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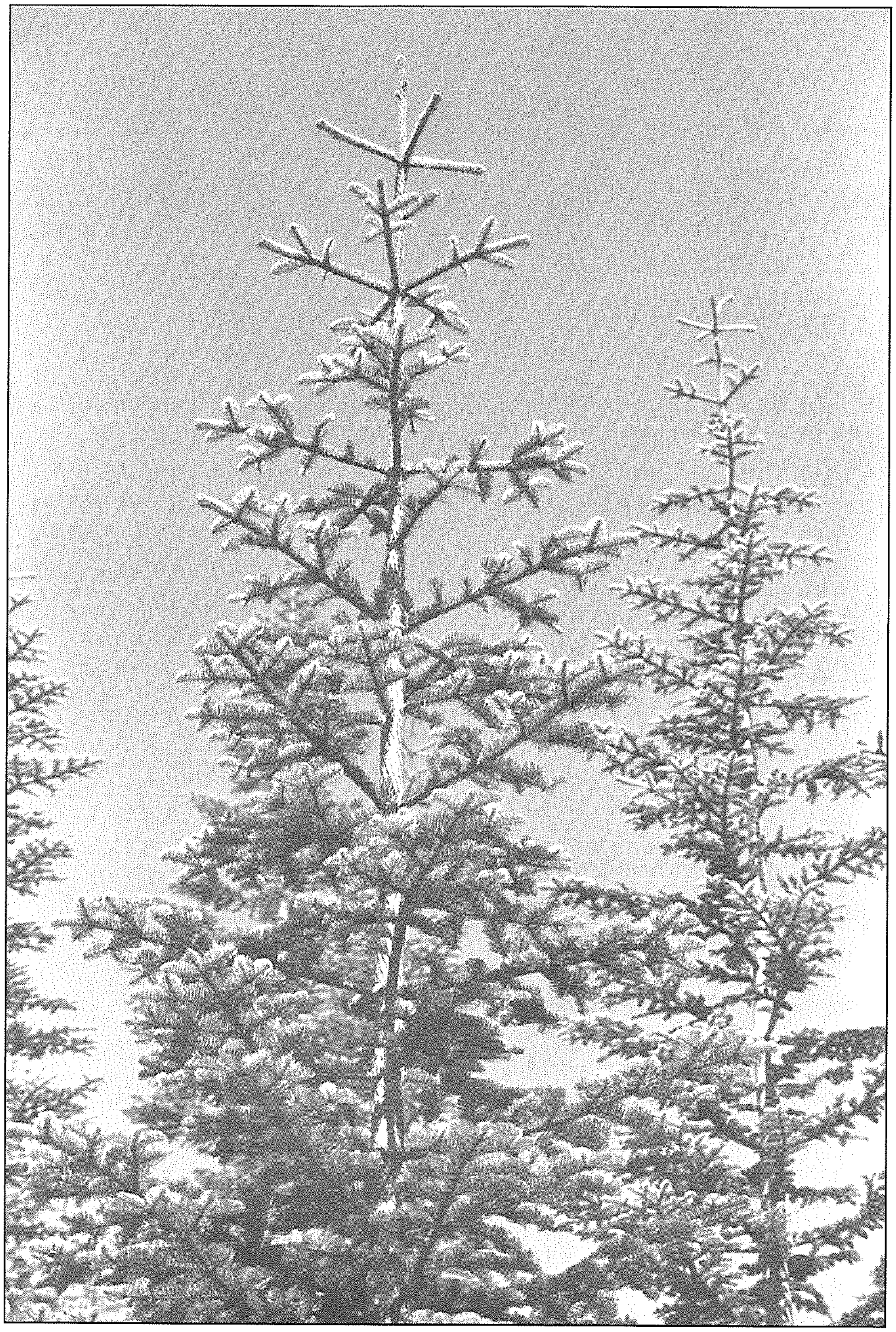
Predicting Height Increment of Young-Growth Red Fir in California and Southern Oregon

K. Leroy Dolph



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An equation is given to estimate 10-year height increment for young-growth red fir trees in California and southern Oregon. The independent variables are the individual tree, stand, and site characteristics significantly related to a tree's height growth. Data used to develop the equation came from stem analysis of 492 trees sampled from 56 stands in the study area. Parameter estimates for the predictive equation were obtained using least-squares linear regression.

Retrieval Terms: stem analysis, increment (height), California, Oregon, red fir, California red fir, Shasta red fir

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Many of today's growth and yield prediction systems use the individual tree rather than the forest stand as the basic prediction unit. In these models based on individual trees, stand development is simulated by predicting increments in diameter and height of the individual trees that comprise the stand.

This paper presents an equation to estimate future periodic (10-year) height increment of individual red fir trees in California and southern Oregon. The information needed to estimate 10-year height increment includes initial diameter, height, and live crown percent of the subject tree, an estimate of the concurrent 10-year diameter growth, and a rating of the degree of dwarf mistletoe infection. In addition to these individual tree characteristics, the stand and site factor information needed for estimating height growth includes stand density (basal area per acre), stand location (by National Forest), slope percent, aspect, elevation, and an estimate of site index for red fir (base age 50 years at breast height).

Tree, stand, and site information were recorded at 56 sample locations randomly located in young-growth stands throughout the high-elevation red fir forests of California and southern Oregon. At each sample location, from 4 to 10 randomly selected trees were felled and sectioned so that growth, both in height and diameter, for the last 10-year period could be accurately measured. Least-squares regression techniques were used to relate 10-year height growth to the significant tree, stand, and site variables and to obtain estimates of the model parameters.

The linear regression model accounted for 75.5 percent of the variability in 10-year height increment of the young-growth red fir trees observed on the study plots.

Introduction

The Prognosis Model for Stand Development (PROGNOSIS) was developed for use in the Inland Empire area of northern Idaho, eastern Washington, and western Montana (Stage 1973; Wykoff and others 1982). PROGNOSIS is a stand growth simulator based on individual trees. The model estimates changes expected in heights and diameters of sample trees in a stand during the next growth period, and accounts for mortality by reducing the trees-per-acre representation for each sample-tree record. Thus, the basic unit of the projection is the individual tree, and the development of the stand is, accordingly, the sum of the development of its component trees.

New "variants" of PROGNOSIS result when the model is calibrated for different geographic areas. Three variants of PROGNOSIS have been developed for growth projection and yield estimates for most of the major commercial tree species in California, but growth equations for red fir have not yet been included in these variants. A model for predicting diameter increment of individual red fir trees has been developed (Dolph 1992) and, along with the height increment model reported in this paper, will constitute a set of red fir growth equations for these PROGNOSIS variants.

This paper describes a linear regression equation for predicting future 10-year height increment for red fir in California and southern Oregon. This equation is designed to be used within existing PROGNOSIS variants for silvicultural and management planning for the red fir type. Because California red fir (*Abies magnifica* A. Murr.) and its commonly recognized variety Shasta red fir (*Abies magnifica* var. *shastensis* Lemm.) are considered to be almost identical in silvical characteristics (Hallin 1957), no attempt was made to distinguish between them during the sampling phase of the study. In this paper they are referred to collectively as "red fir."

Methods

Fifty-six natural stands of young-growth red fir were randomly sampled throughout the study area during the field seasons of 1984 - 1988. The study area coincides with the range of the natural distribution of red fir in California, southern Oregon, and extreme western Nevada *(fig. 1)*. This area occupies the high elevations, roughly between 5,000 and 9,000 feet (1524 to 2743 m) from Lake County, California, northward through the north Coast and Klamath ranges, and from Kern County, California, northward through the Sierra Nevada and the Cascade ranges to about the latitude of Crater Lake, Oregon (Gordon 1980). Red fir strata were identified on National Forest timber-type maps and randomly selected for sampling. Field crews then identified suitable young-growth red fir stands within the selected strata for plot installation and measurement.

Each stand was sampled using a cluster of five variable-radius plots arranged in an "L" shape, with plot centers 132 feet (40.2 m) apart along north and east compass lines. This sample plot layout was selected to be consistent with procedures used in the USDA Forest Service Pacific Southwest Region's Compartment Inventory and Analysis (CIA) program. Each plot in the L-shaped cluster was independently evaluated for study suitability by the following criteria:

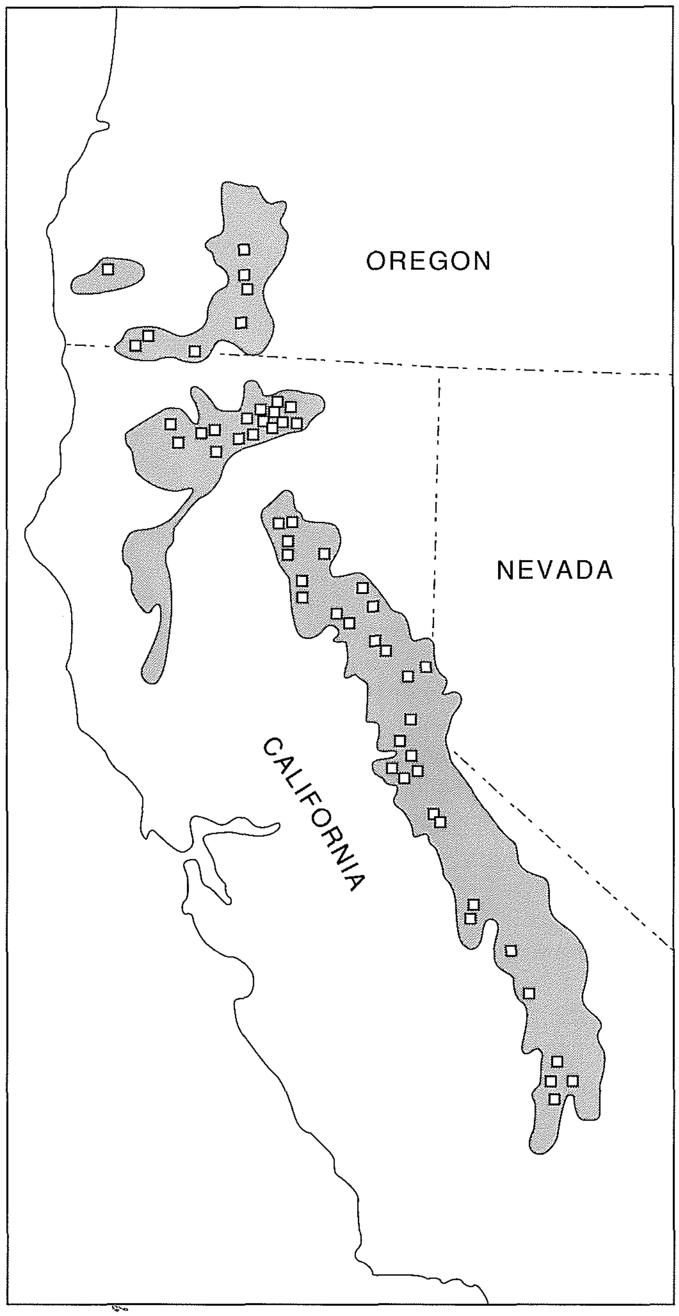

Figure 1—Natural range of red fir and study plot locations.

• Homogeneous site—Only one distinct soil type, slope percentage, or aspect was present on a 0.2-acre (0.08-ha) circular plot around the plot center (radius 52.7 ft [16.06 m]).

• Significant amount of red fir—At least 20 percent of the trees 1.0 inch (2.54 cm) and greater in diameter at breast height (d.b.h.) were red fir.

• Young-growth—No more than 25 percent of the plot trees were older than 120 years at breast height.

• Untreated stand—No silvicultural treatment was evident during the 10 years before measurement.

In stands where at least two of the five plots met these four criteria, all suitable plots were measured. If there were fewer than two suitable plots, no measurements were taken in that stand. The number of measured plots therefore ranged from two to five in each of the clusters; a total of 254 plots were measured in the 56 stands.

Stand and Tree Measurements

Basal area per acre was determined at each plot center by counting all trees that qualified for tallying with a wedge prism. Prisms with basal area factors of 20, 40, or 60 were used depending on stand composition. Each tally tree was assigned a tree number and the following characteristics and measurements were recorded for each.

- Species
- Diameter at breast height (D.b.h.) (outside bark)
- Crown position
- Damage, defect, and tree class
- Total height
- Height to base of live crown

On each tree 3.0 inches (7.6 cm) d.b.h. and larger, age and past 10-year radial growth were measured from increment cores extracted at breast height (4.5 ft [1.37 m] above the ground on the uphill side of the tree). Radial growth for the past 10-year period was measured to the nearest 0.05 inch (0.13 cm), using a hand lens when necessary.

Two trees, on the average, on each plot were then felled and sectioned to determine the past 10-year height growth. A random number table was used to determine which trees would be sampled for height growth. Trees older than 120 years at breast height and trees with dead, broken, or otherwise deformed tops were not sampled.

Each tree was marked at breast height before felling, and all subsequent height measurements were taken from this reference point after the tree was on the ground. Height to the tip of the tree, excluding the current season's growth, was recorded first. Height of the tree when growth started 10 years ago was determined next by cutting cross-sections down the stem until the lowest section that contained 10 complete growth rings was found. Height to this section was then recorded. Height increment for the 10-year growth period was determined from the difference of these two measurements.

The d.b.h. of each tree, at the start of the most recent 10-year growth period, was determined using the radial wood growth measurement and a backdating procedure. The backdating procedure to determine past outside bark diameters is described in another report (Dolph 1989). The past d.b.h. values for all the trees on a plot were then combined and past basal area per acre was obtained. To calculate basal area at the beginning of the growth period, it was assumed that trees that died during the 10-year period had the same diameter values at the start and end of the period. Live crown percent was calculated from total height and height to the base of the live crown. Since live crown percent changes slowly during a 10-year period (Stage 1975), it was assumed constant over the period. Means and ranges are given for the major tree, stand, and site characteristics *(table 1)*.

Site Factors

Major environmental characteristics of each plot were determined on a 0.2-acre circular plot around the prism plot center. The following information was recorded:

• Slope percent, measured with a clinometer along the line of slope passing through the plot center

• Aspect, measured with a hand compass along the line of slope and recorded as azimuth from true north to the nearest degree

• Site index, recorded as the total height of the best-growing, dominant tree on the plot at the index age of 50 years at breast height. Site index for most of the plots was determined directly from stem analysis of selected site quality trees when they occurred within 66 feet (20.1 m) of the plot center. For plots where no site quality trees were present within the 66-foot radius of the plot center, site index estimates were made using height and age data of the nearest suitable tree and the site index table for red fir (Dolph 1991).

Site factor information recorded for the entire cluster included:

• Elevation of the vertex plot of the L-shaped cluster, determined from U.S. Geological Survey maps and recorded to the nearest 100 ft (30.5 m)

• Latitude of the cluster, determined from USDA Forest Service maps, and recorded to the nearest minute.

Table 1—***Summary of the major untransformed variables for development of the red fir height increment model.[1] Sample size equals 492***

Variable	Minimum	Maximum	Mean
10-year diameter growth (inches)	0.1	5.7	1.9
10-year height growth (feet)	1.3	24.3	10.5
Diameter at breast height (inches)	1.7	28.9	13.6
Total height (feet)	3.5	116.2	55.6
Live crown ratio (percent)	23.0	98.0	60.1
Site index (feet)	23.0	110.0	61.4
Total plot basal area (sq ft/acre)	20	823	235
Slope (percent)	0	60	21
Elevation (feet)	4900	9000	6724

[1]Except for 10-year diameter and height growth, values indicated are for the beginning of the 10-year growth period.

Analysis

Three groups of variables were thought to affect height growth of the individual trees: (1) tree size and vigor, (2) competitive status, and (3) site factor variables. Combinations of the following independent variables and transformations of several of these variables were initially tested for predicting 10-year height increment:

Tree size and vigor
- D.b.h.
- Total height
- Live crown percent
- Mistletoe rating (Hawksworth 1977)
- Concurrent 10-year diameter growth

Competitive status
- Plot basal area/acre
- Basal area in larger trees
- (Basal area in larger trees)/(d.b.h. of the subject tree)

Site factor variables
- Latitude
- Location (by National Forest)
- Elevation
- Percent slope
- Aspect
- Site index

Tree, stand, and site factor variables (and transformations of these variables) of greatest value in predicting the 10-year height growth of red fir were identified using the best subsets regression procedure of Minitab (Minitab Inc. 1989). The best subsets of independent variables were defined as those which (1) minimized the residual mean squared error and Mallows' C_p statistic (Hocking 1976), with C_p close to the number of parameters, (2) maximized the coefficient of determination (R^2), and (3) came closest to meeting the assumptions of regression analysis. Of these best subsets, the one chosen for the model was selected on the basis of the number of variables included, biologically meaningful relationships of the dependent and independent variables, and low multicollinearity of the predictor variables. Variance inflation factors (VIF's) were computed for each of the model coefficients to detect collinearity among the selected independent variables. After the best subset of predictor variables was identified, the regression coefficients, standard error, R^2, and VIF's were computed using Minitab (Ryan and others 1985).

Results and Discussion

The model that best describes the relationship between 10-year height growth of individual red fir trees and the tree, stand, and site characteristics is expressed as

$$E[HG] = LOC + MIS + B_1 \cdot DSQ + B_2 \cdot \ln(HT) + B_3 \cdot HTSQ + B_4 \cdot CR + B_5 \cdot SRDG + B_6 \cdot COS(ASP) \cdot SL + B_7 \cdot ELEV + B_8 \cdot SI + B_9 \cdot \ln(BA)$$

in which

E[HG] = the expected value of the periodic (10-year) height growth in feet

LOC = a constant term (intercept) that is dependent on location by National Forest *(table 2)*

MIS = a constant term (intercept) that is dependent on the tree's dwarf mistletoe rating *(table 2)*

DSQ = $D^2/1000$ in which D = the diameter of the subject tree (outside bark in inches) at breast height at the beginning of the 10-year growth period

ln(HT) = natural logarithm of total tree height in feet at the beginning of the growth period

HTSQ = (total tree height squared)/1000

CR = live crown percent = (live crown length/total tree height)• (100)

SRDG = square root of the change in inside bark diameter at breast height during the 10-year growth period in inches

COS(ASP) = cosine of the plot aspect expressed in degrees from true north

SL = slope of the sample plot (percent/100)

ELEV = elevation of the vertex plot of the L-shaped cluster in hundreds of feet

SI = site index of the plot expressed as the total height in feet of a dominant red fir at a reference age of 50 years breast height

ln(BA) = natural logarithm of the total basal area (square feet per acre) of the sample plot, at the beginning of the 10-year growth period

$B_1, B_2, ... B_9$ = regression parameters estimated from the sample data.

Table 2—***Variables and coefficients of the height increment model for red fir***

Variables[1]		Coefficient
	National Forest	
	Klamath	-18.986
Location	Shasta-Trinity	-18.905
intercepts	Sierra	-16.125
(LOC)	Stanislaus	-17.121
	All other Forests	-18.146
	Hawksworth's 6-class mistletoe rating	
Mistletoe rating		
intercepts	0 - 1	0.0
(MIS)	2 - 3	-1.079
	≥4	-1.406
DSQ	(B_1)	-7.077
ln(HT)	(B_2)	4.0577
HTSQ	(B_3)	-0.5760
CR	(B_4)	0.0460
SRDG	(B_5)	7.0663
COS(ASP) • SL	(B_6)	2.5763
ELEV	(B_7)	-0.0796
SI	(B_8)	0.1082
ln(BA)	(B_9)	0.5423

[1]See Results and Discussion section for definition of these terms.

The linear regression, with the coefficients given *(table 2)*, accounted for 75.5 percent of the variability in 10-year height increment observed on the study plots, with a standard error of estimate of 2.28 feet. Variance inflation factors of the model coefficients were all less than 8.0, indicating low multicollinearity of the predictor variables.

Each tree was treated as an independent observation for the development of the predictive equation. In actuality, the clusters (which were selected randomly) are the experimental units, and the tree measurements are subsamples within the clusters. Ignoring this random cluster effect results in a slight underestimate of the variance associated with the regression. The actual amount the variance is underestimated is unknown since a variance component model was not developed, but it is assumed to be small and the random cluster effect was not considered significant in calculating the variance estimate associated with the regression.

Putting confidence limits on multiple regressions requires computation of the Gauss or c-multipliers. The c-multipliers are the elements of the inverse matrix for sums of squares and products as they appear in the normal equations. The inverse matrix is not presented in this paper, but is available to anyone wishing to define confidence intervals for any combination of independent variables.[1]

The equation predicts periodic height increment as a function of initial tree size and competitive status, concurrent diameter increment, and site conditions. The predictive equation can be used to estimate height increment during the last 10-year growth period, when concurrent diameter growth can be measured from increment cores, with the statistical reliability described. However, when the equation is embedded in the stand growth simulator (PROGNOSIS) to predict future height increment, estimates of concurrent diameter increment instead of measured values must be used. The resulting height increment predictions therefore will be less reliable than the statistics presented here indicate, depending on the accuracy of the diameter increment predictions.

Height growth estimates calculated with values outside the range of the sample data *(table 1)* should be used with caution if used at all. The height growth model for red fir was developed from data collected in young-growth stands (trees less than 120 years old at breast height) and is intended for use in young-growth stands. Extrapolations of the basic data may easily result in negative 10-year height growth values, especially for trees with large diameters (30 inches d.b.h. and larger) with slow diameter-growth rates (less than 1.0 inch in 10 years).

[1]Data on file at Pacific Southwest Research Station, 2400 Washington Avenue, Redding, CA 96001.

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