)
Incense cedar	318	5.1 (0.1 - 33.0)	24.3 (4.6 - 112.0)	0.62 (0.10 - 1.0)	86.9 (0.1 - 276.6)	95.5 (0.0 - 437.8)	85.3 (0.0 - 443.3)	110.8 (2.4 - 341.9)	3.1 (0.1 - 10.0)
Ponderosa pine	239	10.3 (0.1 - 34.0)	55.3 (4.7 - 160.4)	0.56 (0.05 - 1.0)	22.0 (0.0 - 224.5)	22.0 (0.0 - 450.1)	15.5 (0.0 - 446.9)	46.9 (0.5 - 288.6)	7.0 (1.0 - 19.0)
Sugar pine	115	13.1 (0.2 - 34.1)	66.0 (5.3 - 168.6)	0.55 (0.20 - 1.0)	30.2 (0.0 - 238.4)	32.7 (0.0 - 290.6)	28.5 (0.0 - 357.6)	61.3 (0.8 - 257.7)	5.7 (0.5 - 11.0)

Table 5. Mean and range for the tree-level ΔH_5 data from undamaged trees.

Species	Number of trees	D_1	H_1	CR_1	$SCCH_1$	Scaled $PCCH_1$	$PCCH_1$	ΔH_5
Douglas-fir	1,632	8.1 (0.1 - 43.8)	49.9 (4.6 - 203.2)	0.62 (0.12 - 1.0)	42.7 (0.0 - 299.9)	50.6 (0.0 - 772.2)	39.9 (0.0 - 807.8)	6.5 (0.4 - 17.5)
Grand & white firs	458	7.3 (0.1 - 33.5)	46.3 (4.6 - 167.4)	0.62 (0.12 - 1.0)	56.3 (0.0 - 323.5)	68.0 (0.0 - 375.5)	53.3 (0.0 - 374.9)	5.6 (0.5 - 18.2)
Incense cedar	267	5.7 (0.1 - 33.0)	26.5 (4.6 - 112.0)	0.64 (0.14 - 1.0)	77.1 (0.1 - 273.0)	79.4 (0.1 - 409.1)	68.9 (0.0 - 408.2)	3.3 (0.1 - 10.0)
Ponderosa pine	215	10.8 (0.1 - 34.0)	57.9 (5.1 - 160.4)	0.56 (0.16 - 1.0)	19.0 (0.0 - 224.5)	19.2 (0.0 - 450.1)	13.4 (0.0 - 446.9)	7.2 (1.1 - 19.0)
Sugar pine	87	15.0 (1.0 - 34.1)	75.7 (8.1 - 168.6)	0.54 (0.24 - 1.0)	17.3 (0.0 - 158.6)	16.5 (0.0 - 160.3)	14.4 (0.0 - 164.7)	6.1 (1.4 - 11.0)

work that developed a new variant of ORGANON for the Stand Management Cooperative (SMC).

The first set of control plots was from the Stampede Creek Levels of Growing Stock (LOGS) installation (Curtis 1992). This LOGS installation was established in 1968 in a naturally established stand of even-aged Douglas-fir, 25 yr old at breast height. Based upon the measured tree heights in 1993, when the stand was 50 yr old at breast height, the Hann and Scrivani (1987) site index for the stand was 112.0 ft. The three 0.2-ac control plots on the installation have been re-measured every 5 yr since establishment. Because the 1998 re-measurement was the most recent available to this project, 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 ≥1.6 in. *D*, and *H* for a small subsample of the trees. Starting at the first re-measurement (i.e., 1973), *HCB* was also measured on a small subsample of the trees by means of the same procedure used in this study.

The second set of control plots was from the Fawn Saddle SMC Type II installation, established in 1986 in a 16-yr-old, at breast height, plantation of Douglas-fir. Based upon 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 (each 0.5 ac) on the installation have been re-measured every 4 yr since establishment; two of the plots were also re-measured in 1996. Re-measurements up to and including 1998 were made available to this project; thus data were available from three 4-yr growth periods for the validation analysis. All five plots on the installation had not been treated at the time of the last re-measurement. Tree attributes recorded at each measurement included species and D of every tree ≥1.6 in. D, and H and HCB for a subsample of approximately 40 of the trees on each plot. In this study, 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 than the method used to collect HCB data in both this study and at the Stampede Creek LOGS installation (Maguire and Hann 1987), the conversion equation described in Hann and Hanus (2002) was used 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 from each study. The 5-yr remeasurement cycle made the definitions 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 4-yr (and sometimes 2-yr) growth periods at Fawn Saddle, those data required interpolation and extrapolation techniques to define D_2, H_2, and HCB_2. To avoid measurement error, the 5-yr growth periods were defined to use actual measurement values (instead of interpolated or extrapolated values) for D_1, H_1, HCB_1, and $EXPAN_1$. As a result, the two 5-yr growth period data sets created from the Fawn Saddle data were composed of the 1986 measurement data and the 1994 re-measurement data for the start of the two growth periods. Interpolation was used to estimate D_2, H_2, and HCB_2 values for 1991, and extrapolation was used to estimate the values for 1999. These procedures are described in Hann and Hanus (2002).

Several additional attributes were calculated for each plot and installation combination. H_1 was subtracted from H_2 to determine ΔH_5. $SCCH_1$ was computed for each growth period with H_1, HCB_1, and $EXPAN_1$, and the CW_1 equations described in Hann (1999) and Hann and Hanus (2001). H_1 and HCB_1 were calculated on trees with missing values with the equations of Hanus et al. (1999) and Hanus et al. (2000), respectively. To improve the accuracy and precision of the predictions, the equations were first calibrated to each growth period's measurements of H_1 and HCB_1 by means of the procedures described in Hanus et al. (1999) and Hanus et al. (2000). Only trees with a measured H_1, H_2, and HCB_1 were included in the validation data set. A summary of the resulting validation data can be found in Table 6.

Table 6. Summary statistics for the tree-level ΔH_5 data from the validation data sets.

Data	Growth period	Variable	Number of observations	Mean	Variance	Minimum	Maximum
Stampede Creek							
	All	ΔH_5	208	7.6668	12.0938	0.2000	24.0000
		H_1	208	78.4014	439.0712	29.0000	115.0000
		CR_1	208	0.4460	0.0162	0.0548	0.7000
		CCH_1	208	26.9465	1843.280	0.0000	174.1323
	1973-1977	ΔH_5	26	8.4615	10.8185	1.0000	13.0000
		H_1	26	57.4615	226.8185	29.0000	74.0000
		CR_1	26	0.5640	0.0081	0.3878	0.7000
		CCH_1	26	29.0537	1880.230	0.0438	134.8989
	1978-1982	ΔH_5	50	8.0100	12.2295	2.0000	16.0000
		H_1	50	66.6600	269.2494	31.0000	86.0000
		CR_1	50	0.5038	0.0119	0.2545	0.6914
		CCH_1	50	31.3183	2444.980	0.0000	164.7105
	1983-1987	ΔH_5	50	8.3900	17.9315	1.0000	24.0000
		H_1	50	75.6700	269.9144	35.0000	95.0000
		CR_1	50	0.4740	0.0111	0.1667	0.6543
		CCH_1	50	28.6581	1999.710	0.0000	174.1323
	1988-1992	ΔH_5	41	7.6829	8.6220	1.0000	13.0000
		H_1	41	90.3171	186.1220	47.0000	106.0000
		CR_1	41	0.3877	0.0094	0.0548	0.5714
		CCH_1	41	19.6627	1065.230	0.0057	150.8651
	1993-1997	ΔH_5	41	5.8463	5.6460	0.2000	10.9000
		H_1	41	97.4146	301.0988	40.0000	115.0000
		CR_1	41	0.3249	0.0086	0.1000	0.4667
		CCH_1	41	25.4754	1766.830	0.0118	170.6430
Fawn Saddle							
	All	ΔH_5	384	12.6279	10.2572	0.1000	22.0000
		H_1	384	62.0367	193.3597	24.8000	87.9000
		CR_1	384	0.7112	0.0087	0.4303	0.8824
		CCH_1	384	8.2048	185.6213	0.0000	111.4790
	1987-1991	ΔH_5	194	13.3912	6.0406	4.3000	21.2000
		H_1	194	51.0361	60.2177	24.8000	63.4000
		CR_1	194	0.7746	0.0053	0.4303	0.8824
		CCH_1	194	7.6347	140.5582	0.0000	68.1909
	1995-1999	ΔH_5	190	11.8484	13.4084	0.1000	22.0000
		H_1	190	73.2689	79.2966	38.4000	87.9000
		CR_1	190	0.6466	0.0039	0.4310	0.8232
		CCH_1	190	8.7868	231.9460	0.0002	111.4790

DATA ANALYSIS

UNDAMAGED AND DAMAGED TREES COMBINED

The "potential/modifier" approach of Ritchie and Hann (1986), Wensel et al. (1987), and Hann and Ritchie (1988) was used to model ΔH_5. In this approach, first the $P\Delta H_5$ of the tree is predicted, then a multiplicative modifier is used to adjust $P\Delta H_5$ for vigor and competitive status of the tree:

$$\Delta H_5 = (P\Delta H_5)(\Delta HMOD) + \varepsilon \qquad [1]$$

where,

$\Delta HMOD$ = Height growth rate modifier function

ε = Random error

The $\Delta HMOD$ equation used by Hann and Ritchie (1988) and Ritchie and Hann (1990) was:

$$\Delta HMOD = a_0[a_1 e^{a_2 SCCH_1} + (e^{a_3 SCCH_1^{a_4}} - a_1 e^{a_2 SCCH_1}) e^{-k_1 (1.0 - CR_1)^{k_2} e^{a_5 SCCH_1^{k_3}}}] \qquad [2]$$

where,

a_i = Parameters to be estimated by weighted nonlinear regression, $i = 0,\ldots,5$

k_j = Predetermined parameters from Ritchie and Hann (1990), $j = 1,\ldots,3$

Equation [1], with Equation [2], was fit to the full damaged and undamaged tree modeling data sets, with both unweighted and weighted nonlinear regression and a weight of $(P\Delta H_5)^{-2}$. A comparison of the two fitting procedures by means of Furnival's (1961) index of fit (FIF) indicated that the weighted nonlinear regression approach best characterized the data. White fir and grand fir were combined for this and subsequent analyses because Ritchie and Hann (1990) found no difference in ΔH_5 between the two species in the study area.

In a second set of fits, the predetermined parameters were estimated by weighted, nonlinear regression. Analysis of these various sets of fits indicated that Equation [2] could be simplified to:

$$\Delta HMOD = b_0[e^{b_1 SCCH_1} + (e^{b_2 SCCH_1} - e^{b_1 SCCH_1}) e^{-b_3 (1.0 - CR_1)^2}] \qquad [3]$$

without affecting the quality of the fit to the data.

The data sets available to fit Equation [1] with Equation [2] or [3] include stands that had been cut previously. Past experience with fitting ΔH_5 models to thinned research plots revealed that the ΔH_5 equations developed for unthinned stands over-predicted the ΔH_5 of thinned stands, and that the amount of over-prediction varied both by the amount of BA removed in the thinning and by the time since the thinning (Hann et al. 2002). 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, the following approach was applied to the data set for each species to evaluate the impact of operational cuttings upon predicted ΔH_5 and to eliminate the data showing a statistically significant, negative impact:

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

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 $YCUT \geq 21$
= 0.0 Otherwise

2. The following equation was then fit to each species data set:

$$\Delta HMOD = [b_0 + \sum_{i=1}^{4} d_i IC_i][e^{b_1 SCCH_i} + (e^{b_2 SCCH_i} - e^{b_1 SCCH_i})e^{-b_3(1.0-CR_i)^2}]$$

with weighted nonlinear regression and a weight of $(P\Delta H_5)^{-2}$.

3. The parameters of the cutting indicator variables (i.e., the d_i's) were tested for significance below '0' using the one-sided t-test and a P-value of 0.05.

4. The resulting t-statistics were examined in reverse sequence (i.e., starting with d_4) to determine if any of the parameters were significantly negative. If a significant parameter was found, then the signs of the parameters for all of the most recent cuts were also examined to determine if all of them had negative signs as well (even if the parameters were not significantly negative). Those data meeting these conditions were removed from the modeling data set. This approach was taken because sample size was often small in the small $YCUT$ classes. The resulting reduced data set formed the final modeling data set for the species in question. The values reported in Tables 1, 2, 3, and 4 are for these reduced data sets.

As a comparison, the following $\Delta HMOD$ equation used by Wensel et al. (1987), Wensel and Robards (1989), and Yeh and Wensel (1999) for mixed conifer stands in northern California was also fit to the reduced Douglas-fir data set containing both undamaged and damaged trees:

$$\Delta HMOD = \frac{b_0 e^{b_1 (SCC66_1/100)^{b_2}}}{1 + e^{b_3 - b_4 CR_1}} \qquad [4]$$

The parameters and their standard errors for Equation [1], with Equation [4], were estimated by means of weighted nonlinear regression, with a weight of $(P\Delta H_5)^{-2}$.

Fits of Equation [1] with Equation [3] to each species or species group's reduced data set produced many similar parameter estimates among the species groups. It appeared that Douglas-fir, white fir, grand fir, and incense-cedar shared many common parameters and that ponderosa pine and sugar pine could also be similar. Therefore, the following two "giant" modifier equations were formed to evaluate whether the parameter estimates were significantly different between species groups:

$$\Delta HMOD = B_{0,1} [e^{B_{1,1} SCCH_i} + (e^{B_{2,1} SCCH_i} - e^{B_{1,1} SCCH_i}) e^{-B_{3,1}(1.0-CR_i)^2}] \qquad [5.1]$$

$$\Delta HMOD = B_{0,2} [e^{B_{1,2} SCCH_i} + (e^{B_{2,2} SCCH_i} - e^{B_{1,2} SCCH_i}) e^{-B_{3,2}(1.0-CR_i)^2}] \qquad [6.1]$$

where,

$B_{0,1} = b_{0,1} + b_{0,1,1} (1.0 - I_{DF}) + b_{0,1,2} I_{IC}$

$B_{1,1} = b_{1,1} + b_{1,1,1} (1.0 - I_{DF}) + b_{1,1,2} I_{IC}$

$B_{2,1} = b_{2,1} + b_{2,1,1} (1.0 - I_{DF}) + b_{2,1,2} I_{IC}$

$B_{3,1} = b_{3,1} + b_{3,1,1} (1.0 - I_{DF}) + b_{3,1,2} I_{IC}$

$B_{0,2} = b_{0,2} + b_{0,2,1} I_{SP}$

$B_{1,2} = b_{1,2} + b_{1,2,1} I_{SP}$

$B_{2,2} = b_{2,2} + b_{2,2,1} I_{SP}$

$B_{3,2} = b_{3,2} + b_{3,2,1} I_{SP}$

$I_{DF} = 1.0$ if the tree is a Douglas-fir, 0.0 otherwise

$I_{IC} = 1.0$ if the tree is an incense-cedar, 0.0 otherwise

$I_{SP} = 1.0$ if the tree is a sugar pine, 0.0 otherwise

Equation [1], with either Equation [5.1] or [6.1], was fit to the reduced data sets using weighted nonlinear regression. The resulting parameters were tested to determine if they were significantly different from '0' using the two-sided t-test and a P-value of 0.05. Insignificant parameters were set to '0' and the remaining parameters were re-estimated with weighted nonlinear regression.

The parameters $b_{0,1}$, and $b_{0,2}$, are corrections upon $P\Delta H_5$ for Douglas-fir and ponderosa pine trees, respectively, with a '0' value of $SCCH_t$. Therefore, they should not be significantly different from '1'. A two-sided t-test was performed on the two parameters, which revealed that $b_{0,1}$, was significantly <1, indicating that the potential height growth for the Douglas-fir, white fir, grand fir, and incense-cedar equation was too high for the measured ΔH_5 data. Possible reasons for this finding include:

1. The dominant height growth equation used to form $P\Delta H_5$ was biased or was not appropriate for the study area.
2. The growing conditions for the 5-yr growth periods measured in the study were different from the average growing conditions experienced by the trees making up the dominant height growth equations.

The dominant height growth equations used in this study were developed from a subset of the felled trees used in the study, and the equations were validated on an independent data set from the study area (Hann 1998). It is unlikely, therefore, that the first possibility was the cause for the significant difference of $b_{0,1}$, from '1'.

To examine the second possibility, all of the felled Douglas-fir trees used to develop the dominant height growth equations with a $SCCH_t$ of '0' were extracted from the data set and their measured ΔH_5 values were compared to $P\Delta H_5$. The ratio of $\Delta H_5/P\Delta H_5$ was formed and the mean calculated. A total of six site quality Douglas-fir trees met the selection criteria. The mean of their ratios was 0.9091, indicating that the measured ΔH_5 for the most recent 5-yr growth period was lower than that experienced by the dominant height growth of site quality Douglas-fir trees over the 50+ yr that they had been alive.

For Equation [1] with Equation [5.1], incense-cedar was the only species with a significant correction parameter on $b_{0,1}$ (i.e., $b_{0,1,2}$). The value of the parameter was <1, indicating that the incense-cedar trees were growing more slowly than the potential growth of Douglas-fir. The factor for converting SI_{DF} to SI_{IC} originally was based upon a subjective comparison of the dominant heights of the two species in the original data set. The following procedure was used to refine the incense-cedar conversion factor:

1. Starting with the original conversion factor of 0.7, a value of 0.01 was subtracted from the conversion and new SI_{IC} values were computed for each incense-cedar tree.
2. New values of $P\Delta H_5$ were then computed using the revised estimates of SI_{IC}.

3. Equation [1] with Equation [5.1] was then refit to the reduced, combined undamaged and damaged data set with the new estimates of $P\Delta H_5$ for incense-cedar.

4. If the resulting incense-cedar correction (i.e., $b_{0,1,2}$) was significantly different from '0' ($P = 0.05$), then steps 1 through 4 were repeated until a value of $b_{0,1,2}$ was achieved that was not significantly different from '0'. The revised conversion factor was then set to this value.

With the final model forms defined, four other modifier equations that replaced $SCCH_1$ with either *Scaled* $PCCH_1$ or $PCCH_1$ were formed:

$$\Delta HMOD = B_{0,1}[\, e^{B_{1,1}(Scaled\ PCCH_1)} + (e^{B_{2,1}(Scaled\ PCCH_1)} - e^{B_{1,1}(Scaled\ PCCH_1)})\, e^{-B_{3,1}(1.0-CR_1)^2}\,] \quad [5.2]$$

$$\Delta HMOD = B_{0,1}[\, e^{B_{1,1}PCCH_1} + (e^{B_{2,1}PCCH_1} - e^{B_{1,1}PCCH_1})\, e^{-B_{3,1}(1.0-CR_1)^2}\,] \quad [5.3]$$

$$\Delta HMOD = B_{0,2}[\, e^{B_{1,2}(Scaled\ PCCH_1)} + (e^{B_{2,2}(Scaled\ PCCH_1)} - e^{B_{1,2}(Scaled\ PCCH_1)})\, e^{-B_{3,2}(1.0-CR_1)^2}\,] \quad [6.2]$$

$$\Delta HMOD = B_{0,2}[\, e^{B_{1,2}PCCH_1} + (e^{B_{2,2}PCCH_1} - e^{B_{1,2}PCCH_1})\, e^{-B_{3,2}(1.0-CR_1)^2}\,] \quad [6.3]$$

Equations [5.2] and [5.3] were then fit with weighted nonlinear regression to the reduced, combined data set for Douglas-fir, grand fir, white fir, and incense-cedar, while Equations [6.2] and [6.3] were fit with weighted nonlinear regression to the reduced, combined data set for ponderosa pine and sugar pine.

Finally, the predictive ability of Equation [1] with Equation [5.1] for Douglas-fir was evaluated by means of the validation data set described in Table 6. Predicted ΔH_5 ($Pred\Delta H_5$) values were computed for each tree in the validation data set and the difference (δ_i) of actual ΔH_5 minus $Pred\Delta H_5$ was calculated. The following validation statistics were then computed. $Pred\Delta H_5$ was used, with both the estimated value of b_0 and with setting b_0 to a value of '1':

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

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

With Bias $R_a^2 = 1.0 - \dfrac{MSE}{Var(\Delta H_5)}$

Without Bias $R_a^2 = 1.0 - \dfrac{[m/(m-1)][MSE-\bar{\delta}^2)]}{Var(\Delta H_5)}$

where,

$\bar{\delta}$ = The mean difference

MSE = The mean square error

R_a^2 = Adjusted coefficient of determination

m = Number of observations in the validation data set

$Var\,(\Delta H_5)$ = Variance of measured ΔH_5

$$Var(\Delta H_5) = \frac{\sum_{i=1}^{m} \Delta H_{5,i}^2 - m(\overline{\Delta H_5})^2}{(m-1)}$$

$\overline{\Delta H_5}$ = Mean of actual $\Delta H_{5,i}$

$$\overline{\Delta H_5} = \frac{\sum_{i=1}^{m} \Delta H_{5,i}}{m}$$

$\bar{\delta}$ 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 of '1' for R_a^2 that includes possible bias indicates that the regression equation is both unbiased and that it explains all of the variation in the validation data set. A value of '1' for R_a^2 that has removed possible bias indicates that the regression equation explains all of the variation in the validation data set, if the possible bias is removed. It should be noted that if $\bar{\delta}$ were '0' for a data set, the R_a^2 with bias would be somewhat larger than the R_a^2 without bias because the equation for the latter includes $m/(m-1)$, which is always >1. A negative value for either indicates that a mean ΔH_5 predicts better than the regression equation. The validation statistics were computed for each of the five growth periods and for the combined data.

DAMAGED TREES

The following process was used to examine whether or not damaging agents have a significant impact upon ΔH_5 of trees in the study area:

1. A ΔH_5 equation was developed for those species combinations with adequate data from undamaged trees. An examination of the various data sets indicated that only Douglas-fir had an undamaged data set of sufficient size (Tables 2 and 4). Therefore, Equation [1] with Equations [5.1], [5.2] and [5.3] were fit to just the Douglas-fir data with weighted nonlinear regression.
2. $Pred\Delta H_5$ from the equations developed in the first step of the analysis were calibrated to each plot containing undamaged Douglas-fir trees in order to reduce variation caused by between-plot differences in the ΔH_5 relationship. This calibration

was done by regressing each plot's undamaged ΔH_5 on $Pred\Delta H_5$ by means of the regression model:

$$CPred\Delta H_{5,i,j} = k_{i,j}(Pred\Delta H_{5,i}) + \varepsilon$$

where,

$CPred\Delta H_{5,i,j}$ = $Pred\Delta H_{5,i}$ calibrated to the j^{th} plot, $i = 1$ for Equation [1] with Equation [5.1]; $i = 2$ for Equation [1] with Equation [5.2]; $i = 3$ for Equation [1] with Equation [5.3]

$k_{i,j}$ = undamaged tree plot-level calibration for the i^{th} equation and j^{th} plot estimated by means of weighted linear regression with $(P\Delta H_{5,j})^{-2}$ as the weight.

The parameter $k_{i,j}$ was set to '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. A P-value of 0.10 was used in the t-test to make plot-level calibration more frequent.

3. The correction factors (CF) for a damaging agent and its severity were calculated by regressing the measured ΔH_5 for all trees with the damage to $CPred\Delta H_5$:

   $$D\Delta H_5 = \lambda_1(CPred\Delta H_5) + \lambda_2 I_s(CPred\Delta H_5) + \varepsilon$$

   where,

   $D\Delta H_5$ = ΔH_5 for Douglas-fir trees that were damaged by a particular agent

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

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

   I_s = 0 if severity of damage is light, and $I_s = 1$ if the damage is judged to be severe.

The damaged tree parameters λ_1 and λ_2 were estimated by means of weighted linear regression with a weight of $(P\Delta H_5)^{-2}$. Then λ_1 and λ_2 were tested for significant differences from '1' and '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, then λ_1 was re-estimated by means of the following equation fit to the combined light and severe damage data, with weighted linear regression and a weight of $(P\Delta H_5)^{-2}$:

$$D\Delta H_5 = \lambda_1(CPred\Delta H_5) + \varepsilon$$

The resulting value for λ_1 was reported as the CF for both levels of severity. If the parameter λ_2 was significant and parameter λ_1 was not, then the CF for light damage was set to '1' and λ_2 was re-estimated by the following equation fit to just the severe damage data by using weighted linear regression and a weight of $(P\Delta H_5)^{-2}$:

$$D\Delta H_5 = \lambda_2(CPred\Delta H_5) + \varepsilon$$

The resulting value for λ_2 was reported as the CF for the severe level of damage.

RESULTS

UNDAMAGED AND DAMAGED TREES COMBINED

Table 7 contains the parameter estimates and associated standard errors for Douglas-fir fit to Equation [1] with Equations [3] and [4] using the reduced data from both undamaged and damaged trees. Table 8 contains parameter estimates and associated standard errors for Douglas-fir, white fir, grand fir, and incense-cedar that were fit to Equation [1]

Table 7. Parameter estimates, standard errors (in parentheses), mean square error (MSE) and Furnival's Index of fit (FIF) for Equations [3] and [4] fit to the Douglas-fir data set.

Parameter	Equation [3]	Equation [4]
b_0	0.90796992 (0.0077162)	0.97991022 (0.0194337)
b_1	-0.02334853 (0.0020905)	-0.51789018 (0.029394)
b_2	-0.00385089 (0.0002646)	1.26035324 (0.0760089)
b_3	3.08985199 (0.2857669)	1.66999131 (0.3652612)
b_4	NA (NA)	9.81904158 (1.354984)
MSE	0.0461	0.0654
FIF	1.9357	2.3055

Table 8. Estimated parameters and standard errors (in parentheses) for Equations [5.1], [5.2], and [5.3] fit to the damaged and undamaged Douglas-fir, grand fir, white fir, and incense-cedar trees.

Parameter	Equation [5.1]	Equation [5.2]	Equation [5.3]
$b_{0,1}$	0.92140706 (0.0074986666)	0.91587419 (0.007498666)	0.90606084 (0.0071812255)
$b_{1,1}$	-0.02457621 (0.0025709920)	-0.02424952 (0.002570992)	-0.03062176 (0.003753665)
$b_{1,1,2}$	0.01004371 (0.0026962938)	0.01164513 (0.002696294)	0.0 (NA)
$b_{2,1}$	-0.00407303 (0.000223607)	-0.00354511 (0.000223607)	-0.00550338 (0.00030000)
$b_{2,1,2}$	-0.00230131 (0.0006557439)	-0.00310673 (0.0006557439)	-0.00188210 (0.000707107)
$b_{3,1}$	2.89556338 (0.2308203631)	2.56498076 (0.230820363)	2.02280978 (0.2117143122)
$b_{3,1,1}$	4.79467237 (1.3479343382)	4.00558516 (1.3479343382)	0.0 (NA)
$b_{3,1,2}$	-6.41794937 (1.4162771867)	-5.90384214 (1.4162771869)	-1.65703795 (0.3257461128)
MSE	0.0502	0.0506	0.0493
FIF	1.9136	1.9218	1.8969

Table 9. Estimated parameters and standard errors (in parentheses) for Equations [6.1], [6.2], and [6.3] fit to the damaged and undamaged ponderosa pine and sugar pine trees.

Parameter	Equation [6.1]	Equation [6.2]	Equation [6.3]
$b_{0,2}$	1.01337186	0.99763365	1.00429696
	(0.0240295651)	(0.022384593)	(0.021326744)
$b_{1,2}$	-0.14889850	-0.12033571	-0.13906023
	(0.072700000)	(0.054491008)	(0.046616199)
$b_{2,2}$	-0.00322752	-0.00144112	-0.00652422
	(0.0009848858)	(0.000911043)	(0.001019804)
$b_{2,2,1}$	-0.00356203	-0.00765633	0.0
	(0.001435270)	(0.001933908)	(NA)
$b_{3,2}$	0.92071847	1.29483751	1.0
	(0.2138334866)	(0.237554057)	(NA)
$b_{3,2,1}$	0.0	-1.18133008	0.0
	(NA)	(0.340707074	(NA)
MSE	0.0703	0.0691	0.0687
FIF	2.0357	2.0175	2.0157

with Equations [5.1], [5.2], and [5.3], respectively, with the reduced data from both undamaged and damaged trees. Table 9 contains parameter estimates and associated standard errors for ponderosa pine and sugar pine that were fit to Equation [1] with Equations [6.1], [6.2], and [6.3], respectively, with the reduced data from both undamaged and damaged trees. These tables also contain both the weighted *MSE* and Furnival's (1961) index of fit (FIF) for each type of equation. Because the fits to the equations used $(P\Delta H_5)^{-2}$ as a weight, the resulting weighted mean square errors (*MSE*) are difficult to interpret. FIF adjusts for the impact of weighting in a manner allowing comparison of weighted and unweighted runs. It is equal to *MSE* for unweighted fits (Furnival 1961), and, like *MSE*, the smaller the size of FIF, the better the fit to the data, with a '0' value of FIF indicating a perfect fit to the data. Table 10 presents the validation statistics arising from the use of Equation [1] with Equation [5.1] to predict the ΔH_5 of Douglas-fir trees in the validation data set.

Table 10. Validation statistics for Douglas-fir Equation [1] with Equation [5.1].

$b_{0,1...}$	Data	Growth period	m	δ	MSE	With bias R_a^2	Without bias R_a^2
As Fit	Stampede Creek	All	208	0.17	6.7371	0.4429	0.4425
	Stampede Creek	1973 - 1977	26	0.05	2.9957	0.7231	0.7123
	Stampede Creek	1978 - 1982	50	0.16	8.3577	0.3166	0.3047
	Stampede Creek	1983 - 1987	50	0.87	10.3234	0.4243	0.4552
	Stampede Creek	1988 - 1992	41	0.30	4.8771	0.4343	0.4306
	Stampede Creek	1993 - 1997	41	-0.74	4.6198	0.1818	0.2611
	Fawn Saddle	All	384	-1.41	10.4060	-0.0145	0.1770
	Fawn Saddle	1987 - 1991	194	-1.16	8.0617	-0.3346	-0.1183
	Fawn Saddle	1995 - 1999	190	-1.67	12.7996	0.0454	0.2484
	All	All	592	-0.86	9.1169	0.4475	0.4911
Set to 1.0	Stampede Creek	All	208	-0.47	7.0741	0.4151	0.4310
	Stampede Creek	1973 - 1977	26	-0.66	3.3644	0.6890	0.7187
	Stampede Creek	1978 - 1982	50	-0.51	9.0149	0.2629	0.2697
	Stampede Creek	1983 - 1987	50	0.22	9.5214	0.4690	0.4610
	Stampede Creek	1988 - 1992	41	-0.33	4.9899	0.4213	0.4201
	Stampede Creek	1993 - 1997	41	-1.30	6.1596	-0.0910	0.1901
	Fawn Saddle	All	384	-2.61	15.2278	-0.4846	0.1757
	Fawn Saddle	1987 - 1991	194	-2.40	12.6562	-1.0952	-0.1483
	Fawn Saddle	1995 - 1999	190	-2.82	17.8535	-0.3315	0.2571
	All	All	592	-1.86	12.3630	0.2507	0.4590

DAMAGED TREES

Table 11 contains parameter estimates and associated standard errors for Douglas-fir fit to Equation [1] with Equations [5.1], [5.2], and [5.3], respectively, with data from just undamaged trees. This table also contains the weighted *MSE* and the FIF for each type of equation.

Table 12 presents the number of sample trees observed with a given type and severity of damage for Douglas-fir. Table 13 displays the damage CF values for Equation [1], with the equations containing $SCCH_I$ (Equation [5.1]), *Scaled* $PCCH_I$ (Equation [5.2]), and $PCCH_I$ (Equation [5.3]) that were significantly different from '1' ($P = 0.05$). The type and severity of damage codes found in Table 12 but not in Table 13 indicates that the *CF* values for type and severity of damage codes were not significantly different from '1'. To predict ΔH_5 for a damaged Douglas-fir, the ΔH_5 for an undamaged tree is first estimated with Equation [1] with Equation [5.1], [5.2], or [5.3], and this estimate is then multiplied by the appropriate *CF* from Table 13.

Table 11. Estimated parameters and standard errors (in parentheses) for Equations [5.1], [5.2], and [5.3] fit to undamaged Douglas-fir trees.

Parameter	Equation [5.1]	Equation [5.2]	Equation [5.3]
$b_{0,1}$	0.91527622	0.90970304	0.90778772
	(0.00941116)	(0.00922009)	(0.00877553)
$b_{1,1}$	-0.02860775	-0.02390812	-0.03418849
	(0.00493862)	(0.00406202)	(0.00727255)
$b_{2,1}$	-0.00371298	-0.00300974	-0.00483866
	(0.00033166)	(0.00028284)	(0.0003873)
$b_{3,1}$	2.06809013	2.17105354	1.60104398
	(0.30043304)	(0.3216218)	(0.27015061)
MSE	0.0536	0.0537	0.0515
FIF	2.0853	2.0869	2.0442

Table 12. Number of observations in each damage code by severity for Douglas-fir.

Damage	Severity	Number of Observations
11	1	2
22	1	13
	2	17
24	2	3
25	1	17
43	1	6
	2	4
52	2	2
53	1	1
	2	3
61	1	236
	2	248
62	1	11
	2	3
71	1	72
	2	33
72	1	11
	2	12
73	1	4
	2	3
74	1	3
75	2	27
81	1	5

Table 13. Damage correction factors for Douglas-fir.

Equation	Damage Code	CF for light damage	Standard error for light damage	CF for severe damage	Standard error for severe damage
[5.1]	43	0.7257	0.1041	0.7257	0.1041
	61	0.6953	0.0227	0.5203	0.0191
	62	0.6443	0.0561	0.6443	0.0561
	71	0.9293	0.0492	0.8069	0.0442
	75	NA	NA	0.6955	0.1038
[5.2]	61	0.6966	0.0241	0.5167	0.0210
	62	0.5722	0.0595	0.5722	0.0595
	71	0.8920	0.0270	0.8920	0.0270
	75	NA	NA	0.6848	0.1029
[5.3]	22	0.7833	0.0692	0.7833	0.0692
	61	0.7263	0.0237	0.5499	0.0245
	62	0.6533	0.0618	0.6533	0.0618
	71	0.8634	0.0279	0.8634	0.0279
	75	NA	NA	0.8086	0.0862

Discussion

ΔH_5 Equations for Undamaged and Damaged Trees

A comparison of the *MSE* and FIF found in Table 7 for Equation [1] with either the modified Hann and Ritchie (1988) Equation [3] or the Wensel et al. (1987) Equation [4] shows that Equation [1] with Equation [3] explained substantially more of the variation in Douglas-fir height growth rate than Equation [1] with Equation [4]. This result reaffirms the earlier finding of Hann and Ritchie (1988). Both equations incorporate $P\Delta H_5$, CR_I and a measure of crown closure as predictor variables. Therefore, the difference in performance between the two equations could be caused by:

1. Differences in the dominant height growth equations used to define $P\Delta H_5$
2. Differences in the crown profile equations used to calculate $SCCH_I$ and $SCC66_I$
3. Choice of the basic model form used to relate $P\Delta H_5$, CR_I, and a measure of crown closure to ΔH_5, which would also include the choice of the measure for crown closure (i.e., $SCCH_I$ or $SCC66_I$) used in the model

In this study, $P\Delta H_5$ was calculated using the dominant height growth equations of Hann and Scrivani (1987), whereas the parameters and fit statistics for Equation [4] described in Wensel et al. (1987) used the dominant height growth equation of Biging (1985). A comparison of these two dominant height growth equations (Figure 1) reveals differences between the two in young ages and at higher site indices. However, the differences do not seem to be large enough to cause the difference in performance found in this study.

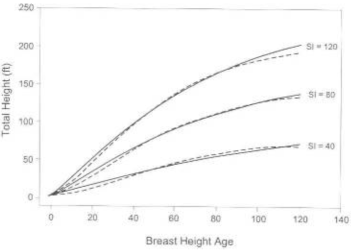

Figure 1. Comparison of the Douglas-fir dominant height growth equation of Hann and Scrivani (1987) (solid lines) to the Douglas-fir dominant height growth equation of Biging (1985) (dotted lines) for site index values of 40, 80, and 120.

In this study, the measures of crown closure for Equations [3] and [4] ($SCCH_I$ and $SCC66_I$, respectively) were calculated with the crown profile equations of Hann (1999) and Hann and Hanus (2001). The parameters and fit statistics for Equation [4], described in Wensel et al. (1987), used the crown profile equations later described by Biging and Wensel (1990).

A comparison of the crown profiles predicted by Hann (1999) and Hann and Hanus (2001) versus the equations of Biging and Wensel (1990) reveals differences between these two sets of equations (Figure 2). For small trees (D = 4.0 in.; H = 35 ft; CR = 0.25 and 0.75), the Biging and Wensel (1990) equations predict approximately the same crown width at the base of the crown as the Hann (1999) equations, but wider crowns toward the top of the tree. For large trees (D = 30.0 in.; H = 140 ft; CR = 0.25 and 0.75), the

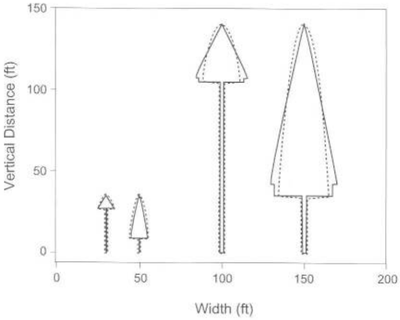

Figure 2. Predicted crown profiles for Douglas-fir from Hann (1999) and Hann and Hanus (2001) (solid lines) and Biging and Wensel (1990) equations (dotted lines). The small trees had D = 4.0 in., H = 35.0 ft., CR = 0.25 and CR = 0.75, the large trees had D = 30.0 in., H = 140.0 ft., CR = 0.25 and CR = 0.75.

Biging and Wensel (1990) equations predict narrower crown widths at the base of the crown than the Hann (1999) equations and wider crowns toward the top of the tree. Again, however, these differences do not seem to be large enough to cause the substantial difference in performance found in this study.

Our conclusion, therefore, is that the difference in performance between Equation [3] and Equation [4] is related primarily to differences in the basic model forms. As a result, the model form of Equation [3] was selected for further development.

Of the five species or species group data sets, only Douglas-fir had significant *YCUT* indicator variables. The signs of the parameters were negative, indicating that trees from recently cut stands had smaller ΔH_5 than would be expected for trees from uncut stands with the same tree and stand attributes. The decrease in ΔH_5 in cut stands was largest in the first 5-yr period after the treatment, and the size of the increase declined as time after cutting increased. Total duration of the cutting impact was 10 yr. These findings are in agreement with those of Hann et al. (2002).

For Douglas-fir, plots with significant *YCUT* indicator variables were eliminated from the final modeling data sets, which resulted in the loss of 262 Douglas-fir trees for modeling. The data summaries in Tables 2, 3, 4, and 5 are for the final modeling data sets.

The $b_{0.1}$ and $b_{0.2}$ parameters are data set specific adjustments upon $P\Delta H_5$ when CCH_t is '0'. Therefore, they should not be significantly different from '1' if the dominant height growth equations used to form $P\Delta H_5$ are appropriate for the species and location. For ponderosa pine and sugar pine, $b_{0.2}$, was not significantly different from '1' (Table 9). For Douglas-fir, white fir, grand fir, and incense-cedar, $b_{0.1}$, was significantly smaller than '1', with values ranging from 0.9214 for Equation [5.1] to 0.9061 for Equation [5.3] (Table 8). For these species, this result indicates that $P\Delta H_5$ for trees with $CCH_t = 0$ was significantly smaller than expected for the 5-yr growth periods measured in this study.

The Hann and Scrivani (1987) dominant height growth equations used to form $P\Delta H_5$ were developed from a subset of the felled trees used in this study. Furthermore, the equations have been validated on an independent data set (Hann 1998). Therefore, it is unlikely that the significant difference of b_0 from '1' indicates a problem with the dominant height growth equations used to form $P\Delta H_5$. Wensel and Turnblom (1998) and Yeh and Wensel (2000) have shown that precipitation and temperature differences between growth periods can have a significant effect upon the growth rates of trees in northern California. These factors could explain the results found in this study.

To explore this possibility further, the felled Douglas-fir trees with CCH_I of '0' that had been used in the development of the dominant height growth equations of Hann and Scrivani (1987) were identified, and the ratio of $\Delta H_5/P\Delta H_5$ was calculated for each tree. The mean of this ratio was 0.909 for the six trees meeting the selection criteria. This result indicates that for the growth periods measured in this study, ΔH_5 of Douglas-fir was lower than the average long-term growth rates determined from stem analysis of the dominant, site quality Douglas-fir trees used in Hann and Scrivani (1987).

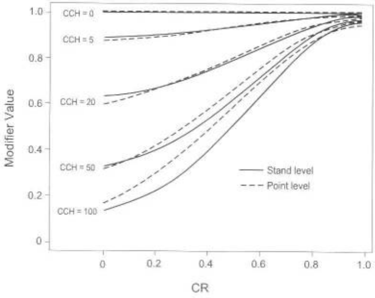

Figure 3. The modifier function for Douglas-fir height growth plotted across CR for five values of CCH.

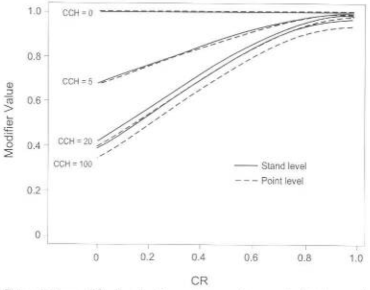

Figure 4. The modifier function for ponderosa and sugar pine height growth plotted across CR for four values of CCH.

The incense-cedar parameter correction in Equation [5.1] (i.e., $b_{0,1,2}$) was driven to insignificance at $P = 0.05$ when the factor for converting SI_{DF} to SI_{IC} was set to 0.66 instead of 0.7, previously used in southwest Oregon. This value is very close to the value of 0.67 recommended by Wensel (1997) for incense-cedar in northern California.

For both species group sets of equations (i.e., Equations [5.1, 5.2, 5.3] for Douglas-fir, white fir, grand fir, and incense-cedar and Equations [6.1, 6.2, 6.3] for ponderosa pine and sugar pine), usage of $PCCH_I$ did provide a small reduction in FIF when compared to the usage of $SCCH_I$ (Tables 8 and 9). The reduction was 0.99% for Equation [5.3] and 0.90% for Equation [6.3]. The usage of scaled $PCCH_I$ produced either an FIF larger than $SCCH_I$ in the case of Douglas-fir, white fir, grand fir, and incense-cedar, or an FIF larger than $PCCH_I$ in the case of ponderosa pine and sugar pine.

For Douglas-fir, grand fir, white fir, and incense-cedar, the modifier equation incorporating $SCCH_I$ predicts a larger reduction in ΔH_5 for the same value of CR and CCH than the modifier equation incorporating $PCCH_I$, particularly for trees with CR values under 0.8 (Figure 3). The difference between the two modifiers is smaller for ponderosa pine and sugar pine (Figure 4). Plotting the differences between $PCCH_I$ and $SCCH_I$ (i.e., $PCCH_I - SCCH_I$) across $PCCH_I$ for Douglas-fir shows a clearly increasing trend across a large range in $PCCH_I$ values (Figure 5). The trend is not as clear, nor the range as large, for ponderosa pine (Figure 6). These results (and the values found in Tables 4 and 5) indicate that Douglas-fir exists in stands with more internal variability in

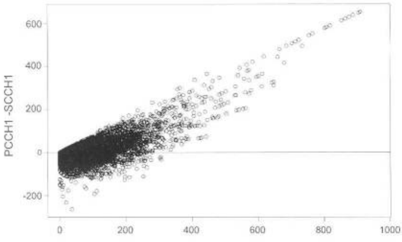

Figure 5. The difference in $PCCH_1$ and $SCCH_1$ across $PCCH_1$ for all living Douglas-fir trees in the SWO-ORGANON project data set.

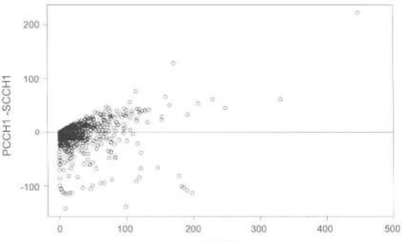

Figure 6. The difference in $PCCH_1$ and $SCCH_1$ across $PCCH_1$ for all living ponderosa pine trees in the SWO-ORGANON project data set.

$PCCH_1$ and in conditions with higher levels of $PCCH_1$ than ponderosa pine. Therefore, the differences in the modifiers for Douglas-fir, grand fir, white fir, and incense-cedar (e.g., Figure 3) are related to the finding that $PCCH_1$ for a given tree can be substantially larger than $SCCH_1$ for the same tree (e.g., Figure 5). Likewise, the similarity between $PCCH_1$ and $SCCH_1$ for ponderosa pine and sugar pine (e.g., Figure 6) is the reason the two modifiers for these species are very similar (e.g., Figure 4).

Examination of the tree and stand attributes after projections 200 yr long, with the old ΔH_5 equations and the new equations, indicated that use of the new equations produces differences in tree and stand development. The following is a general description of how the new equations affect $Pred\Delta H_5$ for the five species groups analyzed in this study:

1. The tallest Douglas-fir, grand fir, white fir, and ponderosa pine trees in a stand showed few or no differences in $Pred\Delta H_5$. The tallest incense-cedar showed a slight reduction because of the lower SI_{DF} conversion factor. The tallest sugar pine also showed a slight reduction because of the decision to use the ponderosa pine dominant height growth equation of Hann and Scrivani (1987) in this study (the sugar pine ΔH_5 equation in Ritchie and Hann (1990) used the Douglas-fir dominant height growth equation).

2. The smallest trees in a stand showed the greatest increase in $Pred\Delta H_5$. Grand and white firs showed the largest increase, and ponderosa pine and sugar pine showed the smallest increases.

3. Co-dominant Douglas-fir and ponderosa pine trees showed a decrease in $Pred\Delta H_5$, and intermediate and suppressed Douglas-fir and ponderosa pine trees showed an increase in $Pred\Delta H_5$.

The validation statistics in Table 10 show that Equation [1] with Equation [5.1] for Douglas-fir explains from 45% to 25% of the variation (as indicated by R^2_a) in the overall validation data, depending upon whether b_0 was used as estimated or set to '1', respectively. The overall validation statistics also indicate that setting b_0 to '1' resulted in an over-prediction bias (as indicated by the negative value for δ 46) of 1.9 ft, instead of an over-prediction bias of over 0.9 ft when the value of b_0 calculated from the modeling data was used. If the overall bias could be removed, then the amount of variation explained would have increased to 49% with the use of b_0 at fit, or to 46% with b_0 set to '1'. The precision of the predictions (as indicated by the *MSE*) was higher (as indicated by the smaller value of the *MSE*) when the value of b_0 calculated from the modeling data was used.

Examination of the period-by-period validation statistics in Table 10 shows that, in only one growth period on one installation (1983 to 1987 at Stampede Creek), setting $b_{0,1}$ to '1' produced a smaller under-prediction bias and a higher level of precision than b_0 as estimated. For the modeling data set, 53% of the data fell into the 1978 to 1982 growth period and 5% fell into the 1988 to 1992 growth period. For a total of 95% of the modeling data, at least 4 yr of ΔH_5 were from these two growth periods. Both of these periods at Stampede Creek showed smaller measured ΔH_5 than predicted from Equation [1] and Equation [5.1] with $b_{0,1}$ set to '1' (Table 10), confirming the earlier analysis that for the growth periods measured in this study, ΔH_5 values for Douglas-fir were lower than the average long-term growth rates determined from the Douglas-fir dominant height growth equation of Hann and Scrivani (1987).

At Fawn Saddle, Equation [1] with Equation [5.1] for Douglas-fir consistently over-predicted ΔH_5. Part of this over-prediction could be related to the difficulty of estimating *SI* in young plantations (Hann et al. 2002). Often *SI* estimates are over-predicted in very young plantations, with the predictions declining as the plantation ages. The estimated SI_{DF} at Fawn Saddle is higher than that for any of the plots measured in this study (Table 2). SI_{DF} in 1990 was estimated to be 153.6 ft, and its estimate in 1998 has dropped to 149.7 ft.

If the bias could be removed, then Equation [1] with Equation [5.1] would explain 49% of the variation in ΔH_5 found in the overall validation data set (Table 10). Hann and Hanus (2002) used the same installations to validate 5-yr diameter growth rate equations. They found that the equations could explain 77% of the variation in the validation data set with the removal of bias. Two factors could explain why the ΔH_5 equations explained less of the variation in this study:

1. The ΔH_5 values on the validation installations came from repeat measurement of *H* on standing trees. As Larsen et al. (1987) demonstrated, *H* measured on a standing tree is very susceptible to measurement error, which would directly increase the amount of unexplainable variation in the ΔH_5 values.
2. Both *H* and *HCB* were subsampled on each of the validation installations. For the remainder of the trees, *H* and *HCB* values were filled in using previously developed

predictor equations (see the description of the validation data sets in the Data section). This procedure introduces measurement error into the calculation of the *CCH* values and, as a result, could also increase the amount of unexplainable variation.

Because the validation data came from only two locations within the study area, it is recommended that $b_{0,1}$ and $b_{0,2}$ be set to '1' for projections of future ΔH_5. This recommendation assumes that the slower ΔH_5 for Douglas-fir found in the validation data set is either atypical of the region or does not indicate permanent deviations in height growth trends related to regional climate change.

Based upon the *YCUT* analysis, the ΔH_5 equations for grand fir, white fir, incense-cedar, ponderosa pine, and sugar pine can be applied to unthinned stands and to all thinned stands, regardless of the amount of time since thinning. The ΔH_5 equations for Douglas-fir can be applied to unthinned stands and to stands thinned more than 10 yr in the past. Estimates of ΔH_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. (2002) to the Douglas-fir equations produced in this study.

IMPACT OF DAMAGE ON ΔH_5

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 (Tables 8 and 11). The following modification of Equation [5.1] was used to examine whether these differences were statistically significant for the largest data set (i.e., Douglas-fir, Table 4):

$$B_{0,1} = b_{0,1} + \varsigma_{0,1}(I_{Damage})$$

$$B_{1,1} = b_{1,1} + \varsigma_{1,1}(I_{Damage})$$

$$B_{2,1} = b_{2,1} + \varsigma_{2,1}(I_{Damage})$$

$$B_{3,1} = b_{3,1} + \varsigma_{3,1}(I_{Damage})$$

where,

$I_{Damage} =$ *1* if the tree is damaged, *0* otherwise

The equation was fit to the combined undamaged and damaged data set by means of 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 significant difference from '0' by means of a *t*-test and $P = 0.05$. From this process, it was determined that the adjustment parameters on the $SCCH_j$ variables (i.e., $\varsigma_{1,1}$ and $\varsigma_{2,1}$) for damaged trees were significantly different from '0'. Therefore, including damaged trees in the modeling data set does significantly affect the estimated parameters of the resulting ΔH_5 equation.

Table 14. Percentage of Douglas-fir with significant damage codes in the sample and in the sampled population.

Damage Code	Percent of sample trees	Percent of sampled population
0	69.27	55.31
22	1.27	1.97
43	0.55	0.86
61	19.82	29.69
62	0.64	0.35
71	4.54	6.73
75	1.15	1.12

Of the 15 damaging agents found in the Douglas-fir ΔH_5 data sets (Table 12), six different damaging agents had a statistically significant impact upon the ΔH_5 of Douglas-fir in southwest Oregon (Table 13). Table 14 indicates that some of these damaging agents occurred relatively infrequently in both the sample trees (i.e., calculated excluding the trees' $EXPAN_i$) and in the sampled population (i.e., calculated including the trees' $EXPAN_i$) for the stands sampled in the study. An exception to this finding was suppression damage in small trees (damage code 61), where nearly 30% of the Douglas-fir trees in the sampled population were affected.

The impact of the damaging agents always produced a reduction in ΔH_5 for Douglas-fir (Table 13). Severely damaged trees always produced reductions equal to or greater than the reductions of light damage. For severely damaged trees, the size of the reduction for Equation [1] with Equation [5.1] ranged from 10.80% for trees with natural mechanical injury (damage code of 71) to 45.01% for small suppressed trees (damage code 61). Only four of the six damaging agents were common to Equations [5.1], [5.2], and [5.3]: both suppression agents (damage codes 61 and 62), natural mechanical injury (damage code 71), and excessive lean (damage code 75).

It has been shown previously that for trees with many of these damaging agents, values for H (Hanus et al. 1999), HCB (Hanus et al. 2000), and ΔD_5 (Hann and Hanus 2002) are significantly different from those of undamaged trees. Table 15 presents a summary of the effects upon H, HCB, and ΔD_5 of those damaging agents found to have a signifi-

Table 15. Effects of selected damaging agents upon H (Hanus et al. 1999), HCB (Hanus et al. 2000) and ΔD_5 (Hann and Hanus 2001). The damaging agents selected were those found to have an effect upon ΔH_5 for Douglas-fir. A ranking of 1 indicates the largest reduction or increase.

Equation	Damage Code	Effect on H	Ranking of effect on H	Effect on HCB	Ranking of effect on HCB	Effect on ΔD_5	Ranking of effect on ΔD_5
[5.1]	43	Increase	3	No Change	NA	No Change	NA
	61	Increase	1	Increase	2	Reduction	2
	62	No Change	NA	Increase	1	Reduction	1
	71	Reduction	2	Increase	4	Reduction	3
	75	No Change	NA	Increase	3	Reduction	4
[5.2]	61	Increase	1	Increase	2	Reduction	2
	62	No Change	NA	Increase	1	Reduction	1
	71	Reduction	2	Increase	4	Reduction	3
	75	No Change	NA	Increase	3	Reduction	4
[5.3]	22	No Change	NA	Increase	5	No Change	NA
	61	Increase	1	Increase	2	Reduction	2
	62	No Change	NA	Increase	1	Reduction	1
	71	Reduction	2	Increase	4	Reduction	3
	75	No Change	NA	Increase	3	Reduction	4

cant effect upon ΔH_5 for Douglas-fir. For damaged trees, all four of the common damaging agents resulted in increased HCB and decreased ΔD_5, compared with undamaged trees. The effect of damaging agents upon H of Douglas-fir was quite mixed. Trees with damage code 61 had larger H values and trees with damage code 71 had smaller H values. Because CR is a function of H and HCB, changes in these values can result in a change in CR. CR decreased in all situations in which there was an increase in HCB and/or a reduction in H. With an increase in H, CR might increase or decrease, depending upon 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 ΔH_5 reduction is attributable to more than a possible change in CR_I.

Reductions in ΔH_5 can be caused by several different alterations resulting from damage. The damaging agents found to significantly reduce ΔH_5 for Douglas-fir can be related to one of these alterations.

1. *Loss of vertical position within the stand leading to increased shading.* The vertical position of the tree's top within the stand can affect the intensity of light striking the crown and, therefore, the amount of photosynthate produced by the crown (Oliver and Larson 1996). CCH is based upon each tree's measured height and therefore indicates vertical position within the stand. However, for a tree with a severe lean (damage code 75), the vertical position of the top of the tree is inferior to what its measured H would indicate. For leaning trees, H is the length of the bole, not the vertical distance from ground to tree top.
2. *Loss of photosynthetically efficient crown.* Grazing by wildlife (damage code 43) can remove young needles and shoots, which are the most photosynthetically efficient leaves at any vertical position within the crown (Mitchell 1975). Trees with suppression damage (damage codes 61 and 62) can exhibit an extreme sparseness of foliage (Hanus et al. 2000).
3. *Loss of xylem, phloem, and/or cambium needed for conducting moisture, mineral salts and photosynthate.* Direct loss of xylem, phloem, and/or cambium can be caused by rolling rocks and logs and abrasion between trees (damage code 71).

These factors probably do not express all of the mechanisms by which damaging agents affect the ΔH of trees. The damage codes used in this study often include many damaging agents, and some of the damage codes have vague definitions—for example, suppression damage codes (61 and 62). Hann and Hanus (2002) found that 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." By definition, 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 might indicate something more than just loss of vertical position, as indicated by the suppressed crown class, or sparse foliage. The field crews' application of the suppression damage codes could be their way of saying, "This is a very poor quality tree with many problems, including suppression."

The findings of this analysis indicate that damaging agents can have a significant impact upon ΔH_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, for a given stand structure, to vary geographically and chronologically. The fact that many of the significant damaging agents encountered in this study occurred relatively infrequently ignores both the relatively large number of different damaging agents encountered (e.g., Table 14 indicates that over 45% of the trees sampled in Douglas-fir population were damaged) and the long duration of most stands, which 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 upon tree attributes such as H, HCB, ΔD, ΔH_5, and mortality rate. It is unfortunate that the long-term data on the characterization and dynamics of damaging agents needed to develop such prediction equations are not now available. We recommend, therefore, a determined effort to collect such data.

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