ulletin 69 January 1991

Diameter Growth Equations for Fourteen Tree Species in Southwest Oregon

David W. Hann
David R. Larsen

FOREST RESEARCH LAB

College of Forestry Oregon State University

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

As a research bulletin, this publication is one of a series that comprehensively and in detail discusses a long, complex study or summarizes available information on a topic.

The Authors

David W. Hann is an Associate Professor, Department of Forest Resources, Oregon State University, Corvallis, and David R. Larsen is a Graduate Research Assistant, College of Forest Resources, University of Washington, Seattle.

Acknowledgments

This study was conducted as part of the Forestry Intensified Research (FIR) Program, a cooperative effort of Oregon State University, the USDA Forest Service, and the USDI Bureau of Land Management. We thank Boise Cascade Corporation and Medford Corporation for their special assistance.

Legal Notice

Disclaimer

To Order Copies

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

Forestry Publications Office
Oregon State University
Forest Research Laboratory 225
Corvallis, OR 97331-5708

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

Research bulletin (Oregon State University. Forest Research Laboratory.)

Diameter Growth Equations for Fourteen Tree Species in Southwest Oregon

David W. Hann
David R. Larsen

Contents

Abstract

Equations are presented that predict individual-tree 5-year diameter growth, outside bark, for 14 tree species in southwest Oregon. The data used to develop the equations came from 19,245 trees sampled from 391 stands in the study area. These equations express diameter growth as a function of diameter at breast height, crown ratio, site index, total stand basal area, and stand basal area in trees with diameters larger than the subject tree's diameter. The parameters of the equations were estimated by using weighted, nonlinear regression.

Introduction

Tree diameter growth or basal area growth equations have traditionally been used as one of the primary types of growth equations for individual tree growth models (Holdaway 1984, Ritchie and Hann 1985, Wykoff 1986, Wensel et al. 1987, Dolph 1988). Along with height growth, diameter growth is needed to calculate volume growth and product potential of individual trees, and it is used with height growth and mortality equations to compute basal area growth and volume growth of stands.

This Bulletin presents equations to predict 5-year diameter increment, outside bark, for the following species in the mixed-conifer zone (Franklin and Dyrness 1973) of southwest Oregon:

Abies concolor (Gord. & Glend.) Lindl. ex Hildebr., white fir

A. grandis (Dougl. ex D. Don) Lindl., grand fir

Acer macrophyllum Pursh, bigleaf maple

Arbutus menziesii Pursh, Pacific madrone

Castanopsis chrysophylla (Dougl.) A. DC., giant chinkapin

Libocedrus decurrens Torr., incense-cedar

Lithocarpus densiflorus (Hook & Arn.) Rehd., tanoak

Pinus lambertiana Dougl., sugar pine

P. ponderosa Dougl. ex Laws., ponderosa pine

Pseudotsuga menziesii (Mirb.) Franco, Douglas-fir

Quercus chrysolepsis Liebm., canyon live oak

Q. garryana Dougl. ex Hook, Oregon white oak

Q. kelloggii Newb., California black oak

Tsuga heterophylla (Raf.) Sarg., western hemlock

These equations form an important component of the southwest Oregon version of the single-tree/distance-independent growth and yield model, ORGANON, that has been developed for the area (Hester et al. 1989).

Previous Work

Because diameter is one of the easiest and most commonly measured of a tree's attributes, there has been much previous work in developing equations for predicting change in diameter at breast height. This review will therefore concentrate only on those published equations that have been developed as components for the following single-tree/distance-independent growth and yield models: the northern Rocky Mountain version of PROGNOSIS (Wykoff 1986), the Sierra Nevada version of PROGNOSIS (Dolph 1988), the Lake States version of STEMS (Holdaway 1984), CACTOS (Wensel et al. 1987), and the western Willamette Valley version of ORGANON (Ritchie and Hann 1985).

There are four major choices that must be made in the process of developing an equation: (1) what basic attribute should be used to form the dependent variable, (2) what basic attributes should be used to form the independent variables, (3) what equation form should be used to transform the basic attributes to independent and dependent variables and then to relate the independent variables to the dependent, and (4) how should the parameters of the equation be estimated?

Forming the Dependent Variable

The change in diameter at breast height can be expressed either as a diameter growth rate or as a basal area growth rate. Holdaway (1984) chose to use diameter growth rate, while Wykoff (1986), Dolph (1988), Wensel et al. (1987), and Ritchie and Hann (1985) chose to use basal area growth rate as their dependent variable. West (1980, p. 76) examined the use of both forms and concluded that "There seemed to be no evidence that diameter or basal area increment should, in general, be preferred in ... growth studies."

Forming the Independent Variables

Most of the basic tree and stand attributes that have been used to form independent variables in diameter or basal area increment equations can be classified into one of six categories: (1) tree size attributes, (2) tree vigor attributes, (3) tree position attributes, (4) stand density attributes, (5) stand size attributes, and (6) site productivity attributes. All studies in this review used diameter at breast height and crown ratio (i.e., crown length divided by total tree height) as their tree size and tree vigor attributes, respectively. In all cases, predicted diameter or basal area increment first increases, then peaks, and finally declines as diameter at breast height increases, and predicted increment increases as crown ratio increases.

However, each researcher chose a different attribute to characterize a tree's position within the stand. Wykoff (1986) and Dolph (1988) used the stand's basal area in trees with diameters larger than the subject tree's diameter; Ritchie and Hann (1985) used the sampling point's crown competition factor (Krajicek et al. 1961) in trees with diameters larger than the subject tree's diameter; Holdaway (1984) used tree diameter divided by average stand diameter; and Wensel et al. (1987) used crown closure of the stand at an elevation of two-thirds of the subject tree's total height. In all of these studies, the largest-diameter or tallest trees in the stand had the highest predicted growth rates, while the smallest or shortest trees had the lowest predicted growth rates.

For stand density measures, Wykoff (1986) chose total-stand crown competition factor, while Holdaway (1984), Ritchie and Hann (1985), and Dolph (1988) chose stand basal area. The equation of Wensel et al. (1987) did not include an additional overall stand density variable. On the other hand, only Holdaway (1984) included a stand size attribute: average stand diameter. For those studies that included a stand density measure, an increase in stand density always resulted in a decrease in predicted growth rate.

The approaches to characterizing a site's productivity have also been quite varied. Holdaway (1984), Ritchie and Hann (1985), and Wensel et al. (1987) all used site index as their measure of a site's productivity. Because of problems with stands that were of mixed species and mixed structures and that had been high graded in the past, Wykoff (1986) chose not to use site index. Instead, the aspect, slope, elevation, habitat type (Daubenmire and Daubenmire 1968), and geographic location (i.e., National Forest) of the stand were used as indicators of productivity. Finally, Dolph (1988) chose to use both site index and the latitude, elevation, and slope of the stand as productivity variables. In all cases where site index was used to index productivity, an increase in site index produced an increase in predicted growth rate.

Equation Form

There are three basic classifications for equation forms: linear, nonlinear that can be linearized through the use of transformations such as logarithms, and intrinsically nonlinear forms. Wykoff (1986), Dolph (1988), and Ritchie and Hann (1985) all used nonlinear equation forms that could be linearized through the use of logarithms.

1. Wykoff (1986):

$$\begin{aligned}\mathrm{BAG} = \mathrm{EXP}\{&\mathrm{HAB} + \mathrm{LOC} + a_1\mathrm{SL}[\cos(\mathrm{ASP})] + a_2\mathrm{SL}[\sin(\mathrm{ASP})] + a_3\mathrm{SL} + a_4\mathrm{SL}^2\\ &+ a_5\mathrm{EL} + a_6\mathrm{EL}^2 + a_7\ln(\mathrm{DBH}) + a_8\mathrm{DBH}^2 + a_9\mathrm{CR} + a_{10}\mathrm{CR}^2\\ &+ a_{11}\mathrm{BAL} + a_{12}\mathrm{BAL}/\ln(\mathrm{DBH} + 1.0) + a_{13}\mathrm{CCF}\} \qquad (1)\end{aligned}$$

where

BAG = basal area growth of the tree,
HAB = a constant term based on habitat type of the stand,
LOC = a constant term based on the National Forest of the stand,
SL = stand slope ratio,
ASP = stand aspect,
EL = stand elevation,
DBH = diameter at breast height of the tree,
CR = crown ratio of the tree,
BAL = basal area in trees with a DBH larger than the subject tree's DBH, and
CCF = crown competition factor for the stand.

2. Dolph (1988):

$$\begin{aligned}\mathrm{BAG} = \mathrm{EXP}\{&\mathrm{LAT} + a_1\ln(\mathrm{DBH}) + a_2\mathrm{DBH}^2 + a_3\mathrm{CR}^2/\ln(\mathrm{DBH} + 1.0)\\ &+ a_4\mathrm{BAL}/\ln(\mathrm{DBH} + 1.0) + a_5\ln(\mathrm{BA}) + a_6\mathrm{EL} + a_7\mathrm{SL} + a_8\mathrm{SL}^2\\ &+ a_9\mathrm{SI}\} \qquad (2)\end{aligned}$$

where

LAT = a constant term based upon the latitude of the stand,
BA = basal area of the stand,
SI = site index of the stand,

and other terms are as defined previously.

3. Ritchie and Hann (1985):

$$\mathrm{BAG} = \mathrm{EXP}(a_0 + a_1 \bullet \ln(\mathrm{DBH}) + a_2 \bullet \mathrm{DBH}^2 + a_3 \bullet \mathrm{CR} + a_4 \bullet \ln(\mathrm{SI}) + a_5 \bullet \mathrm{PCCFL} + a_6 \bullet \mathrm{BA}) \qquad (3)$$

where

PCCFL = crown competition factor (CCF) in trees on the sampling point with a DBH larger than the subject tree's DBH,

and other terms are as defined previously.

The remaining two studies used intrinsically nonlinear equation forms in which the potential, or maximum, growth rate is estimated and then multiplied by a modifier function that reduces the growth rate for increased competition within the stand and thus accounts for reduced tree vigor.

1. Holdaway (1984):

$$\mathrm{DG} = (\mathrm{POT})(\mathrm{MOD}) \qquad (4)$$

where

DG = diameter growth rate of the tree,
POT = potential diameter growth rate of the tree
= $a_0 + a_1\mathrm{DBH}^{a2} + a_3[(\mathrm{SI})(\mathrm{CR})(\mathrm{DBH})]^{a4}$
MOD = modifier function for the tree
= $1.0 - \mathrm{EXP}[-(X_1)(X_2)(X_3)]$

in which

$X_1 = a_5\{1.0 - \mathrm{EXP}[a_6(\mathrm{DBH}/\mathrm{AD})]\}^{a7} + a_8$
$X_2 = a_9(\mathrm{AD} + 1.0)^{a10}$
$X_3 = [(\mathrm{MBA} - \mathrm{BA})/\mathrm{BA}]^{1/2}$

AD = mean stand diameter,

MBA = maximum basal area for the stand,

and all other terms are as defined previously.

2. Wensel et al. (1987):

$$BAG = (POT)(MOD) \qquad (5)$$

where

POT = potential basal area growth rate for the tree

$= [a_1 SI^{a2} + a_3 DBH^{2a4}]^{1/a4} - DBH^2$

MOD = modifier function for growth rate of tree basal area

$= \{EXP[a_5(CC_{66})^{a6}\}/\{1.0 - EXP[4.0 - a_7 CR]\}$

CC_{66} = crown closure of the stand at two-thirds of the height of the subject tree,

and other terms are as defined previously.

The definition of the members of the "potential" growth rate population differed between the two studies. The "potential" equation used by Holdaway (1984) divided the dominant and codominant trees for each species into mutually exclusive 1-inch DBH, 10-foot site index and 10-percent crown ratio cells. The "potential" population was then defined as the 5 percent of the trees within each cell with the fastest diameter growth rates. Wensel et al. (1987, p. 13), on the other hand, selected their trees for measuring potential diameter growth rate for each species "from the largest 33 percent of the trees in each stand (by basal area) provided that the trees had live crown ratios greater than 0.5."

Parameter Estimation

The choice of the method for estimating the parameters of an equation depends upon the form of the equation and whether the error is additive or multiplicative, and upon whether the data violate any of the assumptions of regression. As an example of the latter consideration, the variance of residuals about diameter or basal area growth rate equations can exhibit heterogeneity (West 1980, Martin and Ek 1984).

Wykoff (1986) and Dolph (1988) linearized equations (1) and (2), respectively, through the use of logarithms and then estimated the parameters by using linear regression. The use of the log transformation assumes that the error about the untransformed dependent variable is multiplicative. As a result, the log transformation can homogenize variances that increase with the size of the dependent variable so that weighting is unnecessary. The estimated parameters are unbiased for predicting the log of basal area growth, but they are biased for predicting basal area growth itself (Flewelling and Pienaar 1981).

While a number of log-bias correction procedures have been developed, most of them assume that the residuals are normally distributed (Flewelling and Pienaar 1981). Ritchie and Hann (1985) compared both the use of the log transformation and unweighted, linear regression and the use of weighted, nonlinear regression for estimating the parameters of equation (3). They found that the residuals of the log of basal area growth were not normally distributed and, as a result, that correction for log bias was difficult. They therefore used weighted, nonlinear regression with a weight of $1.0/DBH^2$. It should be noted that the parameters estimated from nonlinear regression are only unbiased asymptotically as sample size increases.

The parameters of the POT portion of Holdaway's (1984) equation (4) were estimated by nonlinear regression. The dependent variable for the modifier function was then formed by dividing actual diameter growth rate by predicted potential diameter growth rate. The parameters of the modifier were then estimated in two steps by nonlinear regression that had been constrained to avoid implausible parameter estimates. In the first step, the parameters for X_2 were estimated with X_1 set to 1. With the parameters of X_2 determined, the parameters of X_1 were then estimated. This two-step process was used to guarantee that X_1 would equal 1 when DBH was equal to AD. What effect this two-step estimation process has upon the statistical properties of the modifier function's parameters is difficult to assess. However, when validating equation (4) on an independent data set, Holdaway (1984) found that it over-predicted diameter growth.

Wensel et al. (1987, p. 13) tried to estimate all of the parameters in their equation (5) simultaneously by nonlinear regression, but they found that the approach "confounded the potential and competition effects." They therefore used an iterative approach in which they first fit the potential equation to the potential data set on the assumption that the modifier value was 1. Second, the modifier function was fit to all trees in the data set by the previously determined "potential" equation. Finally, the parameters of the "potential" equation were re-estimated by using all trees in the data set and the modifier function parameters determined in the second step. Again, it is difficult to assess the effect upon the statistical properties of the parameters of using this iterative estimation process rather than the more usual simultaneous method.

Data Description

The data for this study were collected during the summers of 1981, 1982, and 1983 as part of the southwest Oregon Forestry Intensified Research (FIR) Growth and Yield Project. The study area (Figure 1) extended from near the California border (42° 10' N) on the south to the Cow Creek drainage (43° 00' N) on the north and from the Cascade crest (122° 15' W) on the east to approximately 15 miles west of Glendale (123° 50' W). Elevation ranges from 900 to 5,100 feet, January mean minimum temperature from 23° to 32°F, and July mean maximum temperature from 79° to 90°F. Annual precipitation varies from 29 to 83 inches, with less than 10 percent of the total falling during June, July, and August.

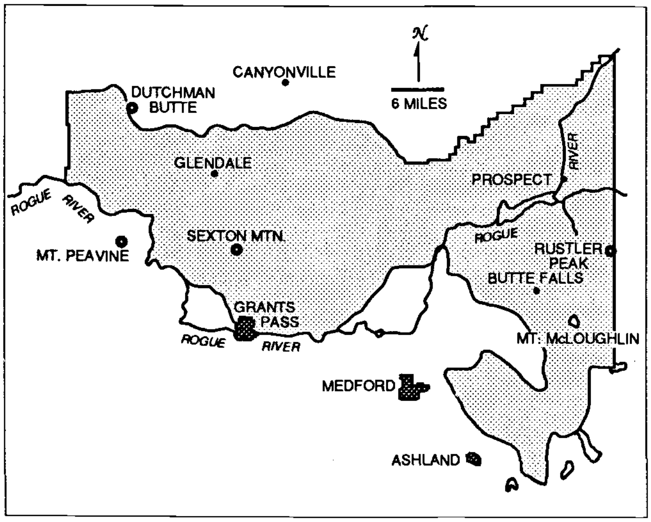

Figure 1. The study area (shaded).

Temporary plots were established within 391 stands selected from the study area. The following criteria were used to select these stands:

1. The majority of the trees in the stand must have an age under 120 years old when measured at breast height;
2. The majority of the trees in the stand must be either Douglas-fir, white fir, grand fir, ponderosa pine, sugar pine, incense-cedar, or a mixture of them (hereafter, these will be called the "six targeted conifer species");
3. The stand must have a uniform stand structure so that the species mix, competitive structure, and resulting potential management practices are essentially unchanged throughout the stand;
4. The stand must have a common bedrock, landform, and soil series, and be similar in aspect, slope, and elevation throughout the stand;
5. The stand must not have been treated within the past 5 years.

Within each stand, a cluster of from 4 to 10 variable-radius plots and 2 nested, fixed-area subplots was installed in a random fashion to measure the attributes on all trees taller than 6 inches high. A variable-radius plot with a basal area factor of 20 was used for trees with an 8.1-inch or greater diameter outside bark at breast height (DBH); a circular fixed-area subplot with a radius of 15.56 feet was used for trees with a 4.1- to 8-inch DBH; and a circular fixed-area subplot with a radius of 7.78 feet was used for trees with a DBH of 4 inches or less.

Tree measurements taken at the end of the most recent 5-year growth period (i.e., measurements subscripted with a 2) included a mortality indicator of whether the tree died in the past 5 years, DBH (DBH_2), total tree height (H_2), height to live-crown base (HCB_2), and horizontal distance from plot center to tree center (DIST). In addition, past 5-year radial growth and height growth were measured on subsamples of the trees.

The dating of when trees died was based upon physical features of the dead tree as described in USDA Forest Service (1978) and Cline et al. (1980). Breast-height diameter was measured to the nearest 0.1 inch with a diameter tape. Both height measurements were taken by the tangent method (Curtis and Bruce 1968, Larsen et al. 1987). The position of the base of the crown was determined by visual reconstruction of the crown such that any gaps in the crown were filled-in with branches from below the crown base. The distance from plot center to tree center was determined by measuring the horizontal distance from plot center to tree face and then adding one-half DBH_2, expressed in feet, to it.

Past radial growth at breast height was measured with an increment borer on all trees with a DBH large enough to accept the borer (approximately 2 inches DBH). The boring occurred on the side of the tree facing plot center, and the resulting core was measured to the nearest 40th of an inch, ignoring the current year's growth. The inside-bark radial growth measurements were converted to outside-bark diameter and basal area growth measurements by using the prediction equations for the ratio of diameter inside bark to diameter outside bark as developed for the six targeted conifer species of southwest Oregon by Larsen and Hann (1985) and for California hardwoods by Pillsbury and Kirkley (1984). Finally, the diameter growth measurements for the six targeted conifer species were adjusted, by using the equation presented in Zumrawi (1990), to eliminate the measurement bias that occurs when increment borings are used instead of repeated measurements of DBH to determine outside-bark diameter growth.

All undamaged trees under 25 feet tall were measured for 5-year height growth rates with a 25-foot telescoping pole. For trees taller than 25 feet, a subsample of up to six trees on each plot was felled and sectioned at the first and sixth whorls; the ages at these whorls were determined to ensure a true 5-year growth period, and finally the distance between the two whorls was measured for 5-year height growth.

Because the objective of the project is to predict future rather than past diameter growth rates, it was necessary to backdate all of the tree measurements in order to estimate their values at the start of the previous 5-year growth period (i.e., measurements subscripted with a 1). The procedures used to backdate the tree measurements are described in detail in Hann and Wang (1990). For trees that died during the growth period, it was assumed that the values at the start of the growth period were the same as those at the end of it.

It should be pointed out that backdating the attributes used to construct the independent variables can introduce measurement errors into the independent variables. If the measurement error in the independent variable is independent of the error of the residuals about the regression surface, then the parameters are unbiased (Kmenta 1971). However, if the measurement error is correlated with the error of the residuals, then biased parameters can occur. Unfortunately, the measurement error associated with backdating can only be eliminated through repeated measurements from permanent plots, and methods for ascertaining whether the errors are correlated are not readily available. As a result, the potential problems introduced by backdating temporary data sets are usually ignored.

Once the basic tree variables had been backdated to the start of the growth period, a number of tree, tree-position, and stand variables were then calculated. Crown ratio at the start of the growth period (CR_1) was determined as follows:

$$CR_1 = 1.0 - (HCB_1)/(HT_1)$$

where

HCB_1 = height to crown base at the start of the growth period and

HT_1 = total height at the start of the growth period.

Three variables—basal area in larger trees (BAL_1), crown competition factor in larger trees ($CCFL_1$), and crown closure at the top of the tree (CCH_1)—were used to quantify a tree's position within the stand at the start of the growth period. BAL_1 has been previously used as a tree-position variable in equations for predicting tree basal area growth (Ritchie and Hann 1985, Wykoff 1986, Dolph 1988); $CCFL_1$ has been used in equations for predicting tree height to crown base (Ritchie and Hann 1987, Zumrawi and Hann 1990); and CCH_1 has been used in equations for predicting tree height growth (Hann and Ritchie 1988).

BAL_1 is the sum of the basal area in trees with DBH_1's larger than the subject tree's DBH_1. Therefore, the largest-diameter tree in the stand would have a BAL_1 value of zero, while the smallest-diameter tree in the stand would have a BAL_1 value near but somewhat less than the stand's total basal area.

Similarly, $CCFL_1$ is the crown competition factor in trees with DBH_1's larger than the subject tree's DBH_1. As described by Krajicek et al. (1961), crown competition factor (CCF) is the ratio resulting when the sum of the square-foot maximum crown areas for all trees of interest in the stand or plot is divided by the square-foot area of the stand or plot. This ratio is then multiplied by 100 to express it as a percentage. Maximum crown areas were computed from the maximum crown width equations developed for southwest Oregon by Paine and Hann (1982).

A series of calculations was made to determine the CCH_1 of a particular tree. First, HT_1 was used to define a reference height. Next, crown widths at the reference height for all trees in the stand were estimated with the relative crown-width equations found in Ritchie and Hann (1985) and the maximum crown-width equations found in Paine and Hann (1982). If the reference height fell above the top of a tree, crown width was zero; if it fell below the crown base of a tree, crown width at crown base was used. Finally, each crown width was converted to crown area by the formula for the area of a circle, and these values were then summed and expressed as a percentage of the area of an acre.

The above three tree-position variables were defined in relation to all trees measured in the stand. Three additional tree-position variables were also computed to determine whether tree position defined in relation to only those trees existing on each sample point would improve the ability to predict diameter growth rate. These variables are basal area in larger trees for the sample point ($PBAL_1$), crown competition factor in larger trees for the sample point ($PCCFL_1$), and crown closure at the top of the tree for the sample point ($PCCH_1$). $PCCFL_1$ has been previously used in equations for predicting tree basal area growth (Ritchie and Hann 1985).

Variables calculated for the stand included total basal area at the start of the growth period (BA_1) and total crown competition factor at the start of the growth period (CCF_1). In addition, sample-point total basal area at the start of the growth period (PBA_1) and sample-point total crown competition factor at the start of the growth period ($PCCF_1$) were also computed.

Also, the site index of each stand was computed with equations developed from a local data set (Hann and Scrivani 1987). However, because the stands in southwest Oregon are often of mixed species with uneven-aged stand structures and can be severely affected by early competing vegetation, local foresters expressed reservations about using site index in the area. Therefore, we also decided to try a number of alternative, productivity-related variables.

Variables measured from maps included elevation, latitude, annual rainfall, rainfall during the growing season, and bedrock type. Information collected from soil pits in each stand included amount and size of coarse fragments, abundance of roots, and the water-holding capacities of each horizon. Finally, variables measured directly on each plot included slope, aspect, and vertical angles to the tops of ridges that might block the sun.

The directly measured variables were then used to compute other productivity variables such as average monthly minimum and maximum temperatures, solar irradiation (Kaufmann and Weatherred 1982), and net photosynthesis (Emmingham and Waring 1977) at the site. Additional variables such as indicators of the occurrence of a given species on a site were also computed.

A summary of the variables used in the equations for predicting final individual-tree diameter growth rate is presented in Table 1.

Data Analysis

We decided to use the general approach of Wykoff (1986), Dolph (1988), and Ritchie and Hann (1985) instead of the approach of Holdaway (1984) and Wensel et al. (1987) for three reasons:

1. We were uncomfortable with the definitions of the "potential" populations used by Holdaway (1984) and Wensel et al. (1987) because they seemed to be somewhat arbitrary.
2. We were concerned about the statistical properties of the iterative parameter estimators used by Holdaway (1984) and Wensel et al. (1987).
3. With the approaches of Wykoff (1986), Dolph (1988), and Ritchie and Hann (1985), the ability to linearize equations (1) and (2) through the application of logarithms would allow the use of powerful independent-variable screening tools that are available in many linear regression packages. If desired, the resulting parameter estimates could then be re-estimated by using nonlinear regression.

Both basal area growth and diameter growth were tried as the dependent variable, and it was decided to use diameter growth for two reasons. First, many of the other component equations for the southwest Oregon version of ORGANON used tree diameter rather than basal area (e.g., Paine and Hann 1982, Walters et al. 1985, Walters and Hann 1986a,b, Larsen and Hann 1987, Ritchie and Hann 1987, Hann and Wang 1990) and, as a result, it was necessary for the model to be able to project tree diameters into the future. Second, transformation of the basal area growth equation to predict diameter growth provided unreasonable predictions for trees with small diameters.

The alternative productivity variables were examined by using a number of all-combination screening runs on the log linearization of equation (3); the logarithm of diameter growth was used as the dependent variable and the parameters were estimated with the linear regression package REX (Grosenbaugh 1967). Various transformations of the alternative productivity variables were tried, with one set of runs including log of site index as as independent variable and a separate set of runs without a site index variable. From these runs, we found that site index was the strongest productivity variable and that, while some alternatives were significant, no combination of them explained more than 3 or 4 percent of the variation when used alone or more than 2 percent when used with site index. Because of the considerable cost associated with collecting and computing many of the statistically significant alternative productivity variables, we decided not to include any of them in the final diameter growth equation.

We also used all-combination screening to examine alternatives to the following independent variables in equation (3): $\ln(DBH_1)$, CR_1, $PCCFL_1$ and BA_1. As alternatives for $\ln(DBH_1)$, we tried $\ln(DBH_1+K1)$ with K1 being assigned values of 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, or 3.0. Adding a positive constant to the log transformation of diameter increases predicted diameter growth for trees with small diameters. We found that the value of 1.0 provided the lowest mean square error for all but one minor species. To standardize the equation form, we chose to use $\ln(DBH_1+1.0)$ for all species.

For the crown ratio (CR_1) term, we tried both CR_1 and $\ln[(CR_1+K2)/1.0+K2)]$, with K2 being either 0.0, 0.1, 0.2 or 0.3. From the screenings, the

Table 1. Selected descriptive statistics for the data set on diameter growth rate.

Species	Number of trees	Tree-diameter growth rate (in./5 yr.)		Tree diameter (in.)		Tree crown ratio		Stand site index (ft)		Stand basal area in trees larger than subject tree (ft^2/acre)		Stand basal area (ft^2/acre)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
SOFTWOODS													
Douglas-fir	11,974	0.97	0.00-4.68	13.8	0.3-83.8	0.50	0.02-1.0	93.4	54.1-141.1	94.6	0.0-380.0	191.9	0.1-393.2
Grand fir	942	1.07	0.00-5.48	12.5	0.8-48.9	0.55	0.01-1.0	94.8	59.4-124.3	100.3	0.0-387.2	177.8	10.5-393.2
Incense-cedar	1,008	0.71	0.00-4.88	10.1	0.2-66.3	0.54	0.05-1.0	88.8	54.8-124.3	110.8	0.0-322.4	166.0	2.6-331.9
Ponderosa pine	1,594	0.88	0.00-5.18	14.9	0.1-59.6	0.47	0.05-1.0	88.8	54.8-141.1	74.5	0.0-272.1	172.9	6.5-331.9
Sugar pine	350	1.34	0.00-4.98	18.1	1.1-59.9	0.52	0.10-1.0	86.3	54.1-126.6	49.4	0.0-261.8	171.8	3.5-326.2
Western hemlock	105	0.82	0.00-3.08	8.4	1.4-21.4	0.70	0.02-1.0	88.9	63.2-124.3	64.3	0.0-295.0	111.7	14.8-321.8
White fir	1,373	0.97	0.00-3.68	13.4	0.6-51.1	0.53	0.03-1.0	92.4	62.3-141.1	108.0	0.0-385.0	189.2	10.0-393.2
HARDWOODS													
Bigleaf maple	41	0.58	0.20-2.20	7.7	1.9-19.8	0.38	0.13-0.96	99.8	75.7-141.1	153.8	2.0-267.1	186.2	38.1-270.8
California black oak	300	0.36	0.10-1.50	13.1	2.0-48.4	0.40	0.05-1.00	85.9	54.8-121.1	97.6	0.0-294.4	172.8	46.2-302.9
Canyon live oak	89	0.45	0.10-1.60	4.6	2.4- 9.2	0.57	0.08-1.00	84.0	54.1-107.9	168.0	0.0-291.3	186.7	14.8-293.5
Giant chinkapin	399	0.49	0.10-1.60	6.3	1.1-26.5	0.47	0.07-1.00	92.2	54.1-125.6	126.6	0.0-302.0	168.9	14.8-326.2
Madrone	793	0.51	0.10-3.00	9.0	1.5-44.5	0.41	0.01-1.00	91.3	54.1-141.1	104.7	0.0-303.2	171.6	3.0-317.9
Oregon white oak	29	0.21	0.10-0.30	8.8	2.9-24.4	0.42	0.23-0.64	60.0	55.3- 80.2	78.1	3.3-194.8	149.3	119.6-197.0
Tanoak	63	0.44	0.10-1.20	4.9	1.3-11.8	0.51	0.18-0.97	93.1	73.0-117.0	104.3	0.0-229.7	147.1	2.6-239.0

second expression with a K2 value of 0.2 resulted in the lowest mean square error for all of the species.

In addition to the $PCCFL_1$ variable, the alternative tree-position variables we examined included stand crown competition factor in larger trees ($CCFL_1$), stand and point crown closure at treetop (CCH_1 and $PCCH_1$), stand and point basal area in larger trees (BAL_1 and $PBAL_1$), stand and point basal area in larger trees squared ($BAL_1{}^2$ and $PBAL_1{}^2$), $BAL_1/\ln(DBH+K3)$, $PBAL_1/\ln(DBH+K3)$, $BAL_1{}^2/\ln(DBH+K3)$, and $PBAL_1{}^2/\ln(DBH+K3)$, with K being set to 1, 2, 3, 4, 5, and 6. From these screenings, we found that $BAL_1{}^2/\ln(DBH+5)$ had the lowest mean square error for six of the species. The equations for the remaining eight species did not include a stand position variable.

The final set of variables we screened across were used to characterize total stand density. We first tried point basal area (PBA_1) and crown competition factor ($PCCF_1$) and stand basal area (BA_1) and crown competition factor (CCF_1). Of these, BA_1 minimized the mean square error. We next tried powers of 0.5, 1.0, 1.5, and 2.0 on BA_1. Of the seven species that included a BA_1 term in their equations, six minimized their mean square error with a power of 0.5 and the remaining one (western hemlock) had a minimum with a power of 1.0. We therefore chose to standardize on a value of 0.5, which increased the mean square error for western hemlock only slightly. The best equation form to emerge from this variable selection process was

$$DGRO = EXP\{b_0 + b_1 \bullet \ln(DBH_1 + 1) + b_2 \bullet DBH_1{}^2 + b_3 \bullet \ln[(CR_1 + 0.2)/1.2] + b_4 \bullet \ln(SI - 4.5) + b_5 \bullet (BAL_1{}^2)/[\ln(DBH_1 + 5)] + b_6 \bullet BA_1{}^{1/2}\} \quad (6)$$

where

$DGRO$ = future 5-year diameter growth rate, inches,

DBH_1 = diameter at breast height at the start of the growth period, inches,

CR_1 = crown ratio at the start of the growth period,

SI = Hann and Scrivani's (1987) definition of Douglas-fir site index for the stand, feet,

BAL_1 = basal area at the start of the growth period in trees with diameters larger than the subject tree, square feet, and

BA_1 = total stand basal area at the start of the growth period, square feet.

We examined both the use of the log transformation and linear regression combination and the use of weighted, nonlinear regression to estimate the parameters of equation (6). Like Ritchie and Hann (1985), we also found that, because of their skewness and kurtosis statistics, the residuals of the log-tranformation were not normally distributed. As a result, standard log-bias correction procedures (Flewelling and Pienaar 1981) produced mean residuals that were not zero for diameter growth itself. In addition, Furnival's (1961) index of fit for the weighted, nonlinear equation was lower than the log-transformation equation. Therefore, we chose to use weighted, nonlinear regression to estimate the parameters.

Alternative weights based on the reciprocal of DBH_1, DBH_1 squared, predicted diameter growth (Y), and predicted diameter growth squared were also evaluated with Furnival's (1961) index of fit to determine which weight minimized the index. The best turned out to be the reciprocal of predicted diameter growth. Therefore, it was necessary to use an iterative fitting procedure, analogous to the iterative procedure described in Kmenta (1971) for linear regression, to estimate the regression parameters. The first step in this process was to estimate the parameters by using unweighted, non-linear regression procedures. These parameters were then entered into the weight function and the parameters re-estimated by weighted, non-linear regression. In the next cycle, the parameter estimates from the previous weighted, non-linear regression fit were entered into the weight function and the parameters re-estimated with these new weights. This process continued until the new parameter estimates were identical to the previous ones.

Distinguishing between white fir and grand fir can be difficult in southwest Oregon because the two species can interbreed. Therefore, analysis of covariance was used to determine if they had statistically similar diameter growth equations. Analysis of covariance was also used to evaluate whether four data sets with small sample sizes could be combined with two stronger data sets to produce the following two groups of species: giant chinkapin and tanoak; Oregon white oak, California black oak, and canyon live oak.

As a final check of the equations, both the weighted and the unweighted residuals were examined for systematic trends across predicted diameter growth and the independent variables. This analysis was done by (1) dividing the range of predicted diameter growth and the independent variables into classes, (2) computing the mean weighted or unweighted residual and the standard deviation of the residuals in each class, (3) plotting the mean residual, the mean residual plus two standard deviations, and the mean residual minus two standard deviations across the mean class values for predicted diameter growth or the independent variable, and (4) visually examining the plots for systematic trends that might indicate lack of fit. The mean residual plus two standard deviations and the mean residual minus two standard deviations were added to the plots to indicate the magnitude of the variation existing in the residuals. If the residuals in each cell were normally distributed, then these two values would approximately bracket 95 percent of the residuals in the cell.

Results and Discussion

As a result of the analyses of covariance, white fir was combined with grand fir, giant chinkapin was combined with tanoak, and all of the coefficients except b_0 in the California black oak, Oregon white oak, and canyon live oak group were combined. Table 2 gives the regression coefficients and the adjusted coefficient of determination for each of the resulting 12 species groups. A zero value for a coefficient indicates that the coefficient was not significantly different from zero ($p = 0.05$). Regression coefficients with truncated values were not significant ($p = 0.05$) but were required to give desired behavior; therefore, the truncated value reported in Table 2 was forced into the equation.

The standard errors in Table 2 were computed under the assumption that each tree was randomly selected from the population. Because all trees on a plot were measured, their selection was not truly random; therefore, their measurements are probably correlated with each other. As a result, the standard errors presented in Table 2 are probably underestimated (Dolph 1988).

The residual analysis indicated that there were no systematic trends across predicted 5-year diameter growth or any of the independent variables for both the weighted and the unweighted residuals. For example, Figure 2 shows the graphs of the summary cell statistics for the unweighted residuals plotted across the mean cell value for predicted 5-year diameter growth of Douglas-fir, grand/white fir, ponderosa pine, sugar pine, and incense-cedar. Also plotted on these graphs are the numbers of observations used to compute each cell's values. Visual inspection of these graphs indicates that the mean residual values are centered around zero and that there are no systematic trends away from zero.

Equation (6) can be better understood if it is partitioned into a component for maximum predicted growth rate and three multiplicative modifiers to that maximum rate. The rate component is determined by setting CR_1 to 1 and both BAL_1 and BA_1 to zero. The maximum predicted growth rate is then reduced by a decrease from 1 in the tree's CR_1, by an increase from zero in the tree's BAL_1, or by an increase from zero in BA_1. Partitioning the equation in this fashion allows us to examine more thoroughly how altering the stand's characteristics affects diameter growth.

Figure 3 shows the graphs of the six targeted conifer species' maximum predicted diameter growth rates plotted across DBH_1 for three site in-

Table 2. Regression coefficients and associated statistics for equation (6).[1]

Species	Number of trees	Coefficients							Unweighted adjusted R^2
		b_0	b_1	b_2	b_3	b_4	b_5	b_6	
SOFTWOODS									
Douglas-fir	11,974	-3.33258	0.401284	-0.000444053	1.34652	0.778012	-0.0000496540	-0.0151775	0.5781
		(.11524)	(.014442)	(.000018121)	(.02204)	(.024847)	(.0000014408)	(.0022995)	
Incense-cedar	1,008	0.680328	0.294091	-0.000153983	1.51324	0.0	-0.0000319865	-0.0762573	0.6510
		(.067199)	(.042901)	(.000056416)	(.09973)		(.0000058609)	(.0088595)	
Ponderosa pine	1,594	-1.30372	0.494510	-0.000348437	1.57636	0.419129	0.0	-0.0810353	0.6213
		(.40327)	(.038320)	(.000059459)	(.07202)	(.087825)		(.0064139)	
Sugar pine	350	-1.99775	0.475468	-0.000354162	1.26503	0.519814	0.0	-0.0430817	0.3796
		(.57019)	(.075619)	(.000091941)	(.12129)	(.122921)		(.0105704)	
Western hemlock	105	-6.01009	0.404185	-0.0004	0.950304	1.29805	0.0	-0.0557239	0.4546
		(1.38668)	(.120356)		(.305529)	(.28973)		(.0175274)	
White & grand fir	2,315	-3.57581	0.707145	-0.001070590	1.33263	0.646635	-0.0000462617	0.0	0.5285
		(.30899)	(.033018)	(.000070135)	(.04738)	(.069172)	(.0000025448)		
HARDWOODS									
Bigleaf maple	41	0.0	0.485882	-0.0014	0.0	0.0	0.0	-0.117409	0.2266
			(.101242)					(.021105)	
California black oak	300	-2.76395	0.0925835	-0.0001	0.337396	0.405687	0.0	0.0	0.0934
		(.66505)	(.0474371)		(.096073)	(.145705)			
Canyon live oak	89	-2.56270	-------------------All other values are the same as for California black oak-------------------------						
Giant chinkapin & tanoak	462	-3.88293	0.222768	-0.0007	0.670268	0.746788	-0.0000231015	0.0	0.3306
		(.52589)	(.057638)		(.096330)	(.114032)	(.0000036696)		
Madrone	793	0.210329	0.134582	-0.0003	0.490452	0.0	0.0	-0.0675144	0.3003
		(.089769)	(.041420)		(.081358)			(.0068228)	
Oregon white oak	29	-3.13126	-------------------All other values are the same as for California black oak-------------------------						

[1] Standard errors appear in parentheses beneath each coefficient.

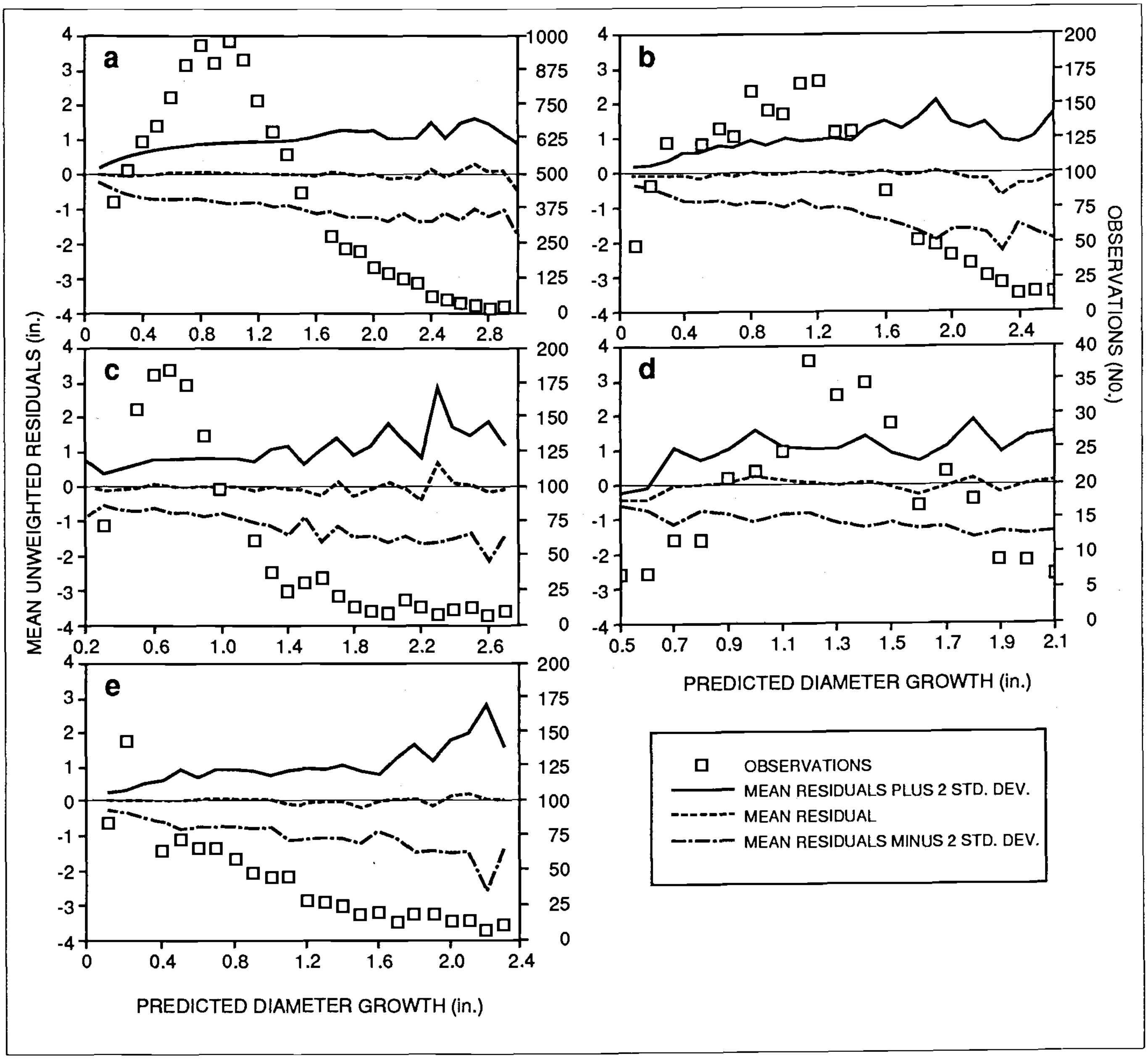

Figure 2. Mean unweighted residuals, mean unweighted residuals plus two standard deviations, mean unweighted residuals minus two standard deviations, and the number of observations in each predicted 5-year diameter growth rate cell plotted across the mean predicted 5-year diameter growth rate for each cell: (a) Douglas-fir, (b) white/grand fir, (c) ponderosa pine, (d) sugar pine, and (e) incense-cedar.

dexes. The maximum diameter growth rate for Douglas-fir is also plotted on each graph to aid in making comparisons. These plots reflect the relative maximum diameter growth rate of the six targeted conifer species. For site index 100, ponderosa pine has the highest maximum diameter growth rate, then sugar pine, incense-cedar, Douglas-fir, and finally grand/white fir. All of these curves exhibit a pronounced mounded shape, with the peak of the mound occurring at DBH$_1$'s that range from 18.1 inches for grand/white fir to 31.7 inches for incense-cedar. Incense-cedar is the only targeted conifer species without site index as an independent variable. The remaining targeted co-

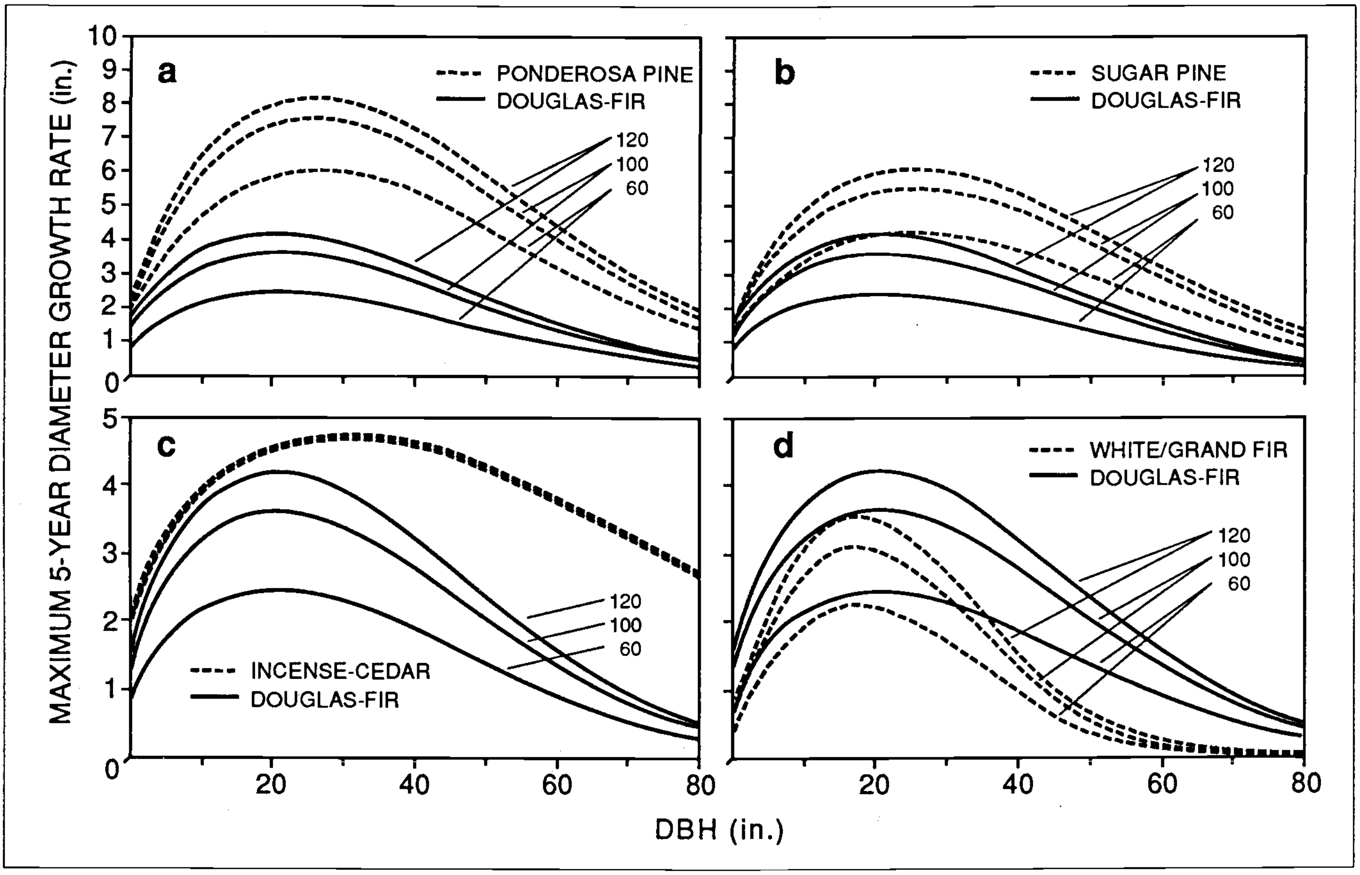

Figure 3. Maximum predicted 5-year diameter growth rate plotted across DBH for site indices of 60, 100, and 120 feet: (a) ponderosa pine and Douglas-fir, (b) sugar pine and Douglas-fir, (c) incense-cedar and Douglas-fir, and (d) white/grand fir and Douglas-fir.

nifer species show an increase in maximum diameter growth rate as site index increases.

Figure 4 is a graph of the crown ratio modifiers of maximum diameter growth rate for the six targeted conifer species. In general, the graphs show that long-crowned trees have proportionally higher diameter growth rates than do short-crowned trees. Ponderosa pine had the lowest curve, indicating that its predicted diameter growth rates are the most sensi-

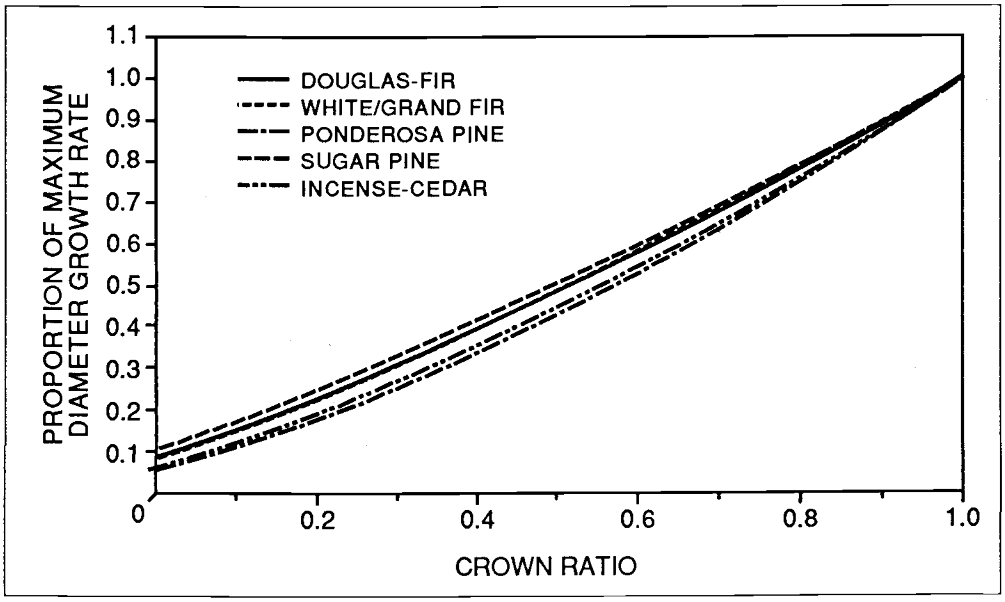

Figure 4. The effect of the tree's crown ratio on the proportion of the maximum predicted 5-year diameter growth rate realized by the tree.

tive to changes in crown ratio. The next most sensitive is incense-cedar, then Douglas-fir, grand/white fir, and sugar pine.

The BAL_1 modifier of the maximum diameter growth rate was significant for only four of the six targested conifer species: Douglas-fir, grand/white fir, and incense-cedar (Figure 5). The graphs in Figure 5 show the reduction in the proportion of the maximum diameter growth rate that occurs as basal area in larger trees increases. This effect is more severe in small-diameter then in large-diameter trees. Because BAL_1 is used to index a tree's competitive position within the stand, a BAL_1 value near zero indicates that the tree is probably in a dominant position, while a large BAL_1 value indicates that the tree is probably in the understory. Therefore, for a given DBH_1, the tree's diameter growth rate should probably decrease as BAL_1 increases, as it does in Figures 5a-c. The figure also shows that a tree with a small diameter is more negatively influenced by a given level of BAL_1 than is one with a large diameter, indicating that older, larger trees are less affected by position in the stand than are younger, smaller trees. A comparison of these plots for the four targeted conifer species shows that incense-cedar is the least sensitive to increases in BAL_1 and that Douglas-fir is the most sensitive.

Finally, Figure 6 shows the BA_1 modifier of the maximum diameter growth rate for those targeted conifer species in which it was significant. The overall effect of the BA_1 modifier is to reduce maximum diameter growth rate as BA_1 increases. The reduction is the greatest for ponderosa pine, with incense-cedar showing almost as large an effect. Douglas-fir has the smallest reduction.

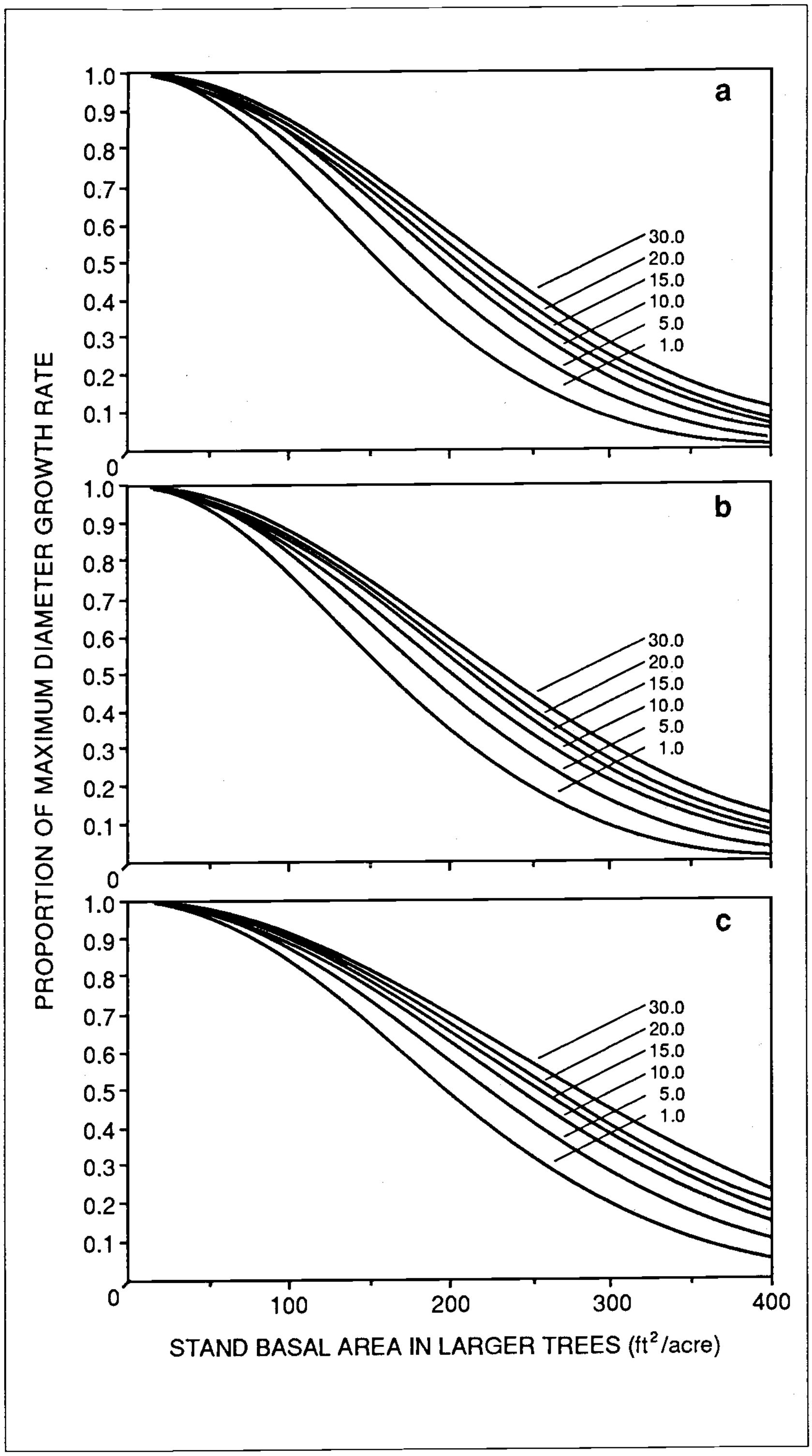

Figure 5. The effect of the stand's basal area in trees with DBH's larger than the subject tree's DBH on the proportion of the maximum predicted 5-year diameter growth rate realized by the tree, for tree DBH's of 1.0, 5.0, 10.0, 15.0, 20.0, and 30.0 inches: (a) Douglas-fir, (b) white/grand fir, and (c) incense-cedar.

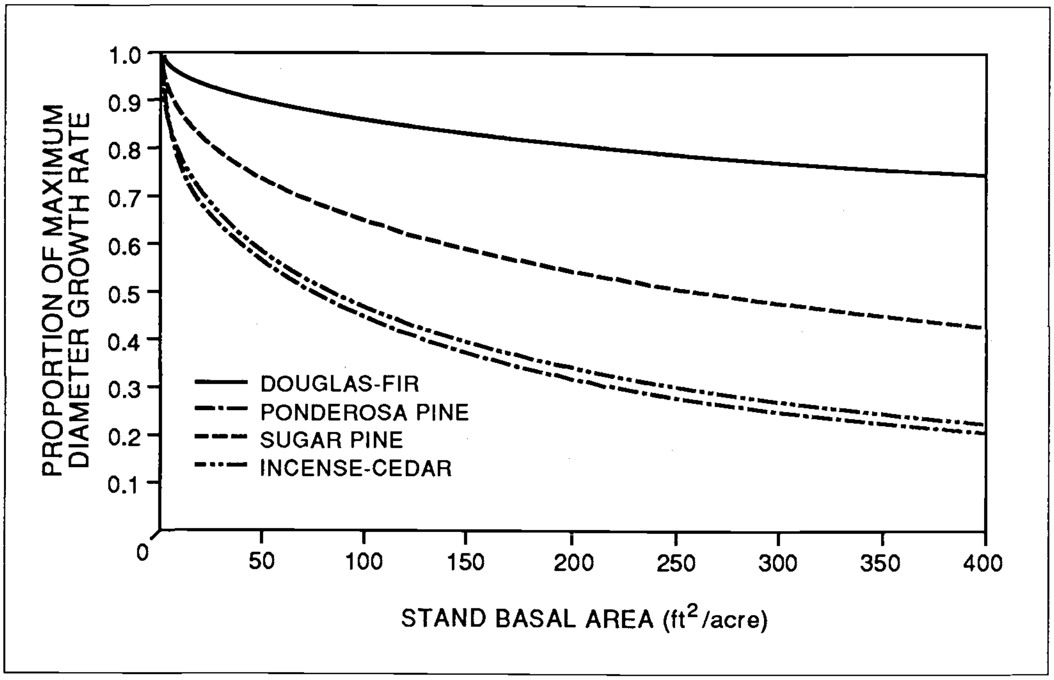

Figure 6. The effect of the stand's basal area on the proportion of the maximum predicted 5-year diameter growth rate realized by the tree.

Interpreting the joint effect of both the BAL_1 and BA_1 modifiers is also instructive. If a species has only a BA_1 modifier, its diameter growth rate will be affected just as severely by understory basal area as by overstory basal area. Therefore, the diameter growth rates of ponderosa pine and sugar pine are reduced by increasing basal area, regardless of their positions within the stand. Species such as grand and white firs, which have only a BAL_1 modifier, will be negatively affected only by the basal area in overstory trees. Interpretation when both of the modifiers are in the equation depends upon the relative effect of the two modifiers. Douglas-fir shows a relatively small reduction across BA_1 and a large reduction across BAL_1. Therefore, Douglas-fir will be more strongly influenced by the overstory than by the understory. On the other hand, incense-cedar shows strong reductions across both BA_1 and BAL_1, indicating that, while the overstory is the most influential, the understory basal area also has a strong influence upon diameter growth rate.

Summary

The individual-tree, 5-year diameter growth rate equations produced in this study are the first reported for the mixed-conifer zone of southwest Oregon. For the six targeted conifer species (i.e., Douglas-fir, white fir, grand fir, ponderosa pine, incense-cedar, and sugar pine), the variation in diameter growth rates explained by these equations ranged from 40 percent for sugar pine to 65 percent for incense-cedar. For the minor conifer and hardwood species, the equations explained between 10 and 45 percent of the variation. Detailed examination of the equations has shown that predictions from them are consistent with our current biological and silvicultural knowledge. However, it should be emphasized that the data used to develop these equations came from temporary plots measured over a 3-year period. Therefore, long-term predictions from these equations should be viewed as being reasonable hypotheses based on current, limited knowledge, rather than as absolute truth.

Literature Cited

CLINE, S.P., A.B. BERG, and H.M. WIGHT. 1980. Snag characteristics and dynamics in Douglas-fir forests, western Oregon. Journal of Wildlife Management 44:773-786.

CURTIS, R.O., and D. BRUCE. 1968. Tree heights without a tape. Journal of Forestry 66:60-61.

DAUBENMIRE, R., and J.B. DAUBENMIRE. 1968. Forest vegetation of eastern Washington and northern Idaho. Washington Agricultural Experiment Station, Pullman, Washington. Technical Bulletin 60. 104 p.

DOLPH, K.L. 1988. Prediction of periodic basal area increment for young-growth mixed conifers in the Sierra Nevada. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. Research Paper PSW-190. 20 p.

EMMINGHAM, W.H., and R.H. WARING. 1977. An index of photosynthesis for comparing forest sites in western Oregon. Canadian Journal of Forest Research 7:165-174.

FLEWELLING, J.W., and L.V. PIENAAR. 1981. Multiplicative regression with lognormal errors. Forest Science 7:337-341.

FRANKLIN, J.F., and C.T. DYRNESS. 1973. Natural vegetation of Oregon and Washington. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. General Technical Report PNW-8. 417 p.

FURNIVAL, G.M. 1961. An index for comparing equations used in constructing volume tables. Forest Science 7:281-289.

GROSENBAUGH, L.R. 1967. REX — FORTRAN - 4 SYSTEM for combinatorial screening or conventional analysis of multivariate regressions. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. Research Paper PSW-44. 16 p.

HANN, D.W., and M.W. RITCHIE. 1988. Height growth rate of Douglas-fir: a comparison of model forms. Forest Science 34:165-175.

HANN, D.W., and J.A. SCRIVANI. 1987. Dominant height growth and site index equations for Douglas-fir and ponderosa pine in southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Bulletin 59. 13 p.

HANN, D.W., and C.H. WANG. 1990. Mortality equations for individual trees in the mixed-conifer zone of southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Bulletin 67. 17 p.

HESTER, A.S., D.W. HANN, and D.R. LARSEN. 1989. ORGANON: Southwest Oregon growth and yield model user manual - Version 2.0. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. 59 p.

HOLDAWAY, M.R. 1984. Modeling the effect of competition on tree diameter growth as applied in stems. USDA Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota. General Technical Report NC-94. 8 p.

KAUFMANN, M.R., and J.D. WEATHERRED. 1982. Determination of potential direct beam solar irradiance. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. Research Paper RM-242. 23 p.

KMENTA, J. 1971. Elements of Econometrics. Macmillan Publishing Co., New York. 655 p.

KRAJICEK, J.E., K.A. BRINKMAN, and S.F. GINGRICH. 1961. Crown competition - a measure of density. Forest Science 7:35-42.

LARSEN, D.R., and D.W. HANN. 1985. Equations for predicting diameter and squared diameter inside bark at breast height for six major conifers of southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Note 77. 4 p.

LARSEN, D.R., and D.W. HANN. 1987. Height-diameter equations for seventeen tree species in southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Paper 49. 16 p.

LARSEN, D.R., D.W. HANN, and S.S. STEARNS-SMITH. 1987. Accuracy and precision of the tangent method of measuring tree height. Western Journal of Applied Forestry 2:26-28.

MARTIN, G.L., and A.R. EK. 1984. A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth. Forest Science 30:731-743.

PAINE, D.P., and D.W. HANN. 1982. Maximum crown width equations for southwestern Oregon tree species. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Paper 46. 20 p.

PILLSBURY, N.H., and M.L. KIRKLEY. 1984. Equations for total, wood, and saw-log volume for thirteen California hardwoods. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. Research Note PNW-414. 52 p.

RITCHIE, M.W., and D.W. HANN. 1985. Equations for predicting basal area increment in Douglas-fir and grand fir. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Bulletin 51. 9 p.

RITCHIE, M.W., and D.W. HANN. 1987. Equations for predicting height to crown base for fourteen tree species in southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Paper 50. 14 p.

USDA FOREST SERVICE. 1978. Region 1 field instructions for stand examination and forest inventory. Region 1, Missoula, Montana. Forest Service Handbook 2409.21, Chapter 300. 113 p.

WALTERS, D.K., and D.W. HANN. 1986a. Predicting merchantable volume in cubic feet to a variable top and in Scribner board feet to a 6-inch top for six major conifers of southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Bulletin 52. 107 p.

WALTERS, D.K., and D.W. HANN. 1986b. Taper equations for six conifer species in southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Bulletin 56. 41 p.

WALTERS, D.K., D.W. HANN, and M.A. CLYDE. 1985. Equations and tables predicting gross total stem volumes in cubic feet for six major conifers of southwest Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Bulletin 50. 36 p.

WENSEL, L.C., W.J. MEERSCHAERT, and G.S. BIGING. 1987. Tree height and diameter growth models for northern California conifers. Hilgardia 55:1-20.

WEST, P.W. 1980. Use of diameter increment and basal area increment in tree growth studies. Canadian Journal of Forest Research 10:71-77.

WYKOFF, W.R. 1986. Supplement to user's guide for the stand prognosis model—version 5.0. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah. General Technical Report INT-208. 36 p.

ZUMRAWI, A.A. 1990. Examining bias in estimating the response variable and assessing the effect of using alternative plot designs to measure predictor variables in diameter growth modeling. Ph.D. dissertation, Oregon State University, Corvallis, Oregon. 78 p.

ZUMRAWI, A.A., and D.W. HANN. 1990. Equations for predicting the height to crown base of six tree species in the central western Willamette Valley of Oregon. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Paper 52. 9 p.

HANN, D.W., and D.R. LARSEN. 1990. DIAMETER GROWTH EQUATIONS FOR FOURTEEN TREE SPECIES IN SOUTHWEST OREGON. Forest Research Laboratory, Oregon State University, Corvallis. Research Bulletin 69. 18 p.

Equations are presented that predict individual-tree 5-year diameter growth, outside bark, for 14 tree species in southwest Oregon. The data used to develop the equations came from 19,245 trees sampled from 391 stands in the study area. These equations express diameter growth as a function of diameter at breast height, crown ratio, site index, total stand basal area, and stand basal area in trees with diameters larger than the subject tree's diameter. The parameters of the equations were estimated by using weighted, nonlinear regression.

HANN, D.W., and D.R. LARSEN. 1990. DIAMETER GROWTH EQUATIONS FOR FOURTEEN TREE SPECIES IN SOUTHWEST OREGON. Forest Research Laboratory, Oregon State University, Corvallis. Research Bulletin 69. 18 p.

Equations are presented that predict individual-tree 5-year diameter growth, outside bark, for 14 tree species in southwest Oregon. The data used to develop the equations came from 19,245 trees sampled from 391 stands in the study area. These equations express diameter growth as a function of diameter at breast height, crown ratio, site index, total stand basal area, and stand basal area in trees with diameters larger than the subject tree's diameter. The parameters of the equations were estimated by using weighted, nonlinear regression.