Research Contribution 49

# Reanalysis of the SMC-ORGANON Equations for Diameter-growth Rate, Height-growth Rate, and Mortality Rate of Douglas-fir

by

David W Hann

David D Marshall

Mark L Hanus

November 2006

Oregon State University

Forest Research Laboratory

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

## The Authors

David Hann is Professor, Department of Forest Resources; David Marshall is Affiliate Professor, Department of Forest Resources and is employed by Weyerhaeuser Company, Federal Way, Washington; and Mark Hanus is Affiliate Professor, Department of Forest Resources, and Vice President for Biometrics & Inventory Services, FORSight Resources LLC, Vancouver, WA.

## Acknowledgments

Funding for this work was provided by the Stand Management Cooperative, University of Washington, Seattle.

## Disclaimer



## To Order Copies

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

Forestry Communications Group
Oregon State University
256 Peavy Hall
Corvallis, OR 97331-5704
FAX:(541) 737-4077
email: ForestryCommunications@oregonstate.edu
Phone:(541) 737-4271
Web site:http://fcg.cof.orst.edu\
Please indicate author(s), title, and publication number if known.

Recycled Paper

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

Research Contribution 49

November 2006

# Reanalysis of the SMC-ORGANON Equations for Diameter-growth Rate, Height-growth Rate, and Mortality Rate of Douglas-fir

by

David W Hann

David D Marshall

Mark L Hanus

Forest Research Laboratory

# Abstract

Hann, DW, DD Marshall, and ML Hanus. 2006. *Reanalysis of the SMC-ORGANON Equations for Diameter-growth Rate, Height-growth Rate, and Mortality Rate of Douglas-fir*. Research Contribution 49, Forest Research Laboratory, Oregon State University, Corvallis.

Using existing data from untreated research plots, we developed equations for predicting 5-yr diameter-growth rate ($\Delta D_5$), 5-yr height-growth rate ($\Delta H_5$), and 5-yr mortality rate ($PM_5$) for Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] in the coastal region of the Pacific Northwest. These equations are revisions of the equations constructed in 1995–1997 for the Stand Management Cooperative's (SMC) version of the ORGANON growth-and-yield model, and they have been developed with substantially larger and more comprehensive data sets than were available in 1995–1997. The new $\Delta D_5$ and $\Delta H_5$ equations were validated with an independent data set. The $PM_5$ equation was evaluated by comparing 100-yr predictions of Reineke's (1933) stand density index to behavior previously reported from measurements taken on long-term research plots. The new $\Delta D_5$, $\Delta H_5$, and $PM_5$ equations appear to be considerably superior in predictive ability and behavior to the original equations.

The effects of the new equations on stand-level predictions were evaluated by comparing the maximum mean annual increments (*MAI*) in total stem volume (ft$^3$) and associated rotation ages (*RA*) predicted from the original SMC-ORGANON model to predictions from the revised SMC-ORGANON model. This analysis was done by making 100-yr projections using 170 plots in young stands from the SMC data sets. Some of the ending values for average crown ratio (*CR*) after 100 yr of projection were near 15%, however, and predictions of basal area (*BA*) for some of these stands peaked and then declined over stand age. Substituting the *HCB* equation published by Hann and Hanus in 2004 for predicting crown recession ($\Delta HCB_5$) eliminated the problem with *BA* peaking over stand age and resulted in somewhat larger average ending *CR*s. The 100-yr projections were then made again with the 2004 HCB equation of Hann and Hanus. On average, the revised model reduced *RA* by 2.1 yr (or 4.3%) and maximum *MAI* by 55.7 ft$^3$/ac/yr (18.9%).



**Keywords:** Growth-and-yield model, stand development, Stand Management Cooperative

## Contents

# List of Tables

# Introduction

The equations developed for predicting the 5-yr diameter growth rate ($\Delta D_5$), 5-yr height growth rate ($\Delta H_5$), and 5-yr mortality rate ($PM_5$) of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] in the Stand Management Cooperative (SMC; Chappell and Osawa 1991) version of ORGANON (SMC-ORGANON; Hann et al. 1997) were completed in 1997. Because of several data problems, measurements from the SMC Type I and Type III installations were not included in the development of these equations (Hann et al. 2003). Only about a third of the Type I installations had been installed long enough to have a single 4-yr remeasurement at the time the modeling data set was created. Furthermore, calculated site index (*SI*) values were inflated because the top-height growth rates were much greater than expected from the top-height-growth equations of Bruce (1981) for the given ages. The Type III installations were installed even later and in younger stands than in the Type I installations so, in addition to the *SI* estimation problem and lack of remeasurements, much of the data available from them were from measurements taken before the stands reached breast height or crown closure. As a result, the competing vegetation still influenced tree development. Finally, the single 4-yr remeasurement period available for the older Type II installations had to be extrapolated to the 5-yr growth period used in ORGANON.

Since the original SMC-ORGANON equations were created, (1) the subsequent 12 yr have allowed for additional plot establishment, remeasurements, and growth, and (2) a new dominant-height-growth equation has been produced that predominantly utilizes data from SMC installations (Flewelling et al. 2001). Comparison of the dominant-height-growth equation of Flewelling et al. (2001) to that of Bruce (1981) shows close agreement for total ages >15 yr. Bruce's *SI* ($SI_B$) (Bruce 1981) can therefore be estimated by predicting dominant height from the equation of Flewelling et al. (2001) at a breast height age (BHA) of 50 yr. Therefore, it is now very likely that a reasonable estimate of $SI_B$ can be determined on the Type I and Type III installations.

Given these developments, the SMC decided to reanalyze the $\Delta D_5$, $\Delta H_5$, and $PM_5$ equations for Douglas-fir in order to better characterize these values in young plantations. The resulting new equations are to be inserted into a revised version of SMC-ORGANON and tested against the original version.

## Data Description

This analysis utilized eight data sets. Four came from the SMC, and three from data collected in previous ORGANON modeling work. The eighth data set came from plots considered to be unaffected by Swiss needle cast that were established by the Swiss Needle Cast Cooperative (SNCC) to monitor Swiss needle cast infection in the Oregon Coast Range (Maguire et al. 2004). The first seven data sets were used in the modeling phase of the analysis, and the eighth was used in validation.

Basic tree measurements needed to model $\Delta D_5$, $\Delta H_5$, and $PM_5$ include diameter at breast height (*D*), total height (*H*), height to crown base (*HCB*), and the expansion factor (*EF)* for each sample tree at each measurement. The *EF* is the number of trees per acre (tpa) that each sample tree represents. Tree and plot attributes measured at the start of the growth period (denoted by a subscript of "S") that have previously been used to predict $\Delta D_5$ (Hann et al. 2003) include the *SI* of the installation, the basal area per acre of the plot ($BA_S$), the $D_S$ and crown ratio ($CR_S$) of the tree, and the *BA*/ac in trees with $D_S$ larger than the subject tree on the plot ($BAL_S$). Attributes previously used to predict $\Delta H_5$ (Hann et al. 2003) include the *SI* of the installation, the $H_S$ and $CR_S$ of the subject tree, and the percent crown closure of the plot at the tip of the subject tree ($CCH_S$). Attributes previously used to predict $PM_5$ (Hann et al. 2003) include the *SI* of the installation and the subject tree's $D_S$, $CR_S$, and $BAL_S$.

### Data from SMC Cooperators

The first SMC data set selected for this analysis was part of the data used to develop the original version of SMC-ORGANON. All of the data donated by the SMC cooperators came from untreated permanent plots in even-aged Douglas-fir stands on public and private ownerships throughout southwestern British Columbia, western Washington, and northwestern Oregon. The 19 installations containing these plots were originally established in both plantations and natural stands to explore a variety of silvicultural objectives. Plot sizes ranged from 0.05 to 1.0 ac, with the 0.2-ac plot being most common. These $\Delta D_5$, $\Delta H_5$, and $PM_5$ data sets are described fully by Hann et al. (2003).

### Data from SMC Installations

The Type I, II, and III installations of the SMC that had been established in pure Douglas-fir plantations were also used in this analysis. Total age (TA) at establishment ranged from 6 to 18 yr on the 29 Type I installations, from 18 to 40 yr on the 12 Type II installations, and from 5 to 10 yr on the 21 Type III installations. The Type I and II installations each contained a single control plot of 0.5 ac. The Type III installations contained one control plot in each of the six planting densities (100, 200, 300, 440, 680, and 1,210 tpa) on an installation. Plot sizes on the Type III installations ranged from 0.496 ac for the 100-tpa planting density to 0.212 ac for the 1,210-tpa density. For all three types of SMC installations, the remeasurement intervals were either 2 or 4 yr, and the total length of measurements ranged from 8 to 12 yr. *H* and *HCB* were subsampled on all of the SMC installations.

The calculation of CCH requires estimates of *H* and *HCB* for all trees on the plot. To fill in *H*, the following equation form was used to characterize the height-diameter relationship for the measured values of *H* and *D* for each measurement on each plot:

$$H = 4.5 + e^{a_0 + a_1 D^{-1}} \quad [1]$$

The parameters $a_0$ and $a_1$ of Eq. [1] were estimated by taking the logarithms of both sides of the equation and fitting the resulting log-log equation to the data with linear regression. Examination of the sizes of the resulting mean squared errors (MSEs) for these fits indicated that correction for log bias was unnecessary. Predictions from Eq. [1] were then used to estimate *H* on trees without direct measurements.

Missing values of *HCB* were estimated using the *HCB* equation of Hann et al. (2003). The equation was first scaled to the actual measurements of *HCB* for each plot and growth period combination by application of weighted simple linear regression through the origin and a weight of $H^{-2}$ (Hann et al. 2003). Hanus et al. (1999, 2000) found that scaling reduced variation caused by between-plot/growth-period differences not explained by the "regional" equations.

Two methods of measuring *HCB* have been used extensively in the Pacific Northwest. In the first method, the lower branches on the longer side of the crown of trees of uneven crown length are transferred mentally to fill in the missing portion of the shorter side of the crown. 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). This method is used in the ORGANON model.

In the second method, 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. The *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 $HCB_{3/4}$ is the method used in the SMC installation data sets, the equation of Hann and Hanus (2002a) was used to convert $HCB_{3/4}$ to *HCB*. This conversion equation predicts very small differences between $HCB_{3/4}$ and HCB for trees with very large CR. Therefore, the correction was small for the young, long-crowned trees in the Type I and III data sets.

Crown length (*CL*) for each tree and measurement was calculated by subtracting *HCB* from *H*. The *CR* was then computed by dividing *CL* by *H*. The *EF* for each sample tree was calculated by taking the reciprocal of the plot area (ac). A dichotomous survival variable was also formed for each tree and measurement, with a value = 1 if the tree survived the next 4-yr growth period and a value = 0 if it did not.

$CCH_S$ was determined by (1) computing the crown width (*CW*) of each sample tree at the height of the subject tree's top, using the largest crown width equations of Hann (1997) and the crown-profile equations of Hann (1999), (2) converting *CW* to crown area (*CA*) by assuming the crowns are circular at a given height, (3) multiplying each sample tree's *CA* by the tree's *EF* and summing across all sample trees, and (4) expressing the sum as a percentage of the plot's area.

Both *TA* and breast height age at the last measurement were needed to calculate site indices for the SMC Type I, II, and III control plots. The *TA* is defined as the number of growing seasons completed by the trees and was determined by converting the date of planting and the date of last measurement to number of growing seasons since planting and then adding to it the total age of seedlings at time of planting.

*BHA* is defined as the average number of growing seasons completed by the top height trees (i.e., the 40 largest diameter trees) on the plot after the trees had reached 4.5 ft in height. Because a tree could reach 4.5 ft in height during a growing season, it is not unusual for BHA to be continuous, rather than integer, numbers. The recognition and correct measurement of fractional *BHA* is particularly critical in the calculation of *SI* in very young stands. For each plot, *BHA* was computed as the average *BHA* from increment cores or whorl counts of those trees with *D* at least as large as the minimum *D* of the top height trees at the last measurement.

Top height for each measurement on each control plot was computed by averaging the heights of the 40 largest diameter trees on the plot (*H40)*. Five alternative means of determining $SI_B$ were evaluated (Appendix 1). We concluded from this evaluation that the traditional method of calculating $SI_B$ could be used with this data set.

ORGANON uses a 5-yr growth period. The procedure used to model PM can directly use the 4-yr measurement data to estimate $PM_5$ (Hann et al. 2003). This is not true for estimating the $\Delta D_5$ and $\Delta H_5$ equations. Therefore, the interpolation and extrapolation procedures described by Hann et al. (2003) were used to obtain the necessary 5-yr measurements of $\Delta D_5$ and $\Delta H_5$. All possible consecutive 5-yr growth periods were produced for each sample tree, beginning with the first measurement where $D > 0$. Because each 5-yr growth period was required to start with an actual measurement (i.e., not extrapolated values) and the usage of even growth measurement intervals, it was sometimes necessary to overlap the resulting consecutive growth periods. The amount of overlap was limited to 1 yr where this was necessary. Only one of the consecutive growth periods, randomly selected from each tree, was used in the final $\Delta D_5$ and $\Delta H_5$ modeling data sets.

## ORGANON Data Sets

The $\Delta D_5$ analysis of Hann and Hanus (2002a) showed that the model's predictive behavior could be substantially improved by including larger diameter trees in the analysis. Because the SMC data sets did not contain very large trees, we decided to conduct a giant size regression analysis (Cunia 1973) by including the data from three ORGANON modeling projects in the development of the new SMC $\Delta D_5$ equation. An added benefit from this giant size regression analysis is the creation of new $\Delta D_5$ equations for the southwest Oregon and Northwest Oregon versions of ORGANON.

The three ORGANON $\Delta D_5$ studies of Douglas-fir used backdating of temporary plots to collect the modeling data. The southwest Oregon study sampled 527 plots containing Douglas-fir (Hann and Hanus 2002a). Of these, 357 plots had not been thinned within 20 yr of establishment and were therefore used in this analysis. Plots ranged from even-aged to uneven-aged in structure (with tree ages >250 yr) and from pure to mixed species in composition. The northwest Oregon study sampled 136 plots on the College of Forestry's McDonald-Dunn Research Forest (Zumrawi and Hann 1993). Plots were predominantly even-aged in structure with at least 80% of their basal area in Douglas-fir. The western Washington study sampled 34 plots (McKenzie 1994). Plots were predominantly two-tiered in structure and composed primarily of Douglas-fir and western hemlock.

In all three studies, each plot was composed of a minimum of four 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 plot design composed of four subplots: trees with $D \leq 4.0$ in. were selected on a 1/229-ac fixed-area subplot, trees with $D$ = 4.1–8.0 in. were selected on a 1/57-ac fixed-area subplot, and trees with $D > 8.0$ in. were selected on a 20 basal area factor (BAF) variable-radius subplot. For the southwest Oregon study, trees with $D > 36.0$ in. were selected on a 60-BAF variable-radius subplot.

Measurements of $D$, $H$, and $HCB$ at the end of the growth period were taken on all sample trees in all three data sets. Backdating procedures for calculating $D_S$, $H_S$, $HCB_S$, and $EF_S$ are described in Hann and Hanus (2001) for the southwest Oregon data set, in Ritchie and Hann (1985) for the northwest Oregon data set, and in McKenzie (1994) for the western Washington data set. Procedures for calculating $SI$, $BA_S$, and $BAL_S$ are described in Hann and Hanus (2002a) for the southwest Oregon data set, in Zumrawi and Hann (1993) for the northwest Oregon data set, and in McKenzie (1994) for the western Washington data set. Hann and Scrivani's (1987) $SI$ ($SI_{H\&S}$) was used in the southwestern Oregon data set, and $SI_B$ was used in the northwest Oregon and western Washington data sets.

## Data from SNCC Installations

Each 0.2-ac SNCC plot was established in 1998 and remeasured every 2 yr over 6 yr. Swiss needle cast damage was assessed at each measurement by determining the average number of years that the foliage had been retained (*FOLRET*). Previous analysis of this data indicated that $\Delta D$ and $\Delta H$ were reduced when *FOLRET* fell to <2.5 (Douglas Maguire, personal communication). We therefore averaged the *FOLRET* values across all measurements on each plot and eliminated those plots with average *FOLRET* <2.5. This left a total of 27 unaffected plots available for validation. The *BHA* at the establishment of these plots ranged from 6 to 24 yr. Both $H$ and $HCB$ were subsampled on these plots.

The parameters of Eq. [1] were estimated by linear regression on the log-log transformation of Eq. [1] and the measured values of $H$ and $D$ for each measurement on each plot. Predictions from this equation were then used to estimate $H$ on trees without direct measurements. Missing values of $HCB$ were estimated from the $HCB$ equation of Hann et al. (2003). The $HCB$ equation was first scaled to the actual measurements of $HCB$ for each plot and growth period combination by application of weighted, simple linear regression through the origin and a weight of $H^{-2}$ (Hann et al. 2003).

$HCB$ was measured to the lowest live branch ($HCB_{LLB}$) on the SNCC plots. Maguire and Hann (1987) showed that $HCB$ was $\geq HCB_{LLB}$. Therefore, it was necessary to develop and apply the following equation for converting $HCB_{LLB}$ to $HCB$ using the data set of Maguire and Hann (1987):

$$HCB = HCB_{LLB} - 20.7070885[1.0 - e^{-(H - HCB_{LLB}/100)^{1.4}}]$$

$CL$ was then calculated for each tree and measurement and $CR$ was computed by dividing $CL$ by $H$. The $EF$ for each sample tree was calculated by taking the reciprocal of the plot area in acres. $CCH_S$ was then determined as previously described.

Planting ages and BHA were supplied with the data set. Top height for each measurement on each control plot was computed by averaging the heights of the 40 largest diameter trees on the plot (*H40*). $SI_B$ was computed using the last measurement of *H40* and *BHA*.

A 5-yr growth period was determined by linearly interpolating between the $D$ and $H$ values measured in the third and fourth measurements.

# Data Analysis

## $\Delta D_5$ Equation

The first step of the $\Delta D_5$ analysis applied the original control plot equation of Hann et al. (2003) to the data from the SMC Type I, II and III installations and computed the residuals of actual $\Delta D_5$ minus predicted $\Delta D_5$ ($Pred\Delta D_5$). The data used in this and subsequent $\Delta D_5$ analyses were restricted to observations with an actual measurement of $CR_S$. Negative values of $\Delta D_5$ were treated as measurement errors and they were removed from all analyses (this eliminated 98 trees from the SMC data sets). The residuals were then plotted over $Pred\Delta D_5$, $D_S$, $CR_S$, $SI_B$, $BA_{Sa}$, and $BAL_S$ and evaluated for trends. These graphs indicated that the original equation underpredicted $\Delta D_5$ for trees with small diameters and that the underprediction was most severe in the SMC Type III installations.

Hann and Hanus (2002a) found that the following model form allowed for larger predictions of $\Delta D_5$ for trees with small $D$:

$$\Delta D_5 = e^{\sum_{i=0}^{6} b_i X_i} + \varepsilon_{\Delta D} \qquad [2]$$

where

$X_0 = 1.0$

$X_1 = \ln(D_S + k)$

$X_2 = D_S$

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

$X_4 = \ln(SI - 4.5)$

$X_5 = SBAL_S/[\ln(D_S + 2.7)]$

$X_6 = SBA_S^{1/2}$

$b_i$ = regression parameter for $i^{th}$ variable

$k$ = 5.0 in the southwest Oregon analysis

$\varepsilon_{\Delta D}$ = random error on $\Delta D_5$

Eq. [2] was also more effective at characterizing the $\Delta D_5$ of trees with very large $D$. Unfortunately, the data from the SMC cooperators and the SMC installations do not contain trees with large $D$. We therefore decided to include the $\Delta D_5$ modeling data sets from the three ORGANON projects to ameliorate this problem.

In incorporating the ORGANON data into the analysis, we assumed that the relationship of $\Delta D_5$ to $D_S$ and $CR_S$ was the same across all of the modeling data sets. We then added six indicator variables to Eq. [2] in order to recognize differences in how, where, and when the data were collected. These additional variables identified that (1) $SI_{H\&S}$ used in southwest Oregon differed from $SI_B$ used in all of the other data sets, (2) the calculated values of $BA_S$ and $BAL_S$ could be affected by the substantial difference between the ORGANON plot design and the plot design in the SMC data sets (Hann and Zumrawi 1991), and (3) the three ORGANON modeling data sets were collected over relatively short periods on temporary plots in different parts of the Pacific Northwest.

This expansion resulted in the following equation for predicting $\Delta D_5$:

$$\Delta D_5 = e^{\sum_{i=0}^{12} b_i X_i} + \varepsilon_{\Delta D} \quad [3]$$

where

$X_7 = I_{SWO}$

$X_8 = I_{NWO}$

$X_9 = I_{WWA}$

$X_{10} = I_{SWO} \ln(SI_{H\&S} - 4.5)$

$X_{11} = \{I_{ORG}\}\{SBAL_S/[\ln(D_S + 2.7)]\}$

$X_{12} = (I_{ORG})(SBA_S^{1/2})$

$I_{SWO}$ = 1.0 if data came from the SWO-ORGANON data set, = 0.0 otherwise.

$I_{NWO}$ = 1.0 if data came from the NWO-ORGANON data set, = 0.0 otherwise.

$I_{WWA}$ = 1.0 if data came from the WWA-ORGANON data set, = 0.0 otherwise.

$I_{ORG} = I_{SWO} + I_{NWO} + I_{WWA}$

$k$ = an adjustment parameter on $D_S$, estimated to the nearest 0.1 in.

In order to remain congruent with the definition of $X_{10}$, $X_4$ was redefined as

$X_4 = (1.0 - I_{SWO})\ln(SI_B - 4.5)$

Table 1. Sample size and summary statistics, expressed as mean (range), for the tree-level and the plot level $\Delta D_5$ data, by data source. The SNCC data set was used for validation; the remaining data sources were used for modeling.

| Variable | SMC cooperators | SMC installations | ORGANON | SNCC |
|---|---|---|---|---|
| | | **Trees** | | |
| $n$ | 2,643 | 8,824 | 21,627 | 965 |
| $\Delta D_S$ | 0.6 (0.0–3.1) | 2.3 (0.0–5.4) | 1.0 (0.1–5.7) | 2.1 (0.0–5.2) |
| $D_S$ | 7.3 (0.6–36.7) | 3.0 (0.1–20.5) | 18.4 (0.1–81.8) | 7.2 (0.7–18.1) |
| $CR_S$ | 0.49 (0.06–0.90) | 0.88 (0.11–1.00) | 0.45 (0.04–1.00) | 0.86 (0.43–1.00) |
| $BAL_S$ | 90.8 (0.0–365.1) | 20.0 (0.0–201.4) | 91.8 (0.0–460.0) | 42.0 (0.0–142.5) |
| | | **Plots** | | |
| $n$ | 128 | 226 | 487[1] | 29 |
| $BA_S$ | 208.8 (24.6–385.1) | 34.5 (0.1–204.9) | 174.3 (0.1–558.2) | 78.4 (18.9–146.5) |
| $SI_B$ | 115.9 (77.6–137.9) | 132.3 (75.2–187.2) | 110.4 (64.2–142.0) | 134.8 (93.7–167.3) |
| $SI_{H\&S}$ | Not applicable | Not applicable | 99.8 (41.5-146.9) | Not applicable |

[1]There were 357 plots in the southwest Oregon data set that used $SI_{H\&S}$.

Applying the procedures described in Kmenta (1986) and Hann and Larsen (1991), we estimated the parameters of Eq. [3], (i.e., $b_i$), by weighted nonlinear regression with a weight of the reciprocal of $Pred\Delta D_5$, using the $\Delta D_5$ modeling data set described in Table 1. The value of $k$ was determined by starting with a value of 5.0 from Hann and Hanus (2002a) and systematically increasing or decreasing the value by increments of 0.1, refitting the $b_i$ parameters after each increment, until a minimum MSE for the model was achieved. This approach is identical to the application of nonlinear regression in which the parameter is estimated to one decimal place.

As a check of the equation, both the weighted and the unweighted residuals were examined for systematic trends across $Pred\Delta D_5$ and the independent variables. The mean unweighted residual, the standard deviation of the unweighted residuals, and the adjusted coefficient of determination ($R^2_a$) of the unweighted residuals were also calculated. This residual analysis was done for the combined data set and for each of the seven component data sets.

## $\Delta H_5$ Equation

As with the $\Delta D_5$ analysis, the first step of the $\Delta H_5$ analysis applied the original control plot equation of Hann et al. (2003) to the data from the SMC Type I, II, and III installations and computed the residuals of actual $\Delta H_5$ minus predicted $\Delta H_5$ ($Pred\Delta H_5$). The data set used in this and subsequent $\Delta H_5$ analyses was restricted to observations with an actual measurement of $CR_S$. The residuals were then plotted over $Pred\Delta H_5$, $CR_S$, and $CCH_S$ and evaluated for trends. These graphs indicated no significant trends. The average residual showed that the original equation underpredicted $\Delta H_5$ by less than 0.5 ft. Despite these good results, we decided to re-estimate the parameters with the newly expanded modeling data set.

In the "potential/modifier" approach used by Hann et al. (2003), the potential $\Delta H_5$ ($P\Delta H_5$) of the tree is first predicted and then a multiplicative modifier is used to adjust $P\Delta H_5$ for vigor and competitive status of the tree:

$$\Delta H_5 = (\mathrm{P}\Delta H_5)(\Delta HMOD) + \varepsilon_{\Delta \mathrm{H}} \quad [4]$$

where

$\Delta HMOD$ = height-growth rate modifier function

$$= c_0 \left[c_1 e^{c_2 \mathrm{CCH_S}} + \left(e^{c_3 \mathrm{CCH_S}^{0.5}} - c_1 e^{c_2 \mathrm{CCH_S}}\right) e^{-c_4 (1.0 - \mathrm{CR_S})^2 e^{c_5 \mathrm{CCH_S}^{0.5}}}\right] \quad [5]$$

$c_i$ = regression parameter for the $i^{\text{th}}$ variable

$\varepsilon_{\Delta \mathrm{H}}$ = random error on $\Delta H_5$

Table 2. Sample size and summary statistics, expressed as mean (range), for the tree-level and the plot-level $\Delta H_5$ data, by data source. The SNCC data set was used for validation; the remaining data sources were used for modeling.

| Variable | SMC cooperators | SMC installations | SNCC |
|---|---|---|---|
| | | **Tree-level** | |
| Trees (*n*) | 1,510 | 4,920 | 960 |
| $\Delta H_S$ | 6.9 | 14.2 | 13.5 |
| | (0.2–18.5) | (0.7–27.8) | (0.1–24.5) |
| $H_S$ | 47.4 | 19.7 | 40.0 |
| | (7.0–140.9) | (4.6–116.6) | (9.8–86.8) |
| $CR_S$ | 0.56 | 0.88 | 0.86 |
| | (0.09–0.91) | (0.31–1.00) | (0.43–1.00) |
| $CCH_S$ | 38.3 | 2.5 | 6.3 |
| | (0.0–364.4) | (0.0–64.6) | (0.0–72.2) |
| | | **Plot-level** | |
| Plots (*n*) | 105 | 226 | 29 |
| $SI_B$ | 112.6 | 132.7 | 134.8 |
| | (77.6–137.9) | (75.2–187.2) | (93.7–167.3) |

$P\Delta H_5 = f_B[SI_B,(GEA + 5.0)] - H_S$

$GEA = f_B^{-1}[SI_B, H_S]$, growth effective age

$f_B$ = the *H40* function of Bruce (1981)

The parameters of Eq. [4] were estimated using weighted nonlinear regression and a weight of $(P\Delta H_5)^{-2}$ by fitting Eq. [4] to the modeling data set described in Table 2. As a check of the equation, the residuals of both Eq. [4] and Eq. [5] were examined for systematic trends across $Pred\Delta H_5$ for Eq. [4], predicted $\Delta HMOD$ for Eq. [5], and *CR* and *CCH* for both equations. The mean residual, standard deviation of the residuals, and $R_a^2$ of the residuals were also calculated. This residual analysis was done for the combined data set and for each of the two component data sets.

## $PM_5$ Equation

The original mortality equation for SMC ORGANON used the following logistic model form (Hann et al. 2003):

$$PM_5 = [1.0 + e^{-Z}]^{-1.0} + \varepsilon_{PM} \quad [6]$$

where

$Z = d_0 + d_1 D_S + d_2 CR_S + d_3 SI_B + d_4 BAL_S$

$\varepsilon_{PM}$ = random error on $PM_5$

The regression coefficients, $d_i$, of the Z function for Eq. [6] were originally estimated using RISK (Hamilton 1974), a program useful when the capabilities of computers were very modest (Flewelling and Monserud 2002). In this reanalysis, the regression coefficients were estimated by using the maximum likelihood estimation procedures of SAS (Hann and Hanus 2001). The dichotomous survival variable was used as the dependent variable. The variable lengths of the growth periods in the data required that the parameters be estimated by using the following formulation (Flewelling and Monserud 2002):

$$PS_5 = [1.0 + e^{Z}]^{-PLEN} + \varepsilon_{PS} \quad [7]$$

where

$PS_5$ = the 5-yr probability of survival

*PLEN* = length of the growth period in 5-yr increments

= (length of the growth period in yr)/5

$\varepsilon_{PS}$ = random error on $PS_5$

The resulting regression coefficients, $d_i$, of the Z function are identical for both Eq. [6] and Eq. [7]. Because the sample trees have unequal sampling probabilities caused by the use of different plot sizes in the modeling data sets, each observation was weighted by $EF_S$. The parameters of Eq. [7] were estimated by maximum likelihood estimation by fitting Eq. [7] to the modeling data set described in Table 3.

Table 3. Sample size and summary statistics, expressed as mean (range), for the tree-level and the plot-level $PM_5$ data by sources of the data.

| Variable | SMC cooperators | SMC installations |
|---|---|---|
| | **Tree- level** | |
| Trees (*n*) | 149,430 | 46,364 |
| Dead (*n*) | 10,985 | 1,174 |
| *PLEN* | 5.3<br>(3.0–7.0) | 4.1<br>(4.0–6.0) |
| $D_S$ | 7.1<br>(0.1–67.1) | 4.0<br>(0.1–22.1) |
| $CR_S$ | 0.47<br>(0.13–0.97) | 0.78<br>(0.14–1.00) |
| $BAL_S$ | 116.5<br>(0.0–400.2) | 36.5<br>(0.0–225.6) |
| | **Plot-level** | |
| Plots (*n*) | 650 | 169 |
| $SI_B$ | 112.9<br>(56.1–156.0) | 132.3<br>(75.2–187.2) |

An evaluation of how well the equation fit the modeling data was based on the size of a $\chi^2$ "goodness-of-fit" (or "lack-of-fit") statistic (Hamilton 1974, Hann et al. 2003). A small value for both statistics indicates a good fit to the data. The $\chi^2$ goodness-of-fit statistic was computed as follows:

1. The sample trees were divided into 25 1-in. diameter classes. The actual number of trees surviving and the predicted number of trees surviving in each class were then determined. (The 25-in. class included all trees with $D \geq 25.1$)
2. The difference of actual survival rate minus predicted survival rate was calculated for each class.
3. Each difference of each class was squared and then divided by predicted survival rate (the "$\chi^2$ contribution"). Survival is commonly used in this type of evaluation to avoid inflating the statistic because of division by the small numbers usually associated with mortality.
4. The $\chi^2$ lack-of-fit statistic was formed by summing the $\chi^2$ contributions across all classes.

A significance test can be formed by comparing this goodness-of-fit statistic against a critical $\chi^2$ value (Snedecor and Cochran 1980). As a comparison, the $\chi^2$ goodness-of-fit statistic was also calculated for the control plot mortality equation of Hann et al. (2003).

## $\Delta D_5$ Validation Procedures

The predictive ability of Eq. [3] was evaluated using the validation data set described in Table 1. *Pred*$\Delta D_5$ was computed for each tree in the validation data set and the difference ($\delta_{i,\Delta D}$) of actual $\Delta D_5$ minus *Pred*$\Delta D_5$ was calculated. The following validation statistics were then computed (Hann and Hanus 2002a):

$$\bar{\delta}_{\Delta D} = \sum_{i=1}^{m} \frac{\delta_{i,\Delta D}}{m}$$

$$\mathrm{MSE}_{\Delta D} = \sum_{i=1}^{m} \frac{\delta^2_{i,\Delta D}}{m}$$

$$\text{with-bias } R^2_{a,\Delta D} = 1.0 - \frac{\mathrm{MSE}_{\Delta D}}{\mathrm{Var}(\Delta D_5)}$$

$$\text{without - bias } R^2_{a,\Delta D} = 1.0 - \frac{[m/(m-1)][\mathrm{MSE}_{\Delta D} - \bar{\delta}^2_{\Delta D}]}{\mathrm{Var}(\Delta D_5)}$$

where

$\bar{\delta}_{\Delta D}$ = the mean difference of $\Delta D_5$

$\mathrm{MSE}_{\Delta D}$ = the mean square error of $\Delta D_5$

$R^2_{a,\Delta D}$= adjusted coefficient of variation of $\Delta D_5$

$m$ = number of $\Delta D_5$ validation observations

Var ($\Delta D_5$) = estimated variance of actual $\Delta D_5$

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

$$\overline{\Delta D_5} = \text{mean of actual } \Delta D_5$$

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

$\bar{\delta}_{\Delta D}$ is a measure of bias, and $\text{MSE}_{\Delta D}$ is a measure of precision. It is desirable to have both values as near to 0 as possible. Both values of $R^2_{a,\Delta D}$ 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 $R^2_{a,\Delta D}$ 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 of 1 for $R^2_{a,\Delta D}$ that has removed possible bias 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 $R^2_{a,\Delta D}$ indicates that a mean $\Delta D_5$ predicts better than the regression equation. It should be noted that if $\bar{\delta}_{\Delta D}$ were 0 for a data set, the with-bias $R^2_{a,\Delta D}$ would be somewhat larger that the without-bias $R^2_{a,\Delta D}$ because the equation for the latter includes $m/(m - 1)$, which is always >1.

## $\Delta H_5$ Validation Procedures

The predictive ability of Eq. [4] with Eq. [5] was evaluated using the validation data set described in Table 2. *Pred*$\Delta H_5$ was computed for each tree in the validation data set and the difference ($\delta_{\Delta H,i}$) of actual $\Delta H_5$ minus *Pred*$\Delta H_5$ was calculated. The following validation statistics were then computed (Hann and Hanus 2002b):

$$\bar{\delta}_{\Delta H} = \sum_{i=1}^{m} \frac{\delta_{\Delta H,i}}{m}$$

$$\text{MSE}_{\Delta H} = \sum_{i=1}^{m} \frac{\delta^2_{\Delta H,i}}{m}$$

$$\text{with-bias } R^2_{a,\Delta H} = 1.0 - \frac{\text{MSE}_{\Delta H}}{\text{Var}(\Delta H_5)}$$

$$\text{without-bias } R^2_{a,\Delta H} = 1.0 - \frac{[m/(m-1)][\text{MSE}_{\Delta H} - \bar{\delta}^2_{\Delta H}]}{\text{Var}(\Delta H_5)}$$

where

$\bar{\delta}_{\Delta H}$ = the mean difference of $\Delta H$

$MSE_{\Delta H}$ = mean square error for $\Delta H$

$R^2_{a, \Delta H}$ = adjusted coefficient of determination of $\Delta H$

$m$ = number of $\Delta H_5$ validation observations

$Var(\Delta H_5)$ = variance of measured $\Delta H_5$

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

$\overline{\Delta H_5}$ = mean of actual $\Delta H_5$

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

As with the $\Delta D_5$ validation analysis, $\delta_{\Delta H}$ is a measure of bias, $MSE_{\Delta H}$ is a measure of precision, and both values of $R^2_{a,\Delta H}$ provide a measure of how well the regression equation fits the data.

## Evaluating Effect of New Equations on Stand-level Predictions

The following procedures were used to evaluate the impact of the new $\Delta D$, $\Delta H$, and *PM* equations on stand-level predictions from the SMC-ORGANON model:

1. Data from the SMC Type I, II, and III installations were used to create 170 input tree lists needed to run the ORGANON model (Hann et al. 1997). For each untreated plot on an installation, the first measurement in which all trees on the plot had reached at least 4.5 ft in height was selected for creation of the only input tree list used for that plot.
2. Three new variants of the SMC-ORGANON model were created by sequentially replacing the original equation with the new equations in the basic model: variant 1 with just the new $\Delta D$ equation, variant 2 with both the new $\Delta D$ and the new $\Delta H$ equations, and variant 3 with the new $\Delta D$, new $\Delta H$, and new *PM* equations.
3. Eight 100-yr projections were made on each of the 170 input tree lists. The following four runs were made with the optional "limit on maximum SDI" turned off (see Hann et al. 1997 for a description of this option): (1) original SMC-ORGANON, (2) new variant 1 of SMC-ORGANON, (3) new variant 2 of SMC-ORGANON, and (4) new variant 3 of SMC-ORGANON. Finally, the same runs were made with the optional "limit on maximum SDI" turned on.
4. For each growth projection on each tree list, the following values were plotted across stand age and the trends examined for reasonableness of behavior: *BA*, *TPA*, total stem

cubic foot volume per acre (*TSCFV*), the mean annual increment (*MAI*) of *TSCFV*, the periodic annual increment of *TSCFV*, average *CR*, and *SDI*.

5. The maximum *MAI* and the associated rotation age based on maximizing *MAI* were then extracted from each run's output file. These values were then used to calculate both the difference of original SMC-ORGANON value minus the value of each new variant, and a percent difference, by dividing the difference by the original SMC-ORGANON value and multiplying by 100. Finally, the mean, minimum, maximum, and standard deviation of the 170 difference values and 170 percent-difference values associated with each of the new variants were computed and tabulated.

# Results and Discussion

## $\Delta D_5$ Equation

Table 4 contains the parameter estimates and associated standard errors for Eq. [3]. Graphs of both the weighted and the unweighted residuals across $Pred\Delta D_5$ and the independent variables for both the combined data set and each of the seven component data sets showed no marked trends. Therefore, the trends in the residuals found in this study for the $\Delta D_5$ equation of Hann et al. (2003) have been removed.

Table 4. Parameter estimates and asymptotic standard errors (SE) for predicting the 5-yr diameter-growth rate ($\Delta D_5$) of Douglas-fir, Eq. [3].

| Parameter | Estimate | SE |
|---|---|---|
| $b_0$ | -5.34253119 | 0.08931045 |
| $b_1$ | 1.09840684 | 0.02532546 |
| $b_2$ | -0.05218621 | 0.00090143 |
| $b_3$ | 1.01380810 | 0.01363964 |
| $b_4$ | 0.91202025 | 0.01600426 |
| $b_5$ | -0.01756220 | 0.00036357 |
| $b_6$ | -0.05168923 | 0.00183284 |
| $b_7$ | -0.79016562 | 0.14748049 |
| $b_8$ | -0.06106027 | 0.01641448 |
| $b_9$ | -0.58448386 | 0.02336963 |
| $b_{10}$ | 0.99430139 | 0.02705818 |
| $b_{11}$ | 0.00828762 | 0.00037406 |
| $b_{12}$ | 0.03951423 | 0.00186164 |
| $K$ | 6.0 | Not applicable |

The mean unweighted residual, the standard deviation of the unweighted residuals, and the $R^2_a$ of the unweighted residuals for the combined data set and each of the seven component data sets are shown in Table 5. Equation [3] explains almost 74% of the overall unweighted variation in $\Delta D_5$, and the mean unweighted residuals are inconsequential for all divisions of the data.

Predicted maximum $\Delta D_5$ and the $D_S$ where the peak occurs can be calculated by setting $CR_S = 1.0$, $BAL_S = 0.0$, $BA_S = 0.005454154 D_S^2$, and $SI$ to a value of interest (Hann and Hanus 2002a). For $SI = 120$ (approximately the average for the modeling data set), Eq. [3] predicts a maximum $\Delta D_5$ of 4.47 in. that occurs at $D_S = 12.5$ in., whereas the equation of Hann et al. (2003) predicts a maximum $\Delta D_5$ of 3.27 in. that occurs at $D_S = 18.9$ in. Furthermore, Eq. [3] predicts values of $\Delta D_5$ that are substantially larger than the predictions from the equation of Hann et al. (2003) for $D_S$ <10 in.

Table 5. Mean, standard deviation (SD), and adjusted coefficient of determination ($R^2_a$) of the unweighted residuals for the $\Delta D_5$ Eq. [3] by the component modeling data sets.

| Data set | Observations (*n*) | Mean | SD | $R^2_a$ |
|---|---|---|---|---|
| SMC Type I | 4,886 | -0.065 | 0.5439 | 0.5400 |
| SMC Type II | 488 | -0.030 | 0.4090 | 0.5272 |
| SMC Type III | 3,450 | 0.058 | 0.6557 | 0.5037 |
| SMC Cooperators | 2,643 | 0.050 | 0.2980 | 0.6316 |
| SWO-ORGANON | 11,136 | -0.000 | 0.3731 | 0.5599 |
| NWO-ORGANON | 9,526 | -0.000 | 0.5701 | 0.4870 |
| WWA-ORGANON | 965 | -0.000 | 0.4202 | 0.3448 |
| All | 33,094 | 0.000 | 0.4947 | 0.7382 |

The validation statistics for Eq. [3] are shown in Table 6. These results indicate that Eq. [3] underpredicts $\Delta D_5$ by an average of 0.27

in. (13% of the average $\Delta D_5$). A graph of residuals over $Pred\Delta D_5$ and the independent variables showed no trends. With the bias included, Eq. [3] explains 47.7% of the variation in $\Delta D_5$ over what a mean value would have explained, and removal of the bias would increase the amount of explained variation to 55.8%. In reviewing these figures, it should be remembered that the validation data set covers a relatively small range in tree sizes and stand conditions; as a result, it is expected that the mean value would explain more of the variation than would be the case in a data set covering a wider range of the data. This fact is illustrated in Table 5, where the $R^2_a$s for the component data sets are smaller than the $R^2_a$ for the overall data set.

Table 6. Validation statistics for Douglas-fir $\Delta D_{5,}$ Eq. [3], and Douglas-fir $\Delta H_{5,}$ Eq. [4].

| Equation | m | $\bar{\delta}$ | MSE | With-bias $R^2_a$ | Without-bias $R^2_a$ |
|---|---|---|---|---|---|
| $\Delta D_5$ | 965 | 0.27 | 0.4850 | 0.4773 | 0.5576 |
| $\Delta H_5$ | 960 | -0.74 | 9.874 | 0.2380 | 0.2805 |

Given the results of the residual analysis and the validation analysis, Eq. [3] is judged to be appropriate, not only for the SMC variant of ORGANON, but also for the SWO and NWO variants. Application to the latter two variants requires using the appropriate indicator adjustments to the intercept term (i.e., $b_0 + b_7$ for the SWO variant, $b_0 + b_8$ for the NWO variant), the $SI$ term (i.e., use of just $b_{10}$ with $SI_{H\&S}$ for the SWO variant only), the $BAL_S$ term (i.e., $b_5 + b_{11}$ for both variants), and the $BA_S$ term (i.e., $b_7 + b_{12}$ for both variants).

## $\Delta H_5$ Equation

Table 7 contains the parameter estimates and associated standard errors for Eq. [4]. The parameter estimates are quite similar in magnitude to those reported by Hann et al. (2003). Graphs of both the weighted and the unweighted residuals across $Pred\Delta H_5$ and the independent variables for both the combined data set and each of the four component data sets showed no marked trends.

Table 7. Parameter estimates and asymptotic standard errors (SE) for predicting the 5-yr height-growth rate ($\Delta H_5$) of Douglas-fir, Eq. [4].

| Parameter | Estimate | SE |
|---|---|---|
| $c_0$ | 1.010018427 | 0.004150000 |
| $c_1$ | 0.655258886 | 0.019802618 |
| $c_2$ | -0.006322913 | 0.000445321 |
| $c_3$ | -0.039409636 | 0.003226345 |
| $c_4$ | 0.597617316 | 0.097746004 |
| $c_5$ | 0.631643636 | 0.046004864 |

The mean unweighted residual, the standard deviation of the unweighted residuals, and the $R^2_a$ of the unweighted residuals for the combined data set and each of the four component data sets are shown in Table 8. Equation [4] explains more than 74% of the overall unweighted variation in $\Delta H_5$, and the mean unweighted residuals are inconsequential for all divisions of the data.

The validation statistics for Eq. [4] are shown in Table 7. These results indicate that Eq. [4] overpredicts $\Delta H_5$ by an average of 0.74 ft (which is 5% of the average $\Delta H_5$). A graph of residuals over $Pred\Delta H_5$ and the independent variables showed no trends. With the bias included, Eq. [4] explains 23.8% of the variation in $\Delta H_5$, and removal of the bias would increase the amount of explained variation to 28.0%.

Table 8. Mean, standard deviation (SD), and adjusted coefficient of determination ($R^2_a$) of the unweighted residuals for the $\Delta H_5$ Eq. [4] by the component modeling data sets.

| Data set | Observations (*n*) | Mean | SD | $R^2_a$ |
|---|---|---|---|---|
| SMC Type I | 1,426 | 0.077 | 2.8352 | 0.5699 |
| SMC Type II | 441 | 0.504 | 2.9286 | 0.3851 |
| SMC Type III | 3,053 | -0.072 | 2.6016 | 0.4687 |
| SMC Cooperators | 1,510 | -0.116 | 1.4724 | 0.8021 |
| All | 6,430 | -0.010 | 2.4728 | 0.7423 |

## $PM_5$ Equation

The $\chi^2$ goodness-of-fit statistic computed for the mortality equation of Hann et al. (2003) is 861.4, and the critical $\chi^2$ statistic is 42.98 for the probability of a greater value = 0.01 and 24 degrees of freedom (df) (no parameters were estimated from the data for this application). Because the goodness-of-fit statistic greatly exceeds the critical $\chi^2$ statistic, the mortality equation of Hann et al. (2003) is judged as not adequately characterizing the new mortality data set.

Table 9. Parameter estimates and asymptotic standard errors (SE) for predicting the 5-yr mortality rate ($PM_5$) of Douglas-fir, Eq. [6].

| Parameter | Estimate | SE |
|---|---|---|
| $d_0$ | -3.12161659 | 0.05628046 |
| $d_1$ | -0.44724396 | 0.00262107 |
| $d_2$ | -2.48387172 | 0.07496779 |
| $d_3$ | 0.01843137 | 0.00022000 |
| $d_4$ | 0.01353918 | 0.00015875 |

Table 9 contains the parameter estimates and associated standard errors for Eq. [6]. The $\chi^2$ goodness-of-fit statistic computed for this equation is 33.8, and the critical statistic is 36.19 for the probability of a greater value = 0.01 and 19 df (five parameters were estimated from the data). Because the goodness-of-fit statistic is less than the critical $\chi^2$ statistic, the new mortality equation is judged to characterize the new mortality data set adequately.

## Effect of New Equations on Stand Level Predictions

The incorporation of Eqs. [3], [4], and [6] into SMC-ORGANON and choosing not to use ORGANON's limit on maximum SDI resulted in an average reduction of 2.5 yr (or 2.8%) in the predicted RA that would maximize the production of total stem cubic foot volume per acre (Table 10). The incorporation of just $\Delta D_5$ Eq. [3] resulted in a reduction of 4.1 yr (or 5.0%). Therefore, the inclusion of $\Delta H_5$ Eq. [4] and $PM_5$ Eq. [6] lessened the reduction brought on by the addition of Eq. [3].

Table 10. Comparisons of predicted rotation ages between the old and new variants of SMC-ORGANON with limit on maximum SDI turned off. The new ΔD, ΔH, and PM equations were developed in this study; the new HCB equation used to calculate ΔHCB was developed by Hann and Hanus (2004).

| | | New | | | |
|---|---|---|---|---|---|
| Attribute | Old | ΔD | ΔD & ΔH | ΔD, ΔH, & PM | ΔD, ΔH, PM, & ΔHCB |
| Rotation age | | | | | |
| Average | 79.3 | 75.2 | 76.0 | 76.7 | 81.4 |
| Range | 40.0–120.3 | 40.5–116.2 | 40.0 – 116.5 | 42.3 – 115.9 | 49.6 – 118.0 |
| Change | | | | | |
| Average | | -4.0 | -3.3 | -2.5 | +2.1 |
| Range | | -17.1 – +2.6 | -16.4 – +5.5 | -16.9 – +6.4 | -17.5 – +17.6 |
| % Change | | | | | |
| Average | | -5.0 | -4.1 | -2.8 | +4.3 |
| Range | | -15.3 – +2.9 | -14.6 – +5.7 | -15.1 – +6.6 | -15.7 – +37.3 |

Incorporating Eqs. [3], [4], and [6] into SMC-ORGANON reduced maximum *MAI* an average of 59.0 ft³/ac/yr (or 20.4%) when ORGANON's limit on maximum SDI was not used (Table 11). Incorporation of just $\Delta D_5$ Eq. [3] resulted in a reduction of 48.9 ft³/ac/yr (or 16.9%). Therefore, the inclusion of $\Delta H_5$ Eq. [4] and $PM_5$ Eq. [6] somewhat increased the reduction resulting from the addition of Eq. [3].

Using ORGANON's limit on maximum *SDI* resulted in an average reduction of only 0.2 yr (or 0.0%) in the predicted *RA* that would maximize the production of total stem cubic foot volume per acre (Table 12). The incorporation of just $\Delta D_5$ Eq. [3] resulted in a reduction of 1.7 yr (or 2.2%). Again, the inclusion of $\Delta H_5$ Eq. [4] and $PM_5$ Eq. [6] lessened the reduction resulting from the addition of Eq. [3].

Table 11. Comparisons of predicted maximum mean annual increments (*MAI*) between the old and new variants of SMC-ORGANON with limit on maximum SDI turned off. The new ΔD, ΔH, and PM equations were developed in this study; the new HCB equation used to calculate ΔHCB was developed by Hann and Hanus (2004).

| | | New | | | |
|---|---|---|---|---|---|
| Attribute | Old | *ΔD* | *ΔD & ΔH* | *ΔD, ΔH, & PM* | *ΔD, ΔH, PM, & ΔHCB* |
| Maximum *MAI* | | | | | |
| Average | 277.6 | 228.7 | 221.3 | 218.7 | 222.0 |
| Range | 89.8–420.5 | 91.2–326.1 | 89.7–315.7 | 89.5–313.1 | 94.5–310.6 |
| Change | | | | | |
| Average | | -48.9 | -56.3 | -59.0 | -55.7 |
| Range | | -94.4 – +1.4 | -104.8 – -0.1 | -107.4 – -0.3 | -113.3 –+4.7 |
| % Change | | | | | |
| Average | | -16.9 | -19.5 | -20.4 | -18.9 |
| Range | | -22.4 – +1.6 | -24.9 – -0.1 | -26.1 – -0.3 | -28.0 – +5.2 |

The incorporation of the new $\Delta D_5$, $\Delta H_5$, and $PM_5$ equations in SMC-ORGANON resulted in an average reduction in maximum *MAI* of 46.1 ft³/ac/yr (or 16.9%) when the option of using ORGANON's limit on maximum SDI is chosen (Table 13). The incorporation of just $\Delta D_5$ (Eq. [3]) resulted in a reduction of 36.1 ft³/ac/yr (or 13.2%). In this case, the inclusion of $\Delta H_5$ (Eq. [4]) and $PM_5$ (Eq. [6]) somewhat decreased the size of the reduction resulting from the addition of Eq. [3].

Table 12. Comparisons of predicted rotation ages between the old and new variants of SMC-ORGANON with limit on maximum SDI turned on. The new ΔD, ΔH, and PM equations were developed in this study; the new HCB equation used to calculate ΔHCB was developed by Hann and Hanus (2004).

| Attribute | Old | New | *ΔD* | *ΔD*, *ΔH* *ΔD* & *ΔH* & *PM* | *ΔD*, *ΔH*, *PM* & *ΔHCB* |
|---|---|---|---|---|---|
| Rotation age | | | | | |
| Average | 76.9 | 75.2 | 76.0 | 76.7 | 81.4 |
| Range | 45.8–117.1 | 40.5–116.2 | 40.6–116.9 | 42.3–116.1 | 49.6–118.3 |
| Change | | | | | |
| Average | | -1.7 | -1.0 | -0.2 | +4.4 |
| Range | | -13.1– +10.3 | -12.4 – +9.0 | -13.6 – +8.6 | -14.6 – +15.1 |
| % change | | | | | |
| Average | | -2.2 | -1.2 | -0.0 | +7.1 |
| Range | | -21.4 – +16.1 | -20.1 – +14.2 | -12.6 – +13.6 | -13.5 –+21.2 |

Table 13. Comparisons of predicted maximum mean annual increments (MAI) between the old and new variants of SMC-ORGANON with limit on maximum SDI turned on. The new *ΔD*, *ΔH*, and *PM* equations were developed in this study; the new *HCB* equation used to calculate ΔHCB was developed by Hann and Hanus (2004).

| Attribute | Old | New | *ΔD* | *ΔD*, *ΔH*, *ΔD* & *ΔH* | *ΔD*, *ΔH*, *PM* & PM & *ΔHCB* |
|---|---|---|---|---|---|
| MAI | | | | | |
| Average | 264.7 | 228.6 | 221.2 | 218.6 | 221.7 |
| Range | 89.8–387.8 | 91.2–326.1 | 89.7–315.7 | 89.5–313.1 | 94.3–310.6 |
| Change | | | | | |
| Average | | -36.1 | -43.5 | -46.1 | -42.9 |
| Range | | -71.7 – +1.4 | -81.3 – -0.1 | -81.8 – -0.3 | -81.5 – +4.5 |
| % change | | | | | |
| Average | | -13.2 | -16.0 | -16.9 | -15.4 |
| Range | | -19.1 – +1.6 | -21.6 – -0.1 | -21.9 – -0.3 | -21.6 – +5.0 |

Behavior of 100-yr projections of the remaining stand-level statistics resulting from inserting the new $\Delta D_5$, $\Delta H_5$, and $PM_5$ equations into ORGANON did not meet expectation in some cases. The ending values for average *CR* were often near 15%, and predicted *BA* in some of these stands peaked and then declined over stand age. These problems were attributed to the *HCB* equation of Hann et al. (2003) used to predict crown recession ($\Delta HCB_5$). After several alternative approaches for predicting $\Delta HCB_5$ were evaluated, it was discovered that the *HCB* equation of Hann and Hanus (2004) eliminated the problem with *BA* peaking over stand age and resulted in ending average *CR*s that were somewhat larger than predicted by the *HCB* equation of Hann et al. (2003).

The results of incorporating the new *HCB* equation in ORGANON can be found in the last column of Tables 10–13. The new equation increased average rotation ages from 76.7 yr to 81.4 yr (Tables 10 and 12) and maximum *MAI* from approximately 219 $ft^3$/ac/yr to approximately 222 $ft^3$/ac/yr. The equation of Hann and Hanus (2004) was developed using more recent SMC data than those used by Hann et al. (2003). Therefore, we decided to accept its use for predicting $\Delta HCB_5$ in the revised edition of SMC-ORGANON.

Comparing the *RA* statistics for the new equations in Table 10 with the values in Table 12 and the maximum *MAI* statistics for the new equations in Table 11 with the values in Table 13 shows that the values do not appreciably differ with the choice of either using or not using the limit on maximum SDI. The optional limit on maximum *SDI* is used in ORGANON to constrain predicted maximum densities to reasonable values (Hann et al. 2003). Invoking this option places a cap on the stand's maximum size-density relationship. For a stand that is predicted to exceed the cap, ORGANON will increase the individual tree mortality rates so that the stand does not exceed the cap (Hann et al. 2003). If the individual tree mortality rates are large enough to keep the stand's density below the maximum, then no additional mortality is taken. Therefore, the results in Tables 10–13 indicate that mortality rates predicted from Eq. [6], when used in combination with the other new equations, are large enough to keep the *BA* and *TPA* of the stands below the maximum size-density cap.

In order to further explore the predicted size-density behavior when the limit on maximum *SDI* is not used, 100-yr projections using the new SMC-ORGANON model were made on the 21 SMC Type III high density plots (i.e., the plots planted to 1,210 tpa) available for this study. For each plot, predicted *TPA* and *BA* at the end of each growth period were used to compute a *SDI* value and the trend in how these values changed over stand age was noted. Choosing to use just the individual-tree mortality equations still resulted in predicted size-density behavior that met the expectations of Reineke (1933), Puettmann et al. (1993), and Hann et al. (2003). Resulting predicted maximum *SDI* values for these stands averaged 484 equivalent 10-in. tpa, with values ranging from 468 equivalent 10-in. tpa to 503 equivalent 10-inch tpa. These predicted maximum *SDI* values fall within the ranges reported by Hann et al. (2003) for measured maximum *SDI* data from Douglas-fir plots in the region. We therefore conclude that the new tree-level mortality equation is adequate for controlling long-term stand development and, therefore, use of the limit on maximum size-density is not necessary for Douglas-fir stands grown in the new SMC-ORGANON. Monserud et al. (2005) also found that well-developed tree-level mortality equations negated the need to impose a self-thinning constraint for the PROGNAUS model.

## Literature Cited


Bruce, D. 1981. Consistent height-growth and growth-rate estimates for remeasured plots. *Forest Science* 27: 711–725.

Chappell, HN, and A Osawa. 1991. The Stand Management Cooperative: A cooperative research program in silviculture, growth and yield, and wood quality in the Pacific Northwest. *Hoppa Ringyo* 43: 7–11.

Cunia, T. 1973. Dummy variables and some of their uses in regression analysis, pp 1–146 in *Proceedings of IUFRO seminar: Subject Group S4.02 - Forest Resources Inventory*, Nancy, France. June 25–29, 1973.

Flewelling, JW, and RA Monserud. 2002. Comparing methods for modeling tree mortality, pp. 168–177 in *Second Forest Vegetation Simulator Conference*, NL Crookston and RN Havis, compilers. Proceedings RMRS-P-25, USDA Forest Service, Rocky Mountain Research Station, Fort Collins CO.

Flewelling, J, R Collier, B Gonyea, D Marshall, and E Turnblom. 2001. Height-age curves for planted stands of Douglas-fir with adjustments for density. Working Paper 1, Stand Management Cooperative, College of Forest Resources, University of Washington, Seattle.

Hamilton, DA, Jr. 1974. *Event Probabilities Estimated by Regression*. Research Paper INT-RP-152, USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden UT.

Hann, DW. 1997. *Equations for Predicting the Largest Crown Width of Stand-grown Trees in Western Oregon*. Research Contribution 17, Forest Research Laboratory, Oregon State University, Corvallis.

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

Hann, DW, and ML Hanus. 2001. *Enhanced Mortality Equations for Trees in the Mixed Conifer Zone of Southwest Oregon*. Research Contribution 34, Forest Research Laboratory, Oregon State University, Corvallis.

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

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

Hann, DW, and ML Hanus. 2004. Evaluation of nonspatial approaches and equation forms used to predict tree crown recession. *Canadian Journal of Forest Research* 34: 1993–2003.

Hann, DW, and DR Larsen. 1991. *Diameter Growth Equations for Fourteen Tree Species in Southwest Oregon*. Research Bulletin 69, Forest Research Laboratory, Oregon State University, Corvallis.

Hann, DW, and JA Scrivani. 1987. *Dominant-height-growth and Site-index Equations for Douglas-fir and Ponderosa Pine in Southwest Oregon*. Research Bulletin 59, Forest Research Laboratory, Oregon State University, Corvallis.

Hann, DW, and AA Zumrawi. 1991. Growth model predictions as affected by alternative sampling-unit designs. *Forest Science* 37: 1641–1655.

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

Hann, DW, DD Marshall, and ML Hanus. 2003. *Equations for Predicting Height-to-Crown-Base, 5-yr Diameter-Growth Rate, 5-yr Height-Growth Rate, 5-yr Mortality Rate, and Maximum Size-Density Trajectory for Douglas-fir and Western Hemlock in the Coastal Region of the Pacific Northwest*. Research Contribution 40, Forest Research Laboratory, Oregon State University, Corvallis.

Hanus, ML, DW Hann, and DD Marshall. 1999. *Predicting Height for Undamaged and Damaged Trees in Southwest Oregon*. Research Contribution 27, Forest Research Laboratory, Oregon State University, Corvallis.

Hanus, ML, DW Hann, and DD Marshall. 2000. *Predicting Height to Crown Base for Undamaged and Damaged Trees in Southwest Oregon*. Research Contribution 29, Forest Research Laboratory, Oregon State University, Corvallis.

Kmenta, J. 1986. *Elements of Econometrics, Second Edition*. Macmillan, New York.

Maguire, DA, and DW Hann. 1987. A stem dissection technique for dating branch mortality and reconstructing past crown recession. *Forest Science* 33: 858–871.

Maguire, DA, A Kanaskie, and D Mainwaring. 2004. Growth Impact Study: Growth trends turing (sic) the third 2-yr period following establishment of permanent plots, pp. 24–27 in *Swiss Needle Cast Annual Report 2004*, D. Mainwaring, ed., Oregon State University, Corvallis.

McKenzie, D. 1994. *Diameter Growth Equations and Growth and Yield Projections for Two-tiered Stands in Western Washington*. MS thesis. College of Forest Resources, University of Washington, Seattle.

Monserud, RA, T Ledermann, and H Sterba. 2005. Are self-thinning constraints needed in a tree-specific mortality model? *Forest Science* 50: 848–858.

Puettmann, KJ, DE Hibbs, and DW Hann. 1993. Evaluation of the size-density relationships for pure red alder and Douglas-fir stands. *Forest Science* 39: 7–27.

Reineke, LH. 1933. Perfecting a stand-density index for even-aged forests. *Journal of Agricultural Research* 46: 627–638.

Ritchie, MW, and DW Hann. 1985. *Equations for Predicting Basal Area Increment in Douglas-fir and Grand Fir*. Research Bulletin 51, Forest Research Laboratory, Oregon State University, Corvallis.

Snedecor, GW, and WG Cochran. 1980. *Statistical Methods, Seventh Edition*. The Iowa State Press, Ames.

Zumrawi, AA, and DW Hann. 1993. *Diameter Growth Equations for Douglas-fir and Grand Fir in the Western Willamette Valley of Oregon*. Research Contribution 4, Forest Research Laboratory, Oregon State University, Corvallis.

# Appendix 1: Alternative Methods of Determining $SI_B$ for SMC Installations

We evaluated five alternative means of determining $SI_B$ for the SMC installations. The following were computed for each plot:

$SI_{B,1}$ Calculate $SI_B$ directly, using the last measurement of *H40* and *BHA*.

$SI_{B,2}$ Calculate the *SI* of Flewelling et al. (2001) directly, using the last measurement of *H40* and *TA* but with no adjustment for density. Then predict *H40* at *BHA* = 50 yr, using this estimate of the *SI* and the Flewelling et al. (2001) dominant-height-growth equation. The resulting value of *H40* is an estimate of $SI_B$. The actual number of years that each plot took to reach breast height was used to find the TA associated with a BHA of 50 yr.

$SI_{B,3}$ Calculate the Flewelling et al. (2001) *SI* directly, using the last measurement of *H40* and TA and adjusting for density. Then predict *H40* at a *BHA* = 50 yr, using this estimate of the Flewelling et al. (2001) *SI* and their dominant height growth equation. The resulting value of *H40* is an estimate of $SI_B$.

$SI_{B,4}$ Define $H40_a$ and $BHA_a$ as the first measurement where they are not zero, and $H40_b$ as the measurement 4 yr later, and then calculate $\Delta H40 = H40_b - H40_a$. Using $BHA_a$ and $BHA_b = BHA_a + 4.0$, iteratively increment $SI_B$ and predict $\Delta H40$ until a $SI_B$ value is found in which predicted $\Delta H40$ equals the actual $\Delta H40$.

$SI_{B,5}$ Iteratively increment $SI_B$ and for each iteration calculate the growth effective age (*GEA*) for $H40_a$ ($GEA_a$) and the *GEA* for $H40_b$ ($GEA_b$), restricting the *GEA* values to be ≤ the TA for the plot. Stop iterating $SI_B$ when $GEA_b - GEA_a = 4.0$. *GEA* is determined by solving Bruce's dominant height growth equation to express *GEA* as a function of *H* and *SI*.

The five estimates of $SI_B$ were first compared by plotting each one against each of the others and examining the amount of scatter in each graph. The correlation between each measure was also calculated. This examination indicated very high agreement between the two methods using the equations of Flewelling et al. (2001) (i.e., $SI_{B,2}$ and $SI_{B,3}$ with a correlation of 0.9723), and between the two growth rate methods using $SI_B$ equation (i.e., $SI_{B,4}$ and $SI_{B,5}$ with a correlation of 0.9872). As a result, only one of each pair from each of these two groups of method needed to be compared to the traditional method of determining $SI_B$ (i.e., $SI_{B,1}$). The correlation between $SI_{B,1}$ and $SI_{B,2}$ was 0.8378 and the correlation between $SI_{B,1}$ and $SI_{B,4}$ was 0.8472.

The following statistics were then calculated for each of the five methods: the mean value, the minimum value, the maximum value, the standard deviation of the values, and the coefficient of variation for the values. The closest agreement between methods was for the oldest Type II stands, and the poorest agreement, for the youngest Type III stand (Table A1). We judged the lower average $SI_B$ value and larger coefficient of variation resulting from the application of $SI_{B,1}$ to be more reasonable for the Type III installations. We therefore concluded that $SI_{B,1}$ (the traditional method) provided reasonable estimates of $SI_B$ for the plots on the SMC installations. The rightness of this decision was later verified by the residual analyses reported in Tables 8 and 11. Given a measurement precision of 0.1 in. for *D* and 1.0 ft for *H*, the average residual values are all indistinguishable from 0, indicating that no significant trends by data set were introduced through the decision to use $SI_{B,1}$.

Table A1. Comparative statistics, by type of SMC installation, for the five methods of estimating Bruce's (1981) site index.

| | | *SI* (ft) | | | |
|---|---|---|---|---|---|
| SMC data set | Bruce's site index | Mean | Range | Standard deviation | Coefficient of variation (%) |
| Type I | $SI_{B,1}$ | 134.0 | 73.2–174.2 | 24.7 | 18.5 |
| | $SI_{B,2}$ | 139.1 | 81.5–167.3 | 22.4 | 16.1 |
| | $SI_{B,3}$ | 137.1 | 80.6–164.4 | 22.1 | 16.1 |
| | $SI_{B,4}$ | 135.4 | 77.4–170.1 | 24.6 | 18.2 |
| | $SI_{B,5}$ | 136.0 | 77.4–169.0 | 24.5 | 18.0 |
| Type II | $SI_{B,1}$ | 128.5 | 95.3–157.3 | 19.3 | 15.0 |
| | $SI_{B,2}$ | 128.9 | 95.3–156.6 | 19.0 | 14.7 |
| | $SI_{B,3}$ | 128.7 | 96.6–156.6 | 18.6 | 14.5 |
| | $SI_{B,4}$ | 131.4 | 85.3–185.0 | 28.1 | 21.4 |
| | $SI_{B,5}$ | 128.5 | 85.3–173.9 | 25.4 | 19.8 |
| Type III | $SI_{B,1}$ | 129.9 | 82.9–187.2 | 21.1 | 16.3 |
| | $SI_{B,2}$ | 142.2 | 94.1–166.1 | 15.3 | 10.7 |
| | $SI_{B,3}$ | 142.6 | 98.3–166.7 | 15.0 | 10.5 |
| | $SI_{B,4}$ | 140.2 | 76.4–181.3 | 23.5 | 16.7 |
| | $SI_{B,5}$ | 144.0 | 76.4–193.6 | 25.0 | 17.3 |

# Appendix 2: Abbreviations and Variable Definitions

| Abbreviation or variable | Units | Explanation |
|---|---|---|
| *BA* | $ft^2$/ac | Basal area of the plot |
| *BAF* | $ft^2$/ac/tree | Basal area factor |
| *BAL* | $ft^2$/ac | Plot basal area in trees with D >that of the subject tree |
| BHA | yr | Breast height age: the average number of growing seasons completed by the top height trees (the 40 largest diameter trees) on the plot after the trees had reached 4.5 ft in height. |
| CA | $ft^2$ | Area of the crown, assuming a circle with a diameter of *CW* |
| *CCH* | % | Percent crown closure at the top of the tree for the plot |
| *CL* | ft | Length of the live crown (*H - HCB*) |
| *CR* | none | Live crown ratio (*CL*:*H*) |
| *CW* | ft | Crown width |
| *D* | in. | Diameter at 4.5 ft above ground level (breast height) |
| $\Delta D_5$ | in. | 5-yr diameter increment |
| $\Delta H_5$ | ft | 5-yr height increment |
| $\Delta H40$ | ft | 5-yr change in the average height of the 40 largest diameter trees/ac |
| $\Delta HCB_5$ | ft | 5-yr change in height to the base of the live crown |
| $\Delta HMOD$ | ft | Height-growth modifier function |
| *EF* | no./ac | Expansion factor: the number of trees/ac represented by the sampled tree |
| GEA | yr | Growth effective age: the age of a dominant tree with the same height on the same site as the subject tree: |
| *H* | ft | Total tree height from ground level to the top of the tree |
| *HCB* | ft | Height to a crown base defined as the base of the compacted crown |
| $HCB_{3/4}$ | ft | Height to a crown base defined as the lowest whorl with live branches in at least three quadrants around the stem circumference |
| $HCB_{LLB}$ | ft | Height to a crown base defined as the lowest live branch |
| *H40* | ft | The average total tree height for the 40 largest diameter trees/ac |
| *LCW* | ft | Largest crown width |
| *MAI* | $ft^3$/ac/yr | Mean annual increment |
| $P\Delta H_5$ | ft | Potential 5-yr height increment of a tree |
| *PLEN* | 5 yr | Length of the growth period in 5-yr increments |
| $PM_5$ | none | The probability of mortality during the next 5 yr |
| $Pred\Delta H$ | ft | Predicted 5-yr change in *H* |
| $PS_5$ | none | The probability of survival during the next 5 yr (1-$PM_5$) |
| *RA* | yr | Rotation age |
| *SDI* | Equivalent no. of 10 in. trees/ac | Reineke's (1933) stand-density index |
| *SI* | ft at 50-yr BHA | Site index |
| $SI_B$ | ft at 50-yr BHA | Douglas-fir site index calculated from Bruce's 1981 dominant-height-growth equation |
| $SI_{H\&S}$ | ft at 50-yr BHA | Douglas-fir site index calculated from Hann and Scrivani's 1987 dominant height growth equation |
| *SMC* | none | Stand Management Cooperative |
| *tpa* | trees/ac | Number of trees per acre |
| *TA* | yr | Total age |
| *TSCFV* | $ft^3$ /ac | total stem cubic foot volume per acre |

Oregon State University
Forestry Communications Group
Oregon State University
256 Peavy Hall
Corvallis, OR 97331-5704

Address Service Requested

Non-Profit Org.
U.S. Postage
**PAID**
Corvallis, OR
Permit No. 200