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Volume Growth and Response to Thinning and Fertilizing of Douglas-fir Stands in Southwestern Oregon

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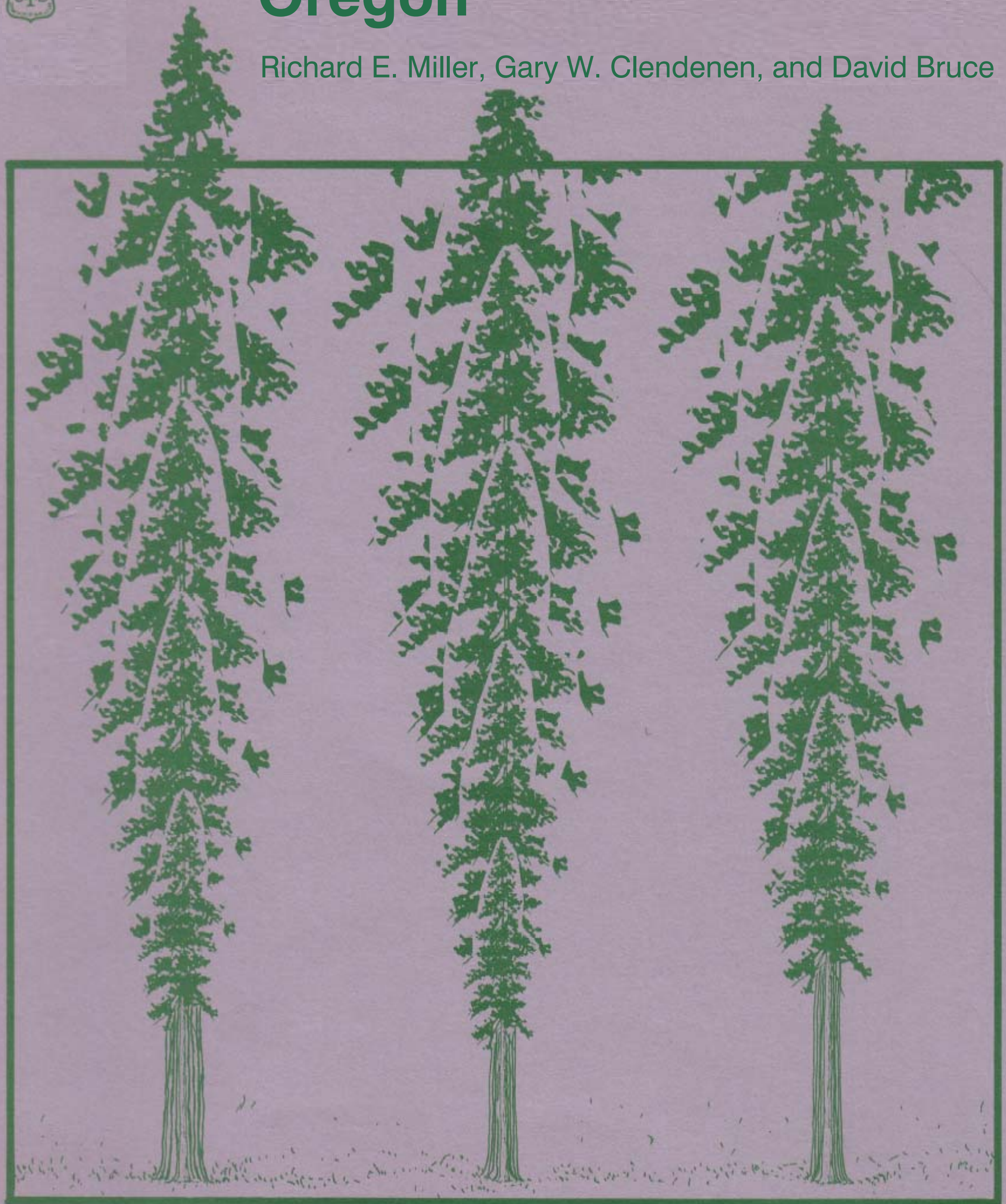

Authors

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Abstract

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From data for 114 thinning and fertilizing trials in forests of southwestern Oregon and northern California with 5 or more years of observation, we produced equations to estimate gross cubic volume growth of 10- to 70-year-old Douglas-fir stands. These equations use stand descriptors (breast-height age, site index, and relative density) and treatment descriptors to estimate annual gross volume growth during a 10-year period for untreated and treated (fertilized or thinned, or both) stands.

These predictions (SWOR) were compared with other growth predictions including DFSIM, a simulation model based on a broader, regionwide data base. Our predictions consistently showed greater gross and net growth of untreated Douglas-fir in this subregion than does DFSIM and generally showed greater volume gains from nitrogen fertilization of unthinned stands, especially on poor quality sites and in young stands. SWOR forecasts reduced gross volume growth during the 10-year period after thinning and predicts faster recovery after early thinning on good sites than on poor. Our data indicated that nitrogen fertilization could increase wood production in about 70 percent of unthinned and thinned Douglas-fir forests in this subregion. Gains in gross growth in a 10-year period after fertilization of 20-year-old site 85 stands with 200 lb of nitrogen per acre were estimated as 800 and 650 cubic feet per acre, respectively, for unthinned and thinned stands.

Keywords: *Pseudotsuga menziesii,* forest fertilization, thinning, silviculture, stand density, growth models.

Contents

Introduction

Forest managers in southwestern Oregon need reliable estimates of untreated stand growth and of potential gains from thinning and fertilizing. Earlier growth estimates for naturally regenerated, coast Douglas-fir *(pseudotsuga menziesii* (Mirb.) Franco) in southwestern Oregon are based on pooled, regional averages for Washington and Oregon (Bruce and others 1977; Curtis and others 1981, 1982; McArdle and others 1961; Peterson 1982; Staebler 1955). Such regional averages seldom are accurate near the geographic limits of a widely distributed species.

We developed equations for estimating gross cubic volume growth of naturally regenerated, 10- to 70-year-old, Douglas-fir stands in southwestern Oregon. Estimates of net growth are provided. These equations were based on tree measurements from 111 thinning and fertilizing trials in Oregon and 3 trials in northern California. Our summary gives forest managers new estimates of volume growth for untreated Douglas-fir and of the volume gains from thinning and fertilization in this subregion.

Methods

The Data

Source and geographic distribution -Tree measurement data initially came from 134 field trials installed by various organizations; [1] about 70 percent of these data were from trials installed by the Regional Forest Nutrition Research Project (RFNRP). Trials were located from the Pacific Coast to the crest of the Cascade Range and from Salem, Oregon, to the Klamath River drainage in northern California. This includes more area than is commonly called "southwest Oregon," but we did this to ensure wide samples of site conditions and a large sample for our analyses.

Description of experimental treatments -These trials tested fertilization in unthinned or thinned, naturally regenerated stands; only two trials were in plantations, and both had many volunteers. The experimental design and plot size differed because these trials were made by many different organizations; however, all trials had at least one untreated (control) plot.

Treatments differed among the trials because of differing experimental objectives and stand conditions; fertilization or thinning occurred only one time. For stands that were both fertilized and thinned, both treatments were applied concurrently in more than 95 percent of the data that were used in the final analyses; only a few fertilizer trials were in previously thinned stands. Thinning intensity ranged from 15- to 80-percent felling of initial basal area. Heaviest intensity was in thinning of overstocked stands that were 20 years and younger; such stands frequently included many western hemlock *(Tsuga heterophylla* (Raf.) Sarg) before thinning.

Nearly all trials tested urea (46 percent nitrogen [N]) supplying 200 Ib N/acre; many of these trials also included a higher dosage of 400 Ib N/acre. Other experimental variations at a few locations included lower and higher dosages of nitrogen; ammonium nitrate (34 percent N) as the nitrogen source; or mixed fertilizers containing phosphorus, potassium, sulfur, or calcium. Almost all fertilizers were applied by hand to the measurement plot and a surrounding buffer area; in only one trial was fertilizer applied by helicopter.

[1] Data were contributed by Boise Cascade Corporation; Bureau of land Management, U.S. Department of the Interior; Georgia Pacific Corporation; Oregon State University; Pacific Northwest Research Station, Pacific Southwest Forest and Range Experiment Station, Shasta-Trinity National Forest, and Siskiyou National Forest, Forest Service, U.S. Department of Agriculture; Roseburg lumber Company; University of Washington (including cooperators in the Regional Forest Nutrition Research Project); and Weyerhaeuser Company.

Standards for plot acceptance

1. Plots ranged from 0.1 to 0.25 acre; smaller plots were rejected. Each plot contained at least 25 trees.

2. The boundary of treatment areas extended beyond the measurement plots; this restriction was waived in some trials with 0.25-acre measurement plots with sapling-size trees because the edge effect of a different treatment was assumed to have an acceptably small influence on growth within these larger plots.

Data assembly and editing

1. Tree diameters at breast height (d.b.h.) were measured at intervals of 2 to 7 years. Although d.b.h. of smaller trees was recorded on a few trials, minimum tree size for growth summaries was uniformly set at 1.6 inches d.b.h. Total height of a subs ample of six or more trees per plot was remeasured periodically; most height trees were in the upper crown classes and were systematically selected by location.

2. Tree data from the contributors were coded in different formats for electronic data processing. The data were translated into a common format for editing, storage, retrieval, and subsequent computations. A standard tree-record format and coding system similar to that recommended by CO8MADS (Committee on Standards of Measures and Data Sharing; Arney and Curtis 1977) was used.

3. An understory of small, perhaps younger stems of western redcedar *(Thuja plicata* Donn ex D. Don), western hemlock, and true firs *(Abies* spp.) often develops in older stands of Douglas-fir. These small stems have little effect on current volume growth, but they may have a large influence on calculated stand statistics of number of trees and average diameter (Curtis and others 1981, 1982). We identified such stems by calculating the mean and standard deviation of d.b.h. for the Douglas-fir component in each plot and measurement. We then coded as "understory" any stem of an associated tolerant species that, on its first appearance in the record, was less in d.b.h. than 2.5 standard deviations from the average diameter of Douglas-fir at that time. These understory stems were excluded from all subsequent computations.

4. No information on number and size of trees that had been cut was available for about 10 percent of the thinned plots. Two different methods were used to reconstruct these statistics. Most plots were revisited and a tally made of stump diameter at 6 inches above ground. Next, over-bark diameter at this stump height and at breast height were measured on 15 or more standing trees on nearby untreated plots to establish data for an equation to estimate d.b.h. from measured stump diameter; these standing trees spanned the range of stump diameters on the thinned plots.

A second, less precise method was used to estimate statistics of cut trees in one trial that was not visited. Here, the diameter distribution (in 1-inch classes) of the thinned plots was subtracted from that of the control plots; this difference was used as the estimated diameter distribution of cut trees.

5. Top height (H40) is the average height of the largest (by d.b.h.) 40 stems per acre. Site index (SI) values were assigned to plots using H40, b.h. age, and King's (1966) index curves. Curtis and others (1981, 1982) point out that H40 is not identical to the stand fraction used by King but state that differences are usually small.

Site quality strongly influences stand growth; therefore the site index assigned to a plot should be the best available estimate of site index for each plot. The SI assigned at the measurement closest to the 50-year b.h. age (King 1966) is likely to be the best estimate for control plots. For fertilized plots, some adjustment of SI measured at this closest measurement was necessary, though, because fertilization may have increased H40; this increase results in an overestimated SI for fertilized plots. Our procedure was, on unfertilized plots and all plots in stands older than b.h. age 50 (about 15 percent of the plots), to assign SI based on H_{40} and b.h. age measured closest to the index age, 50 years b.h. For fertilized plots in stands less than 50 years b.h., the assigned site index was the average SI of the associated unfertilized plot(s) at measurement closest to 50 years times a correction factor, initial H_{40} fertilized plot/initial H_{40} unfertilized plot(s) at the same location.

6. Stand statistics at each measurement and periodic growth or change between successive measurements were summarized by computer programs of PDMS, Plot Data Management System.[2] .

Observed periodic annual increments (gross p.a.i.) were examined for suspicious magnitudes and trends. Questionable increments (those exceeding three standard deviations from p.a.i. predicted from age, site index, and other variables) were reviewed and then corrected, rejected, or accepted. They were corrected when obvious data or coding errors were found, and rejected if the p.a.i. outlier was the result of excessive ingrowth into the 1.6-inch d.b.h. class or of catastrophic mortality unrelated to treatment. For example, the volume of ingrowth trees in young, understocked stands was occasionally a large component of growth. We rejected 12 growth periods in which the volume of ingrowth trees was more than 10 percent of the p.a.i.; these were in young stands with quadratic mean diameter (Dg) under 4 inches. Thus our model, SWOR, should not be used for predicting growth in stands where ingrowth exceeds 10 percent of the gross p.a.i. Finally, all other outliers in this editing that were considered biologically possible were accepted.

Volume of mortality on each plot during each growth period was checked for anomalous losses that could be related to treatment or conditions. Average annual mortality during a given period that exceeded 2 percent of the live volume at the start of the period was considered unusual. Occurrence of unusual mortality was tabulated by trial, plot, and period. When this unusual amount of mortality was primarily in lower crown classes and below-average d.b.h. classes, we considered it suppression mortality. If field observations or prevalent losses in upper crown classes indicated this as catastrophic mortality and this catastrophic mortality was clearly characteristic of that location and not of specific treatments, then data for that period and subsequent periods were rejected from further analysis; rejection occurred in 18 periods. Catastrophic mortality on one or a few plots at a location might be related to treatment, however; the data for a few growth periods with this condition were therefore included in further analyses.

[2] Unpublished reports, copies on file at the Forestry Sciences Laboratory, 3625 93d Avenue S.W., Olympia, Washington 98502.

Table 1-Number of growth periods, average b.h. age, and site index, by treatment

Treatment		Growth periods		Average (range)	
Thinned	Fertilized			B.h. age	Site index (50 yr)
		Number	*Percent*	*Years*	*Feet*
No	No	523	23	36 (6-78)	114 (64-168)
No	Yes	1,038	46	37 (6-78)	115 (64-165)
Yes	No	282	13	28 (6-78)	112 (60-158)
Yes	Yes	412	18	29 (6-78)	114 (54-152)
All treatments		2,255	100		

Data distribution by plots and growth periods -We restricted our analyses to 579 plots at 114 locations where Douglas-fir was 80 percent or more of the initial basal area (appendix table 13). Trees on these plots were measured at 2- to 7-year intervals for 5 to 14 years; thus, p.a.i. was calculated for periods ranging from 2 to 7 years. This p.a.i. was the dependent variable in the regression analysis (growth modeling). No attempt was made to weight observations on the basis of period length because we believed the potential improvement from weighting was small. The total number of acceptable growth periods was 2,255 for stands where Douglas-fir was 80 percent or more of the starting basal area (table 1).

About 46 percent of these 2,255 growth periods were in fertilized-only plots and 23 percent in untreated plots (table 1). Thinned-only plots comprised 13 percent of the growth periods, whereas combined thinning and fertilization was represented in 18 percent of the data. All three treatments seldom were applied at each trial location, but each location included one or more control plots.

Although average site index for the treatments was similar, b.h. age of thinned stands averaged about 10 years younger than unthinned stands. Further breakdown of these periods by age class and site class are shown in appendix tables 14 and 15, respectively. These tables show that the bulk of the data is from stands with b.h. age under 50 years and the data are well distributed across the site classes.

Regression Analysis

Stepwise multiple regression (Norusis 1986) was used to fit two types of estimating equations. The F-value for variables to enter and leave these equations was set at 2.0 and 1.9, respectively. The tolerance level was set at 0.0011. The best stepwise solution was usually accepted; occasionally, some supplemental judgment was used in model selection. The order in which the variables were entered into the stepwise fit was often prespecified during model building to examine effects on the final variables selected. When a best fit was identified, the predicted values were plotted over the predictor variables, and the plotting was examined for reasonableness. Many of the variable transformations were the result of this iterative adjustment that made the models behave in a reasonable manner.

Equations were developed to estimate gross p.a.i in cubic feet, including tip and stump (CVTS), of trees 1.6 inches d.b.h. and larger. This group of equations is termed SWOR. Equations were also developed to estimate initial relative density (IRD in unthinned stands and TRD after thinning); when actual RD is unknown, these equations provide values of RD needed for applying the SWOR equations. Relative density is computed as stand basal area divided by the square root of the quadratic mean stand diameter of all trees 1.6 inches and larger.

A two-step fitting procedure was used to develop the p.a.i. equations. First, an equation was developed to estimate p.a.i. of untreated stands as a function of stand age (b.h. age), SI, and relative density (RD). Second, separate equations were developed for each of the three treatments to estimate the difference (response) from this estimated p.a.i. (control equation) as functions of treatment, b.h. age, SI, RD, and time since treatment. Thus, the estimated response to treatment was the observed growth of the treated plot in a given period less its estimated growth as an untreated plot having the same b.h. age, SI, and RD.

Results and Discussion

General

Equations estimating volume growth and relative density of stands of Douglas-fir (80 percent or more Douglas-fir by basal area) are based on multiple regression equations. Gross p.a.i. of untreated Douglas-fir stands or annual response for a specified treatment can be estimated by substituting known or assumed stand and treatment descriptors into these equations. These descriptors should be within the limits specified below, however, to obtain reasonable estimates. To estimate net p.a.i., multiply gross p.a.i. by an appropriate ratio of net/gross volume growth provided later (table 9) in this report. The recommended limits for descriptor variables are shown in the following tabulation:

Variable and code[3]	Units	Recommended limits
Treatment variables:		
N	Pounds per acre	100-500
d/D	—	0.6-1.0
Stand variables:		
B.h. age	Years	6-70
SI	Feet	70-155
RD, IRD	—	15-110
TRD	—	10-60
Prediction periods:		
Untreated	Years	1-20
Fertilized	Years	1-10
Thinned	Years	1-10
Thinned-fertilized	Years	1-10

[3] See "Abbreviations and Definitions" in appendix.

The Estimators

In this section, the estimating equations are described and sample solutions are given for 1 O-year growth periods with initial b.h. stand ages of 20, 40, and 60 years and SI of 85, 115, and 145. After this, our estimates (SWOR) of volume growth and response are compared with broader, regional averages from RFNRP (Peterson 1982) and from the Douglas-fir growth simulator, DFSIM (Curtis and others 1981, 1982) .

The research trials our estimating equations (SWOR) are based on generally were installed in well-stocked stands. Yet, predictions of volume growth may be desired for stands that are more or less than well-stocked. To provide such predictions, some measure of stand density must be included as a predictor variable. We chose relative density, RD (Curtis 1982), which is readily calculated from stand basal area and stem tallies. RD is closely related mathematically to other commonly used measures of density such as basal area normality calculated from table 25 (McArdle and others 1961) and to stand density index (Reineke 1933). Although RD is used as an independent variable in these p.a.i. estimating equations, it is related to SI and b.h. age, the other independent variables. Lack of independence (multicollinearity) is not a serious problem among the variables in the final equations, however. Collinearity between some variables was encountered in the model-building phase, but highly collinear variables were excluded from the final equations.

Gross p.a.i.'s can be estimated for real or hypothetical stands by substituting known or estimated values, respectively, in the following two types of equations.

Volume growth or response estimators - Separate equations were developed to estimate growth (of untreated stands) and response from the management options: fertilized, thinned, or the combination of thinned and fertilized. To estimate p.a.i. for a given treatment, add the estimated response to the estimated untreated p.a.i. for the same period and stand characteristics. To estimate cumulative growth or response for n years, sum the p.a.i. or response for n successive years. See appendix for abbreviations and definitions of variables in these equations. The equation for estimating annual gross volume growth of untreated stands (U):

$$\text{CONTROL} = \text{Ln(dV)} = a + b * \text{SI} + c * \text{Ln(RD)} + d * A + e * A^{-2} + f * \text{SI}*A^{-1} \quad \text{(1U)}$$

Adjusted R^2 = 0.68, S.E. = 0.22, F = 244, n = 523

According to Weisburg (1980),

$$\text{Adjusted } R^2 = 1 - \frac{(n-1)}{(n-p)} \; (1-R^2, \text{unadjusted}) .$$

Table 2 gives the regression coefficients and their associated F-values (a measure of statistical significance) for equation (1 U) and for the response equations that follow.

To estimate annual response in gross volume growth in fertilized, but unthinned stands:

$$Y_f = Ln(dV) - UNTREATED = a + b * Ln(IRD) + c * SI + d * SI^{-2} + e * dT^2 + f * Ln(N+1) + g * IRD + h * SI*A^{-1} + i * dT^{-1} + j * Ln(SI)*dT^{-1} . \quad (1F)$$

Adjusted $R^2 = 0.33$, S.E. = 0.22, F = 57, n = 1,038

The relatively low R2 value indicates much variation in response to fertilizer that is not accounted for by the equation. Presumably, variables unmeasured in this study must be included in the equation to express response more precisely.

To estimate annual response in gross volume growth in thinned but unfertilized stands:

$$Y_t = Ln(dV) - UNTREATED = a + b * IRD*TRD^{-1}*(d/D)^{-1} + c * Ln(TRD) + d * TRD + e * SI*A^{-1} + f * (dT+2)^{-1} + g * A^{-1} + h * (dT+2) * SI^{-2} + i * SI + j * A . \quad (1T)$$

Adjusted $R^2 = 0.67$, S.E. = 0.22, F = 65, n = 282

To estimate response in stands thinned and fertilized concurrently:

$$Y_{ft} = Ln(dV) - UNTREATED = a + b * SI*dT*A^{-1} + c * Ln(N+1) + d * SI + e * A + f * A^{-2} + g * (dT+2)^{-2} + h * IRD*TRD^{-1}*(d/D)^{-1} + i * (dT+2)^{-1} + j * A^{-1} + k * Ln(SI) + l * d/D . \quad (1FT)$$

Adjusted $R^2 = 0.61$, S.E. = 0.19, F = 59, n = 412

The estimates for stands both thinned and fertilized apply to stands thinned and fertilized in the same year; only a few plots in the data set had a time lag between the treatments.

We undoubtedly reduced variance among our observations by treating both individual growth periods and plots as independent observations. In fact, growth periods from a given plot are autocorrelated, and three or more plots were clustered at each trial location. Consequently, R2 is higher and S.E. is lower to some unknown extent than had the data been from independent growth periods. Considering the large number of trial locations, we assume these effects of reduced variance to be small.

Because the data base was too small to fit independent equations, we provide no estimates for hemlock or mixed-species stands. Data from these forest types were excluded in equation development because preliminary analyses showed that pooled data gave biased estimates of p.a.i. for Douglas-fir stands.

Table 2-Equation coefficients to estimate Ln gross p.a.i. (CVTS) and F-values of specific variables

Equation number	Symbol[a]	Partial F-value	Coefficient
1U	**Untreated equation (n=523)**		
	Log bias adjustment factor		0.021090
	Constant	119	2.1242
	SI	132	.0091542
	Ln(RD)	200	.59346
	A	4	-.0023654
	A^{-2}	30	-102.62
	$SI*A^{-1}$	11	.067920
1F	**Fertilized-only equation (n=1,038)**		
	Log bias adjustment factor		.023430
	Constant	123	2.6702
	Ln(IRD)	58	-.39230
	SI	53	-.0079761
	SI^{-2}	13	-2288.6
	dT^{2}	5	-.00076673
	Ln(N+1)	4	.033740
	IRD	6	.0025429
	dT^{-1}	5	-.85446
	$SI*A^{-1}$	8	.012740
	$Ln(SI)*dT^{-1}$	4	.16725
1T	**Thinned-only equation (n=282)**		
	Log bias adjustment factor		.023550
	Constant	44	2.5538
	$IRD*TRD^{-1}*d/D^{-1}$	89	.73043
	Ln(TRD)	42	-.49463
	TRD	36	.019440
	$SI*A^{-1}$	58	.22561
	$(dT+2)^{-1}$	97	-2.4906
	A^{-1}	44	-28.464
	$(dT+2)*SI^{-2}$	3	-135.60
	SI	32	-.010880
	A	12	-.0067741
1FT	**Fertilized and thinned equation (n=412)**		
	Log bias adjustment factor		.018260
	Constant	6	-3.1357
	$SI*dT*A^{-1}$	62	.013120
	Ln(N+1)	37	.17185
	SI	11	-.011430
	A^{-2}	19	99.680
	Ln(SI)	3	.59268
	$IRD*TRD^{-1}*(d/D)^{-1}$	95	.83274
	$(dT+2)^{-2}$	47	-11.606
	A^{-1}	12	-14.473
	$(dT+2)^{-1}$	33	5.1182
	A	7	-.0067303
	d/D	14	.63933

[a] See "Abbreviations and Definitions" in the appendix.

An adjustment factor is added to the p.a.i. and response equations to remove logarithmic bias. We used 1/2 M8E (mean square error) as suggested by Flewelling and Pienaar (1981). Figures 1 and 2 illustrate average observed and predicted values of p.a.i. plotted over SI and b.h. age after the logarithmic bias adjustment. The equations estimate p.a.i. quite well across all sites and treatments. Across stand ages, our predictions are close for young ages, but with increasing age, numbers of observations decreased and variation increased; consequently the estimates are less precise, although unbiased.

Density estimators - An estimate of RD is needed to use the p.a.i. and response-estimating equations. Either known relative density for specific stands or estimated relative density based on stand averages can be used. Following are two equations for estimating RD that are based on stand variables observed in our data. The first equation was fit for unthinned stands (IRD) and the second for thinned stands (TRD).

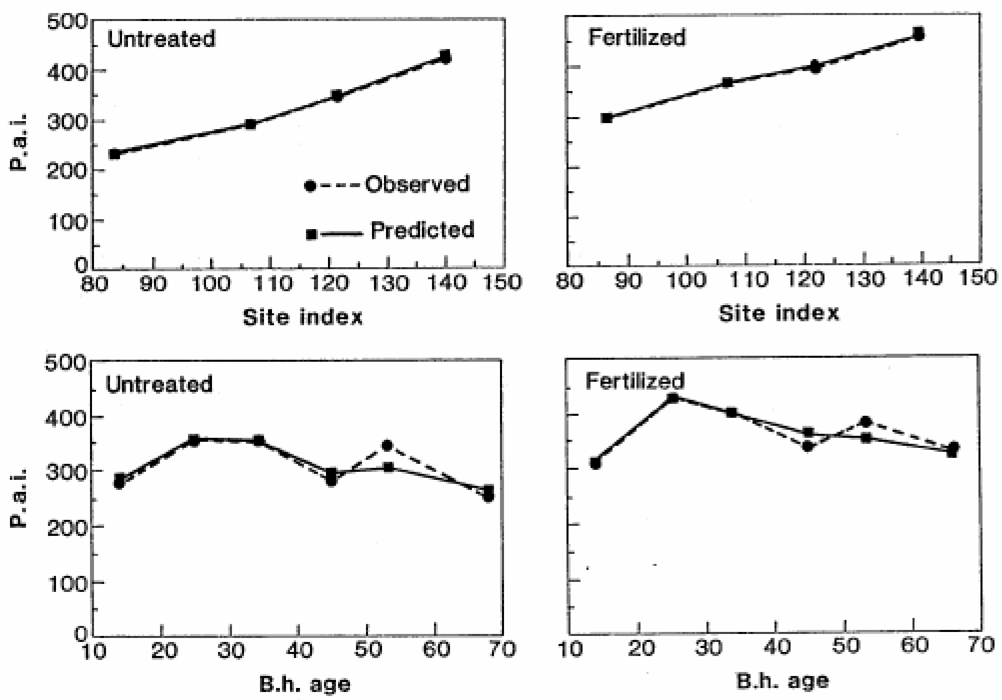

Figure 1 - 0bserved and predicted gross periodic annual volume increment (p.a.i.) for designated classes of site index and age at breast height (b.h.) in untreated and in fertilized stands; predicted p.a.i. was adjusted for logarithmic bias.

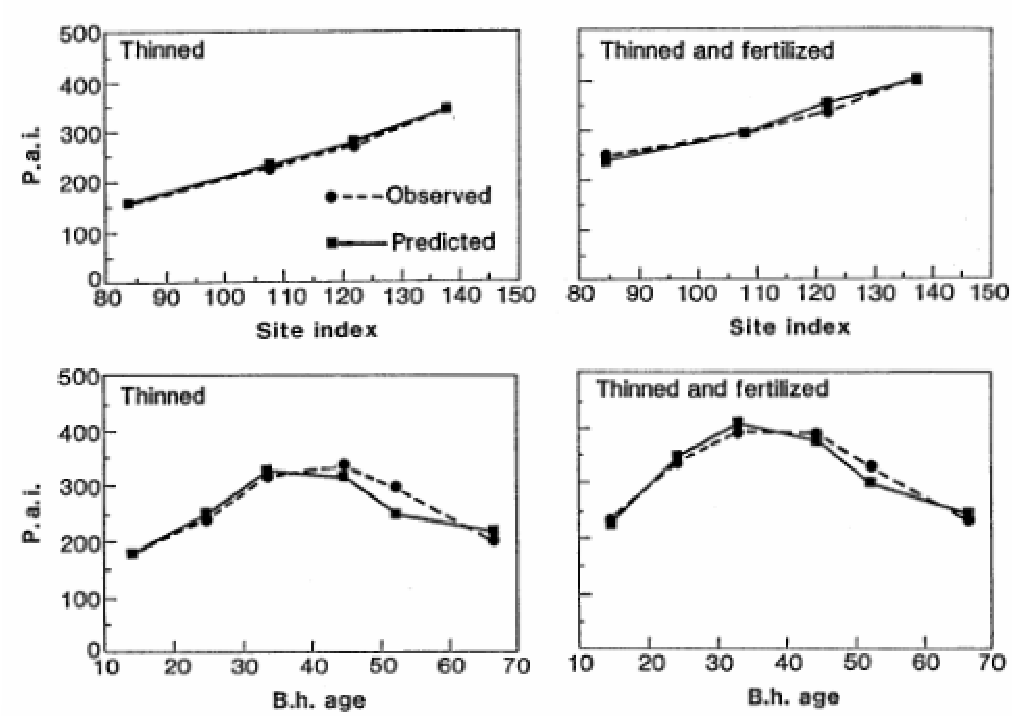

Figure 2-0bserved and predicted gross periodic annual volume increment (p.a.i.) for designated classes of site index and age at breast height (b.h.) in thinned-only and thinned and fertilized stands; predicted p.a.i. was adjusted for logarithmic bias.

To estimate mean relative density of untreated stands or to estimate mean relative density immediately before treatment (IRD) for both fertilized and thinned stands:

$$IRD = a + b * SI + c * A + d * Ln(SI) + e * A^{-1} + f * SI * A^{-1} + j * A^{-2} . \qquad (2U)$$

Adjusted A2 = 0.51, S.E. = 14.8, F = 263, n = 969

And, to estimate average after-thinning relative density:

$$TAD = a + b * IRD + c * Ln(A) + d * SI . \qquad (2T)$$

Adjusted R^2 = 0.80, S.E. = 6.2, F = 170, n = 194

The regression coefficients and F-values for specific variables of the relative density equations are given in table 3.

Gross Growth of Untreated Stands

Trends of estimated gross volume growth in untreated Douglas-fir stands of average density (AD) show an expected pattern of higher levels and earlier peaking of p.a.i. on better site quality than on poorer site quality (fig. 3). Estimated gross p.a.i. for SI 145 stands peaks at about 450 $ft^3 \cdot acre^{-1} \cdot y^{-1}$; whereas for SI 115 and SI 85 stands, highest p.a.i. are about 330 and 230 $ft^3 \cdot acre^{-1} \cdot y^{-1}$, respectively.

Table 3—Equation coefficients to estimate average initial relative density, IRD in unthinned and TAD in thinned Douglas-fir stands

Equation	Symbol[a]	Partial F-value	Coefficient
2U	**Equation for unthinned (n = 969)**		
	Constant	4	-141.68
	SI	22	-.91462
	A	38	-.57443
	Ln(SI)	17	79.991
	A^{-1}	106	-1785.4
	$SI^{*}A^{-1}$	11	3.25457
	A^{-2}	17	3936.4
2T	**Equation for thinned (n = 194)**		
	Constant	106	-38.337
	IRD	141	.31188
	Ln(A)	77	10.5440
	SI	57	.15514

[a] See "Abbreviations and Definitions" in the appendix.

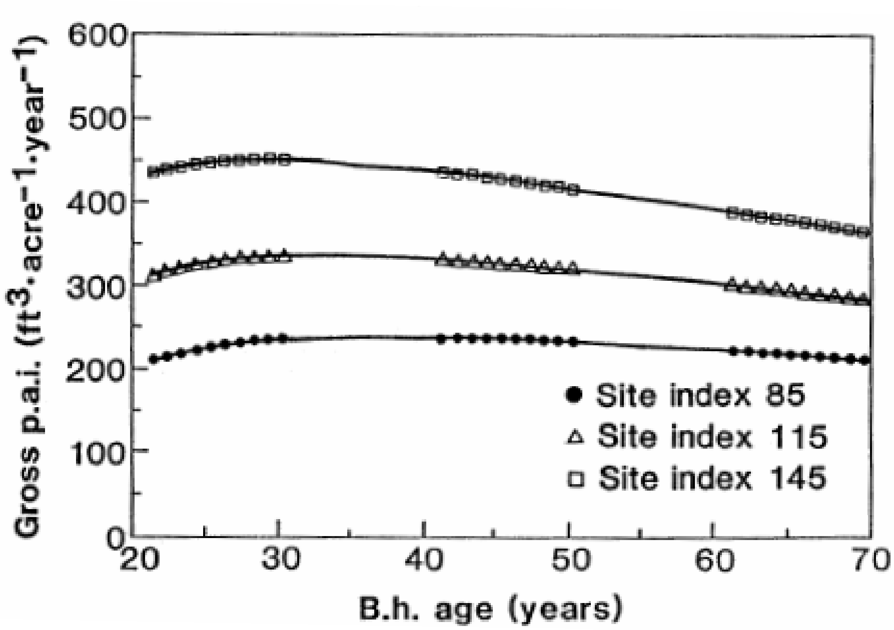

Figure 3—Predicted trends of gross annual volume increment (p.a.i.) of untreated Douglas-fir stands of average density on land of low, average, and high quality.

Comparison with regional averages—Estimates by SWOR of gross volume growth for untreated and average-density stands in southwestern Oregon consistently exceeded those of DFSIM for the same SI, b.h. age, and RD (fig. 4); the differences were greatest for young stands and for SI 85 at all ages. These differences in growth estimates seem to be related to differences in density levels in the original data. Relatively little of the regionwide data used for DFSIM had stands with initial RD exceeding 70. Consequently, DFSIM allows no extra growth above RD = 70, the assumed upper density limit in DFSIM. Higher density levels were found in our southwestern Oregon data (table 4). Thus, SWOR projections could be higher than DFSIM projections because higher levels of RD with attendant greater growth are projected. These differences in yield predictions for untreated stands in southwestern Oregon by the two models suggest a need to modify the upper density limit in DFSIM.

Effect of initial density—SWOR predicts additional gross volume growth with increased initial RD; for example, an 11-12 percent increase in p.a.i. is predicted when RD is 20 percent greater than average RD (fig. 5). Conversely, about 12 percent less-than-average p.a.i. is predicted for stands with 20 percent lower RD.

For average (fig. 6) and other site qualities, SWOR and DFSIM predict similar patterns of increased gross volume growth when RD is increased from 20 percent less through 20 percent more than average RD. The SWOR and DFSIM estimates are closest at RD levels below 70.

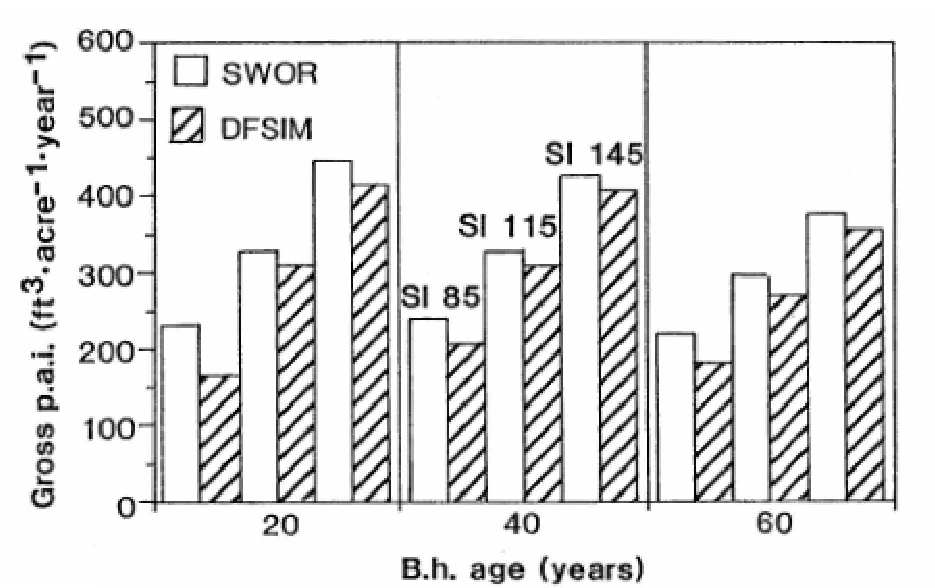

Figure 4—Comparison of predicted average annual gross volume increment (p.a.i.) in *10-year* periods, by age at breast height (b.h.) and site index (SI), for untreated, average-density Douglas-fir stands; subregional (SWOR) vs. regional (DFSIM) predictions.

Table 4—Relative density, RD, of average-density Douglas-fir stands used in SWOR and DFSIM projections, by site index and b.h. age [a]

SI	B.h. age	RD[b] Unthinned	RD[b] After thinning	RD[b] Ratio[c]	d/D[d]
	Years				
85	20	61	26	0.43	0.88
	40	78	38	.49	.88
	60	77	42	.55	.88
115	20	62	31	.50	.83
	40	77	43	.56	.83
	60	76	46	.61	.83
145	20	58	34	.59	.78
	40	71	45	.63	.78
	60	68	49	.72	.78

[a] SWOR = predictions of average p.a.i. (cubic foot volume) of Douglas-fir stands in southwestern Oregon and their response in p.a.i. to treatment.

DFS1M = predictions of p.a.i. from the regional Douglas-fir simulator of Curtis and others (1981, 1982).

[b] RD is the average RD of our sample stands for a specified b.h. age and site index.

[c] RD after thinning/RD unthinned.

[d] Average d.b.h. of cut trees/average stand d.b.h. before thinning.

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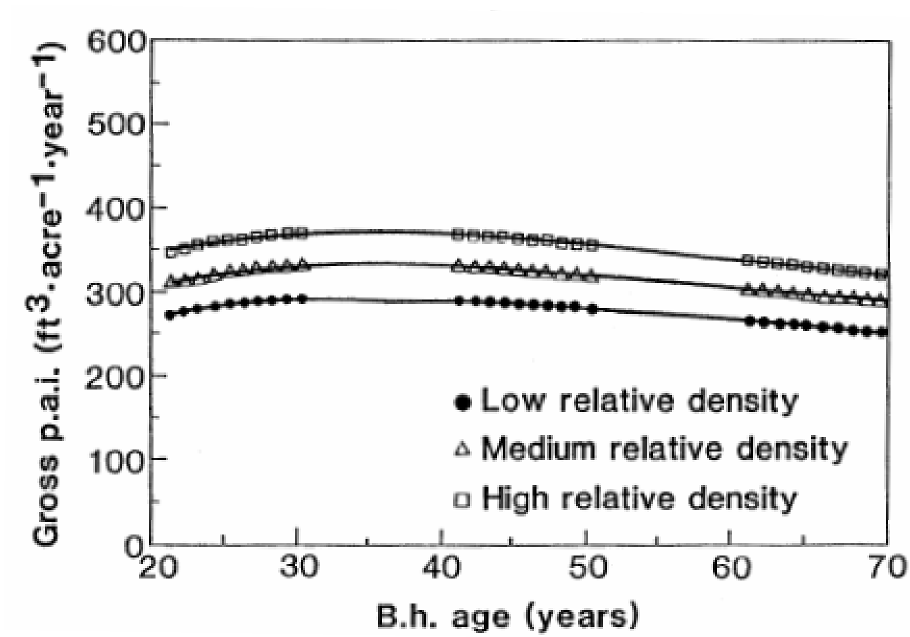

Figure 5—Predicted trends of gross annual volume increment (p.a.i.) of untreated Douglas-fir stands of low, average, and high density on site index (SI) 115 land.

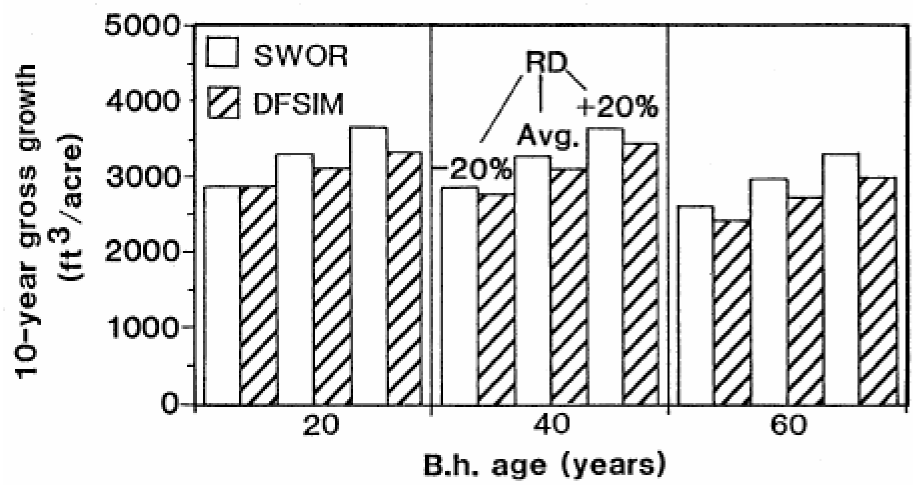

Figure 6—Comparison of predicted total 10-year gross volume growth of untreated, site index (SI) 115 Douglas-fir stands by relative density levels; subregional (SWOR) vs. regional (DFSIM) predictions.

Changes in Gross Growth After N Fertilization of Unthinned Stands

Before they were used for SWOR equation development, our growth data showed that N fertilizer improved growth (corrected a growth-limiting factor) at about 70 percent of trial locations in Douglas-fir stands.

The SWOR equation predicted substantial increases in gross volume growth after 200 lb N/acre is applied to average-density Douglas-fir stands on a wide range of stand ages, and site qualities. Estimated response was greater and lasted longer on poor than on good sites (fig. 7). For average-quality land (SI 115) with average-density stands, estimated cumulative gains in gross volume growth in a 10-year period after fertilization with 200 lb N/acre ranged from 844 cubic feet per acre in 20-year-old stands to 501 cubic feet in 60-year-old stands (table 5).

Doubling the dosage to 400 lb N/acre increased the estimated 1 O-year gain in gross growth of 20- and 60-year-old stands by 11 and 16 percent (to 937 and 581 cubic feet per acre), respectively. This indicated a lower response per pound of N at the higher dosage.

The low proportion of variation in response (33 percent) accounted for by the fertilizer-only equation suggested that other variables besides N, IRD, SI, A, and dT were related t—o response to fertilization in unthinned stands. Additional research is needed to identify and quantify these potential estimators.

Comparison with regional averages-SWOR-estimated gains in gross volume growth after fertilization of average-density stands with 200 lb N/acre generally exceeded regional averages predicted by DFSIM (fig. 8). DFSIM estimates of gain from 200 lb *N/acre* differ by both stand age and site quality (fig. 8). SWOR estimates of response to 200 lb N/acre, however, generally exceeded those of DFSIM for stands of same age, site, and RD. For 40- and 60-year-old stands on good sites (SI 145), SWOR estimated less response than did DFSIM.

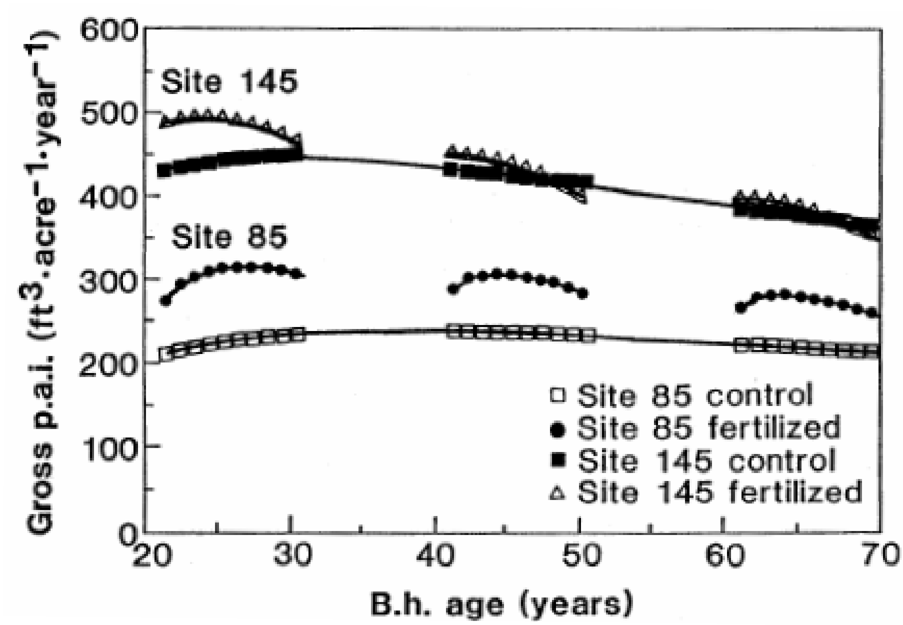

Figure 7—Predicted trends of gross annual volume growth (p.a.i.) after fertilization of average-density Douglas-fir stands with 200 lb *N/acre* on land of low and high quality.

Table 5 - Estimated 10-year gains in gross volume growth of unthinned Douglas-fir stands after 200 lb N/acre is applied to 51 115 stands of low, mean, and high initial density, by b.h. age

	Relative density[a]		
B.h. age	Low	Mean	High
Years	*- - - Cubic feet per acre - - -*		
20	945	844	762
40	669	573	502
60	592	501	432

[a] Mean relative density is the average RD of our sample stands for a specified b.h. age and site index. Low and high relative densities are, respectively, RD's that are 20 percent lower and higher than the average RD.

Figure 8—Comparison of pr2dicted total 1 a-year gains in gross volume growth, by age at breast height (b.h.) and site index (SI), after fertilization of average-density Douglas-fir stands with 200 Ib N/acre; subregional (SWOR) vs. regional (DF8IM) predictions.

Earlier RFNRP analyses showed that by year 6 after fertilization, responses did not significantly differ by site quality (P = 0.05); therefore, RFNRP reported an average 10-year gross gain of 400 cubic feet per acre for all site qualities (Peterson 1982). More recent analyses of RFNRP trials show, however, that cumulative gains in both absolute and relative growth (CVTS) increase with decreasing site quality (Miller and others 1986). Although the RFNRP analyses show that 20- to 60-year-old stands do not significantly differ in their response to N fertilization, our multiple regression analysis of data from some of the same trials combined with data from additional trials indicated that young Douglas-fir stands are most responsive to N fertilization (fig. 8).

Effect of initial stocking—SWOR predicts less volume gain (over untreated p.a.i.) when stands with higher RD are fertilized. With 20 percent greater-than-average stocking, for example, predicted response in 20-year-old SI 115 stands to 200 Ib N/acre is 10 percent lower than response in average-density stands (table 5). Conversely, fertilizer efficiency (volume gain per pound N) is apparently increased by below-average RD.

For the same SI, b.h. age, and RD levels, DFSIM predictions of percentage response to N are generally less affected by differences in initial RD than are SWOR predictions (fig. 9). Both models generally predict reduced gain in gross volume growth when unthinned stands with above-average densities are fertilized.

Predictions by SWOR and DFSIM of reduced fertilizer response in Douglas-fir stands with 20 percent more-than-average initial RD support earlier speculations. Strand and DeBell (1979) reason that volume gains from fertilizing Douglas-fir stands probably decline at above-normal stocking levels. They observed more rapid accumulation of basal area stocking in fertilized stands. They presumed this response increases competition and eventually reduces growth of individual trees, increases rate of mortality, and reduces volume gains from fertilization.

Figure 9—Comparison of predicted percentage of gains in gross volume growth in a 10-year period after fertilization of SI 115 Douglas-fir with 200 lb N/acre; subregional (SWOR) vs. regional (DF8IM) predictions for average initial relative density (IRD) ± 20 percent.

Changes in Gross Growth After Thinning

Thinning reduces stocking. For average-stocked stands in these trials, reduction in RD was greater in poor than in good site-quality stands; for example, at b.h. 20 years, 57, 50, and 41 percent of the IRD was cut on SI 85, 115, and 145, respectively. For a given site quality, relative reductions were greater in younger than in older stands (table 4). After-thinning density (TRD) also differed by site quality and age combinations, and these differences in TRD and percentage of cut affected subsequent trends in annual and total periodic volume growth.

For 4 or more years after thinning, estimated gross annual growth of thinned stands was consistently less than growth of untreated stands (fig. 10). Recovery of gross production was delayed more after early thinning in lower site-quality stands than in higher site quality stands (fig. 10). This slower recovery on poor site stands may be explained by the greater percentage cut and greater d/D ratio on poorer site-quality stands. Projections by SWOR of p.a.i. in the 10-year period after thinning of 20-year-old, SI 145 stands unexpectedly showed that gross p.a.i. of thinned stands exceeded gross p.a.i. of unthinned stands. Our examination of p.a.i. trends at individual trials on high-quality sites provided little evidence to support or reject these projections. We considered and rejected the option of constraining p.a.i. of thinned stands so that p.a.i. could not exceed that of unthinned stands. Without this constraint, the projected, cumulative 10-year reductions in gross growth on young, SI 145 stands are very small relative to growth reductions on other site qualities (fig. 11). This could also explain the apparent faster recovery of gross growth on good sites.

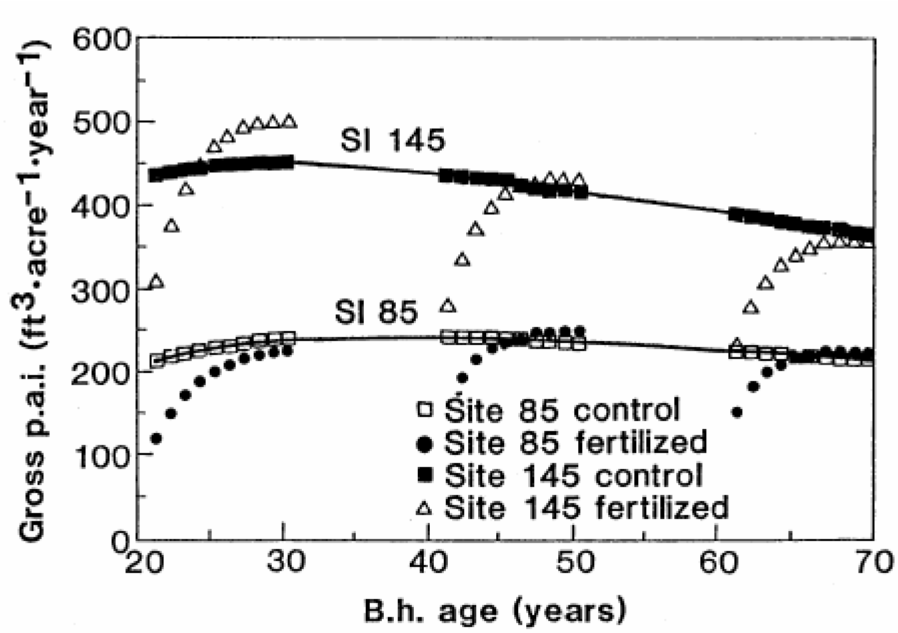

Figure 10—Predicted trends of gross annual volume increment (p.a.i.) after thinning average-density Douglas-fir stands on land of low and high quality.

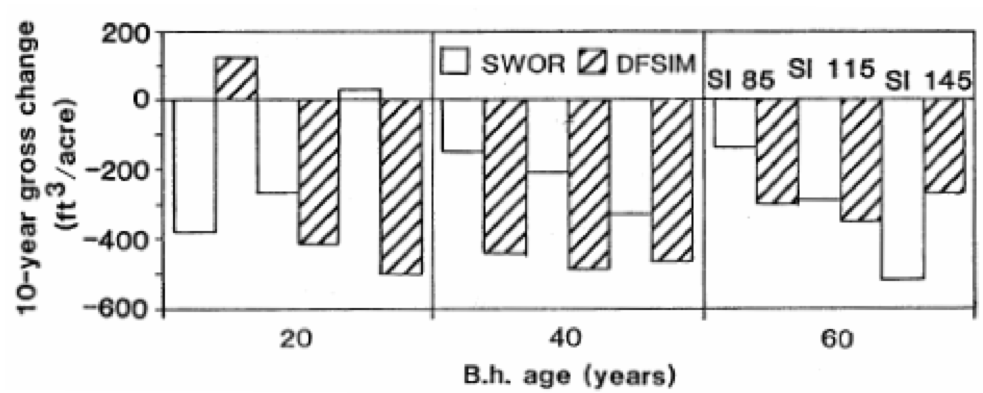

Figure 11—Comparison of predicted total, 10 - year change in gross volume growth, by age at breast height (b. h.) and SI, after thinning average-density Douglas-fir stands; subregional (SWOR) vs. regional (DFSIM) predictions.

Table 6—Estimated 10-year changes in gross volume growth of Douglas-fir stands after thinning 51115 stands of low, mean, and high initial density, d/D = 0.83 at all ages

	Relative density[a]						Cumulative change when IRD is:		
	Before cut (IRD)			After cut (TRD)					
B.h. age	Low	Mean	High	Low	Mean	High	Low	Mean	High
Years	- - - - - - - - - - - - - - - *RD* - - - - - - - - - - - - - - -						- - *Cubic feet/acre* -		
20	50	62	75	27	31	35	-154	-269	-330
40	62	77	92	38	43	48	-131	-208	-214
60	60	76	91	42	46	51	-185	-287	-323

[a] Mean relative density equals the average RD of the sample stands for a specified b.h. age and site index. Low and high relative densities are, respectively, RD's that are 20 percent lower and higher than the average RD.

Comparison with regional averages - When similar thinning intensities and d/D ratios are simulated in DFSIM, major differences appear between these regional estimates and our subregional estimates (SWOR), especially in 20-year-old stands (fig. 11). Although both estimators usually show reduced gross p.a.i. during the 10 years after thinning, SWOR and DFSIM estimates differ markedly for thinning at b.h. age 20 years in SI 85 vs. SI 145 stands. SWOR predicts faster recovery (less reduction in gross p.a.i.) after early thinning on good than on poor sites, but DFSIM predicts the opposite. Some of these differences in prediction, especially for young stands on poor sites, can be explained by differences in the way the DFSIM juvenile and main stand routines project stand development. Some of these disagreements may also be explained by small differences in thinning specifications (DFSIM vs. SWOR). Further comparisons with independent data sets are needed to validate these estimates.

Effect of initial density - Initial density affects both thinning intensity and residual density after thinning. Initial density may also affect the type of thinning, frequently expressed by the d/D ratio. Consequently, p.a.i. after thinning is likely to differ for stands that originally differed in prethinning (initial) density. The conventional concept is that the p.a.i. after thinning remains below precut levels until the site is reoccupied by the residual trees. Presumably, this delay will be least when (1) cutting intensity is low; (2) d/D ratio is low-because the average d.b.h. of cut trees is smaller than that of the original stand; and (3) residual density is close to that required to occupy the site.

In sample solutions of the p.a.i. equations, both IRD and TRD were varied by ±20 percent from the average for each site and age class (table 6). As shown in the following tabulation, the d/D ratio for these sample solutions differed only by site class, because the basic data did not support varying d/D by both site and age:

SI	d/D
85	0.88
115	.83
145	.78

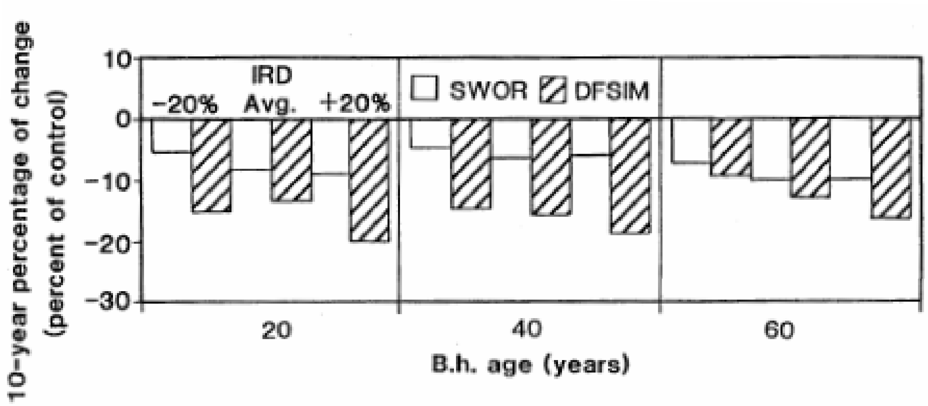

Figure 12—Comparison of predicted percentage of change from untreated stand growth in gross volume growth in a 10-year period after thinning S1 115 Douglas-fir stands; subregional (SWOR) vs. regional (DFSIM) predictions for average initial relative density (IRD) ± 20 percent.

These d/D ratios from our sample stands showed that a higher proportion of relatively smaller trees were cut on higher quality sites. This is another reason for the SWOR projection of faster recovery of p.a.i. after thinning on good sites and slower recovery on poor sites.

For the same IRD and TRD levels (average :t 20 percent), DFSIM consistently estimates larger percentage growth reductions (compared to unthinned) in the 10-year period after thinning than does SWOR (fig. 12). This lesser growth is on fewer trees per acre than in untreated stands; consequently, crop trees should attain merchantable size sooner.

Changes in Gross Growth Concurrent Thinning and Fertilization

Fertilization at time of thinning can offset predicted losses in gross growth after moderate to heavy reductions of growing stock by thinning (fig. 13). SWOR predicts a recovery of annual growth to the level of untreated stands by the second year after thinning and fertilization of average-site stands (51 115).

In the 10 years after fertilization, the estimated gain in gross growth from fertilizing unthinned stands usually is greater than gains from fertilizing thinned stands (table 7). Yet, the lesser volume of mortality in thinned than in unthinned stands ensures that a greater proportion of these smaller growth increases from fertilization of thinned stands will be recovered at harvest.

Comparison with regional averages - Both SWOR and DF51M generally predict more volume gain from fertilizing unthinned than from fertilizing thinned Douglas-fir stands (table 8). SWOR-estimated gains from applying 200 Ib N/acre to thinned Douglas-fir stands are generally less than DFSIM estimates (table 8).

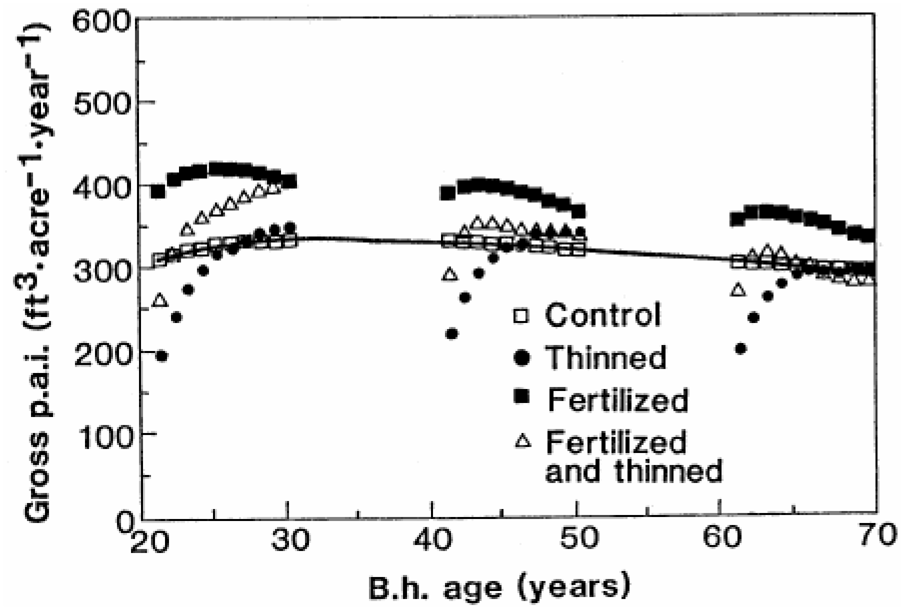

Figure 13—Predicted trends of aross annual volume increment (p.a.i.) after fertilizing thinned and unthmned Douglas-fir stands of average density and site quality.

Table 7-Estimated 10-year change in gross growth of Douglas-fir stands after 200 Ib N/acre is applied to average-density unthinned and thinned stands, by site quality and b.h. age

B.h. age	Gain from fertilization		
	Unthinned	Thinned	Difference (UT- T)
Year	- - - - - - - - - - - *Cubic feet/acre* - - - - - - - - - - - - -		
SI 85:			
20	801	653	148
40	625	356	271
60	564	218	346
SI 115:			
20	844	598	246
40	573	288	285
60	501	198	303
SI 145:			
20	455	304	151
40	105	174	-66
60	75	193	-118

Table 8—Comparison of 10-year change in gross volume growth after fertilization (200 lb N/acre) of average-stocked, thinned Douglas-fir, SWOR vs. DFSIM estimates, by b.h. age and site index

B.h. age	Site index	Source of estimate[a] SWOR	DFSIM
Years	*Feet*	*Cubic feet/acre*	
10-year fertilization gain in thinned stands[b]			
20	85	653	648
	115	598	492
	145	304	330
40	85	356	456
	115	288	369
	145	174	251
60	85	218	392
	115	198	308
	145	183	210
Additional gain from fertilization in unthinned vs. thinned			
20	85	149	2
	115	246	294
	145	151	23
40	85	271	87
	115	285	45
	145	-66	16
60	85	346	59
	115	303	34
	145	-118	11

[a] SWOR = predictions of average p.a.i. (cubic-foot volume) for Douglas-fir stands in southwestern Oregon and their response in p.a.i. to treatment.

DFSIM = predictions of p.a.i. from the regional Douglas-fir simulator of Curtis and others (1981, 1982).

[b] Derived from estimated response after fertilizing plus thinning less estimated response from thinning.

As mentioned previously, the two models differ markedly in their predictions of the effect of early thinning at b.h. age 20 across the range of site quality. SWOR predicts faster recovery of p.a.i. on good than on poor sites, and DFSIM predicts slower recovery (fig. 11). These differing trends of thinning response across site index affect predictions of 10-year response to the combined thinning and fertilization treatment. Thus, SWOR predicts progressively greater gains for SI 85 through 145 (fig. 14). In contrast, DFSIM projects a cumulative 10-year gain of nearly 800 ft3/acre on SI 85 and nearly a 200-ft3/acre loss on SI145 (fig. 14).

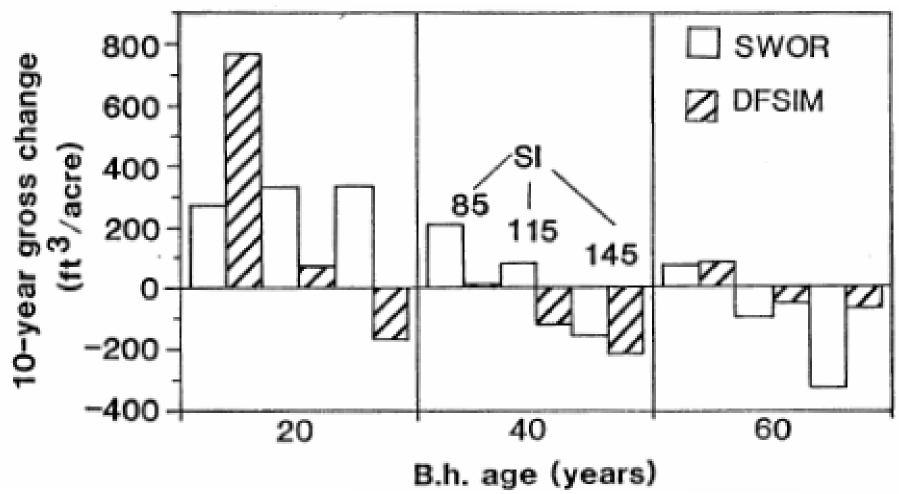

Figure 14—Comparison of predicted, cumulative 10-year change in gross volume Qrowth of untreated growth, by age at breast height (b.h.) and site Index (SI), after thinning and fertilizing (200 Ib N/acre) average-density Douglas-fir stands; subregional (SWOR) vs. regional (DF8IM) predictions.

Effect of initial density-As mentioned previously, above-average initial density usually results in greater reduction in RD, but also in a larger residual RD, than does thinning of understocked stands. Subsequent growth of thinned stands, especially those with high density initially, is projected below that of untreated stands for several years after thinning. According to SWOR estimates, application of 200 Ib N/acre does not reverse this effect of initial RD; estimated growth of thinned and fertilized stands is also greater at lower IRD levels (fig. 15). For IRD levels 20 percent below average levels (table 6), gross 1 O-year growth of thinned and fertilized (200 Ib N/acre) stands exceeds control growth by about 4-17 percent on SI115 (fig. 15). DFSIM estimates of gain from the combined treatment, when compared to controls, are generally lower than SWOR estimates (fig. 15). Trends across the TRD levels, average TRD ± 20 percent, are similar for DFSIM and SWOR.

Net/Gross Volume Growth

The ratio of net/gross volume growth shows the proportion of gross growth retained in the live stand. In this section, we provide average net/gross growth ratios for untreated and treated stands sampled by the southwestern Oregon trials and compare them with DFSIM ratios for the same SI, b.h. age, and RD. We will use these ratios to derive average gains in net volume growth.

Untreated stands-Average net/gross growth ratios for untreated stands decline with stand age; as untreated stands mature, volume lost to mortality takes an increasingly larger portion of gross growth (table 9). Within each age class, mortality claims a slightly greater portion of gross growth on better quality sites because stand development is faster.

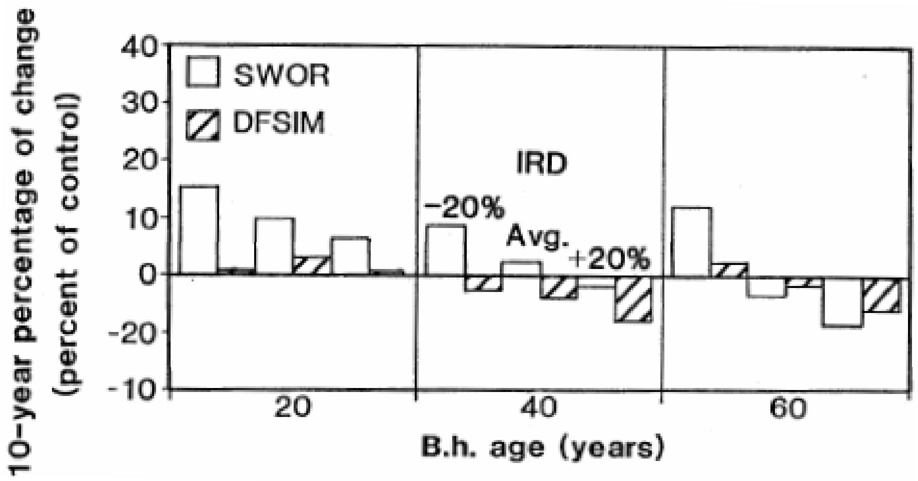

Figure 15—Comparison of predicted percentage of change in gross volume growth of untreated stands in a 10-year period after thinning and fertilizing (200 lb N/acre) SI 115 Douglas-fir stands; subregional (SWOA) vs. regional (DFSIM) predictions for average relative density (AD) ± 20 percent.

Table 9—Comparison of average ratios of net/gross volume growth of average-density Douglas-fir stands in the 10 years after specified stand age, by site quality and treatment; SWOR vs. DFSIM estimates[a]

		Untreated		Fertilized		Thinned		Fertilized and thinned	
B.h. age	SI	SWOR	DFSIM	SWOR	DFSIM	SWOR	DFSIM	SWOR	DFSIM
Years	*Feet*					*Ratio*			
20	85	0.95	—[b]	0.93	0.95	1.00	0.99	1.00	0.99
	115	.93	0.46	.90	.77	1.00	.98	.98	.98
	145	.91	.86	.88	.85	1.00	.97	.97	.97
40	85	.89	.53	.87	.54	.93	.90	.98	.90
	115	.87	.54	.85	.55	.93	.90	.97	.90
	145	.85	.62	.83	.62	.93	.89	.96	.90
60	85	.83	.45	.82	.46	.86	.85	.97	.85
	115	.81	.46	.80	.46	.86	.84	.96	.84
	145	.79	.62	.77	.62	.85	.82	.94	.82

[a] SWOA = predictions of average p.a.i. (cubic-foot volume) for Douglas-fir stands in southwestern Oregon and their response in p.a.i. to treatment.

DFSIM = predictions of p.a.i. from the regional Douglas-fir simulator of Curtis and others (1981, 1982).

[b] DFSIM provides no estimate of mortality in stands having Dg less than 5.5 inches.

Average net/gross ratios measured in southwestern Oregon trials are usually considerably higher than those of DFSIM (table 9). This suggests DFSIM may overestimate mortality in southwestern Oregon stands because a maximum relative density level of RD = 70 is used in that model. DFSIM assumes that increases above this density level are offset by mortality. This assumption is not supported by the southwestern Oregon trials, because average RD of unthinned stands exceeded RD 70 after about 40 years b.h. age (table 4).

Fertilized stands - Average net/gross growth ratios for fertilized, unthinned stands in southwestern Oregon are slightly lower than those for untreated stands (table 9). This suggests fertilization with 200 lb N/acre may increase the proportion of gross growth offset by mortality losses. Fertilization may increase competition. This conclusion is reasonable when fertilization is regarded as a temporary increase in site quality. Douglas-fir growth and yield studies (for example, McArdle and others 1961) show fewer trees are present on better site quality land at a given stand age.

DFSIM projections (Curtis and others 1981, 1982) for the same SI and b.h. age values show no consistent pattern of net/gross ratios for untreated vs. fertilized stands (table 9). Trials installed by the British Columbia Ministry of Forests in British Columbia and by the RFNRP in Washington and Oregon show that N fertilization of coast Douglas-fir stands with urea increases tree growth and the rate of mortality losses in smaller-than-average trees (Miller and others 1986). Fertilization evidently accelerates the normal time-trend implied by Reineke (1933) of decreasing stem numbers (stand density) with increasing average stand diameter.

Thinned stands - As expected, average net/gross ratios for thinned stands are consistently higher than those for unthinned stands (table 9). DFSIM also projects lower mortality losses in thinned stands relative to unthinned. Timely thinning is therefore a way to harvest volume that could be lost to unsalvaged mortality.

Thinned and fertilized stands-SWOR projections suggest that fertilizing further reduces the low mortality losses in thinned stands of b.h. age 40 and older (table 9). This projection appears biologically plausible: thinning reduces stress for light and moisture, and fertilization further reduces the potential stress for nutrients. In contrast, DFSIM estimates of mortality losses are the same in thinned stands irrespective of fertilization.

Net Growth

Net growth (increase in live stand volume) can be estimated by multiplying gross growth by an average net/gross ratio. SWOR ratios (table 9) are averages calculated for a given site and age class; the ratios represent the average stocking levels of the basic data. For nonaverage levels, the net growth estimates for specific SI and b.h. ages are not as precise as the gross growth estimates.

Net growth of Douglas-fir is shown for average-density SI 85, SI 115, and SI 145 stands in tables 10, 11, and 12, respectively. For these three site indices and b.h. ages of 20, 40, 60 years, fertilization increased the estimated 10-year gains in net growth in unthinned stands by as much as 690 cubic feet (table 10). Estimated 10-year net growth after thinning was from 430 cubic feet more to 270 cubic feet less than in unthinned stands. Positive increases in net volume growth are projected after thinning good site stands at 20 or 40 b.h. age (table 12).

Table 10—Estimated average net p.a.i. of Douglas-fir stands in the 10 years after treatment at specified b.h. age on average-density, SI 85 land, per acre basis[a]

B.h. age	Treatment[b]	Gross p.a.i.	Net/gross	Net p.a.i.	Treated p.a.i. minus untreated p.a.i.	
years		*ft³*	*ratio*	- - - - *ft³* - - - -		*percent*
20	0	229	0.95	218	—	—
	200 N	309	.93	287	69	32
	T	191	1.00	191	-27	-12
	T + 200 N	257	1.00	257	38	18
40	0	240	.89	214	—	—
	200 N	302	.87	263	49	23
	T	225	.93	209	-5	-2
	T + 200 N	261	.98	256	42	20
60	0	222	.83	184	—	—
	200 N	278	.82	228	44	24
	T	208	.86	179	-5	-3
	T + 200 N	230	.97	223	39	21

[a] Average net p.a.i. calculated by multiplying SWOR-predicted gross p.a.i. by an average ratio of net/gross volume increment for specified age and site index (from table 9).

[b] 200 N = 200 lb N/acre; T = thinning.

Table 11—Estimated net p.a.i. of Douglas-fir stands in a 10-year period after treatment at specified b.h. age on average-density, SI 115 land, per acre basis[a]

B.h. age	Treatment[b]	Gross p.a.i.	Net/gross	Net p.a.i.	Treated p.a.i. minus untreated p.a.i.	
years		*ft³*	*ratio*	- - - - *ft³* - - - -		*percent*
20	0	328	0.93	305	—	—
	200 N	412	.90	371	66	22
	T	300	1.00	300	-5	-2
	T + 200 N	361	.98	354	49	16
40	0	327	.87	284	—	—
	200 N	384	.85	326	42	15
	T	306	.93	285	1	0
	T + 200 N	335	.97	325	41	14
60	0	297	.81	241	—	—
	200 N	347	.80	278	37	15
	T	268	.86	230	-11	-5
	T + 200 N	288	.96	276	35	15

[a] Average net p.a.i. calculated by multiplying SWOR-predicted gross p.a.i. by an average ratio of net/gross volume increment for specified age and site index (from table 9).

[b] 200 N = 200 lb N/acre; T = thinning.

Table 12—Estimated net p.a.i. of Douglas-fir stands in the 10 years after treatment at specified b.h. age on average-density, SI 145 land, per acre basis[a]

B.h. age	Treatment[b]	Gross p.a.i.	Net/gross	Net p.a.i.	Treated p.a.i. minus untreated p.a.i.	
years		ft^3	*ratio*	- - - - ft^3 - - - -		*percent*
20	0	447	0.91	407	—	—
	200 N	493	.88	434	27	7
	T	450	1.00	450	43	11
	T + 200 N	477	.97	463	56	14
40	0	427	.85	363	—	—
	200 N	437	.83	363	0	0
	T	394	.93	366	3	1
	T + 200 N	411	.96	395	32	9
60	0	379	.79	299	—	—
	200 N	387	.77	298	-1	0
	T	328	.85	279	-20	- 7
	T + 200 N	347	.94	326	27	9

[a] Average net p.a.i. calculated by multiplying SWOR-predicted gross p.a.i. by an average ratio of net/gross volume increment for specified age and site index (from table 9).

[b] 200 N = 200 lb N/acre; T = thinning.

Projected net growth for thinned and fertilized stands exceeded that of thinned-only or untreated stands. Fertilization increased net growth of thinned stands by 130 to 650 cubic feet per acre during the 10 years after fertilization (tables 10-12). In 60-year-old stands, these gains in net growth from fertilizing thinned stands often exceeded net gains from fertilizing unthinned stands (tables 10-12).

Short-term net growth is strongly influenced by density and stand structure through their effects on mortality. Net and gross growth are similar in thinned stands because thinning reduces mortality losses (table 9). Consequently, net growth of thinned and unthinned stands is more similar than is gross growth, and this net growth in thinned stands is concentrated on fewer trees. Fertilization of thinned stands is particularly attractive for increasing merchantable yields on nutrient-deficient sites because a higher proportion of the increased growth from fertilization occurs on crop trees.

Suggestions for Land Managers

Before we did this research, forest managers in southwestern Oregon based their projections or estimates of Douglas-fir growth on either broad regional averages (Bruce and others 1977; Curtis and others 1981, 1982; McArdle and others 1961; Peterson 1982) or on unpublished and published results from individual local trials (Harrington and Miller 1979, Miller and Wert 1979, Miller and Williamson 1974).

SWOR provides a synthesis of 114 field trials with 5 or more years of observation by 1980. But these trials sample an area beyond what is commonly regarded as "southwest Oregon" because they are located from the Pacific Coast to the crest of the Cascade Range and from Salem, Oregon, into northern California. We did this to ensure a wide sample of site conditions and a large sample for our statistical analyses.

Reliability of Estimates

The SWOR model is appropriate for predicting growth of untreated and treated stands of Douglas-fir (80 percent or more Douglas-fir by basal area) but not for the hemlock or mixed conifers also found in the area. Our data base for non-Douglas-fir stands was too small to produce separate estimating equations for these stand types. We recommend not using the SWOR estimating equations for hemlock or mixed-species stands containing less than 80 percent Douglas-fir because the estimated growth of untreated stands and response to treatment will be biased to an unknown degree. The standard error of both gross volume p.a.i. and response to 200 Ib N/acre is 20-25 percent. We therefore can be confident of the average estimates but not of the exact value of individual predictions, especially those near the limits of individual variables we sampled in forests of southwestern Oregon. The precision of estimates from these p.a.i. and response equations is as good or better than other predictors of growth of Douglas-fir stands.

Like all models, SWOR is an abstraction of what happens in the real world to both untreated and treated Douglas-fir stands growing in southwestern Oregon; thus, some uncertainty exists about the accuracy of this and other models. We are uncertain, for example, if SWOR-predicted growth or response are equally applicable throughout southwestern Oregon. This question will be investigated in future analyses.

We checked SWOR estimates in two ways: (1) We compared SWOR estimates of gross growth with measured growth at each plot in the data base; no bias was detected. (2) We compared SWOR estimates with other models based on regionwide data. Major differences sometimes arose between two estimates, but we can only speculate which model is closer to reality. Because the SWOR model is based on data unique to southwestern Oregon, we assume that estimates from this model are more accurate for this area than are those from the regional models, DFSIM and RFNRP. We intend to compare SWOR estimates of growth with growth measured in stands other than those used in this analysis. If growth is accurately measured at enough new locations, this validation should indicate the general accuracy and bias, if any, of SWOR estimates.

Using the Estimates

You can use volume growth estimates provided in this publication for sample SI, b.h. age, and RD values, or you can generate site-specific estimates by using the equations (table 2) that produced these sample estimates-in several useful ways.

To estimate growth of individual stands - By knowing or assuming stand descriptors for an individual stand, you can estimate net or gross volume growth (p.a.i. in CVTS per acre) of untreated Douglas-fir stands or response in treated stands (fertilized or thinned, or both). You need only measure or estimate stand descriptors (b.h. age, SI, and RD [basal area and stems per acre]) and see that the descriptors entering the p.a.i. equations are within the limits of the SWOR data base. The model will not represent stands where the volume of ingrowth trees exceeds 10 percent of the p.a.i. because we deleted such stands from our data base. The equations are suited to the range of data in the set they were derived from; extrapolation is risky.

The equations are solved on an annual basis, and the resulting p.a.i.'s (or responses) are summed to estimate up to a 20-year growth (or a 10-year response). We recommend you not exceed these 20- or 10-year periods. Note that for untreated stands, RD must be updated annually for the correct solution by solving the equation for IRD (equation 2U) and setting RD in the untreated p.a.i. equation (equation 1C) to this value.

To rank stands for treatment - Funds available for fertilization or thinning are seldom sufficient to treat all available acres. Estimating gross or, preferably, net p.a.i. of candidate stands for 10 years after treatment is one way to rank stands for investment. In the absence of an economic analysis, treating those stands with the largest estimated gains in cubic volume is reasonable. This procedure favors fertilizing stands of (1) poor and average site quality before good site quality and (2) young before old stands. If you place premiums on large-diameter stems, then fertilization of good sites, older stands, and thinned stands will be more attractive.

SWOR also indicates greater gains in gross p.a.i. when 200 lb N/acre is applied to unthinned stands than to thinned (table 7). Yet this gain in unthinned stands is distributed on many more stems (so the individual crop tree gain is generally less in unthinned stands), and the lower ratios of net/gross p.a.i. show that a lower proportion of these gains in unthinned stands will be available for harvest.

You can use SWOR-estimated volume response as biological input to conventional break-even analyses (Miller and Fight 1979) or present net worth analyses (Bare 1982, Regional Forest Nutrition Research Project 1977). For precise economic analyses, information about numbers of trees by diameter classes is necessary, and SWOR does not provide this. Although DFSIM also cannot provide stand tables, it can provide estimates of tree numbers, average stand diameter (for all trees), and numbers of trees and stem volumes per acre to several standards of merchantability. When DFSIM and SWOR provide similar estimates of gross growth for 10 years after treatment, you can use stand data from DFSIM in a detailed economic analysis of gains from treatment. When the DFSIM and SWOR estimates are considerably different, DFSIM should not be used to estimate gains from treatment in southwestern Oregon.

To check other estimates of growth - Published growth simulators like DFSIM or DFIT (Bruce and others 1977) will estimate future stand basal area, Dg, stem numbers, and cubic volume gains. Some managers have proprietary estimates of volume growth that can be compared with those provided by SWOR to check for a major discrepancy. Such comparisons may reduce uncertainty but do not show that one estimate is more reliable than another.

Outlook for Forest Fertilization in Southwestern Oregon

These estimates of Douglas-fir stand response to nitrogen fertilization at 111 locations in southwestern Oregon and 3 in northern California indicated cubic volume gains comparable to those of broad regional averages for the same site and age combinations. Volume growth on fertilized plots exceeded that on unfertilized plots at about 70 percent of the 114 locations in Douglas-fir stands but not at any of the 8 hemlock stands we examined.

Even with equal volume gains from fertilization, the economic benefits to land managers will differ depending on several factors including costs of fertilization, time required to carry the investment (years between fertilization and harvest), and net stumpage value of the increased volume from fertilization. More detailed considerations of the economic merits of fertilization are beyond the scope of our paper; however, our data support the conclusion that fertilization can be an effective way to increase wood production in Douglas-fir forests in this area.

Outlook for Thinning in Southwestern Oregon

The results of this study reflect the type of thinning done nearly two decades ago. In young, very dense stands, as much as 80 percent of the starting basal area was felled so stand density could be reduced to about 300 stems/acre. Subsequent volume growth in these stands and in older, commercially thinned stands was less than in nearby, untreated stands for at least 3 years on good quality sites (in young stands) and for more than 10 years in young, poor sites or in older stands (fig. 10).

These temporary reductions in stand growth after moderate and heavy thinning of average-density stands must be weighed against the potential benefits of concentrating site productivity into fewer trees of desired species and quality. Lesser mortality in thinned stands means that net production is a much greater percentage of gross production (table 10).

Decisions about timing of precommercial thinning and about residual tree spacing are important. Reukema (1975) and Reukema and Bruce (1977) provide useful guidelines and discussion. They recommend that precommercial thinning be done when leave trees are 10 to 15 feet tall and 10 to 15 years old (total age, not b.h. age). Average spacing of leave trees depends on the desired tree size at the first comercial entry; the larger the required size at that time, the fewer trees that should be left.

Our field observations and recent discussions with foresters 10 to 15 years after the precommercial thinning in many of these trials indicated that as few as 300 leave trees per acre was excessive for current market conditions. Many crop trees were no longer free to grow, and prospects for a revenue-returning thinning were poor considering current markets for small logs and the high logging costs on steep terrain. Excess stocking after these precommercial thinnings resulted because (1) foresters were understandably concerned, yet locally inexperienced with the potential loss of leave trees from wind throw or snow breakage; (2) foresters were overly optimistic about the development of equipment and markets that would permit early commercial thinnings in their local area; and (3) the original clumpy distribution of these naturally regenerated stands was reduced but still present in many precommercially thinned stands-two or more neighboring dominant trees at b.h. age 5 to 15 years frequently became neighboring codominant trees 10 years later. Excessive stocking causes a dilemma: the forester must either accept reduced growth of crop trees until a profitable commercial thinning can be made or invest additional funds in a second precommercial thinning or in a submarginal commercial thinning.

Despite this review of past thinning experience, we recommend stocking control as a useful silvicultural practice for southwestern Oregon. With the local experience and higher proportion of more uniformly spaced plantations available for precommercial thinning, prescriptions can be applied more confidently now than 20 years ago.

The combination of thinning and fertilizing appears especially promising for increasing per acre growth and crop tree growth in a large proportion of Douglas-fir stands. In western Oregon, Washington, and British Columbia, about 70 percent of the fertilization trials in thinned and unthinned stands responded to 200 lb N/acre (Miller and others 1986). We found a similar percentage in fertilizer trials in southwestern Oregon. The SWOR-estimated gains from fertilization indicate the magnitude of these responses and provide a basis for selecting the most favorable site, age, and RD combinations. These potential benefits must be balanced against the increased costs of a combined treatment.

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Metric Equivalents

1 inch = 2.540 centimeters

1 foot = 0.3048 meter

1 square foot = 0.09290 square meter

1 cubic foot = 0.02832 cubic meter

1 square foot per acre = 0.2296 square meter per hectare

1 cubic foot per acre = 0.06997 cubic meter per hectare

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Appendix

Tables

Table 13—Number of growth periods and plots in pure and mixed stands, by treatment and percentage of Douglas-fir

Treatment	Initial basal area in Douglas-fir (percent)					
	20 - 79[a]	80[b]	90[b]	100[b]	All	All
	Number					*Percent*
Growth periods:						
Control	91	108	275	140	614	24
Fertilized	158	161	532	345	1,196	47
Thinned	32	22	79	181	314	12
F+T	29	37	80	295	441	17
All—						
Number	310	328	966	961	2,565	NA
Percent	12	13	38	37	NA	100
Total	310[a]	2,255[b]				
Plots:						
All—						
Number	80	84	249	246	659	NA
Percent	12	13	38	37	NA	100
Total	80[a]	579[b]				

Table 14—Growth periods in Douglas-fir stands by treatment and age class

		Site index class										
Age		<100		100-115		115-130		>130		All		Age class
class	TMT[a]	0	F	0	F	0	F	0	F	0	F	total
<20	0	9	15	15	18	20	33	28	38	72	104	
	T	19	22	25	41	20	30	21	22	85	115	376
20-30	0	24	19	30	50	44	76	43	109	141	254	
	T	43	46	19	24	23	36	12	28	97	134	626
30-40	0	21	52	19	74	29	73	38	62	107	261	
	T	2	10	12	12	11	22	24	38	49	82	499
40-50	0	38	93	29	47	32	75	10	21	109	236	
	T	1	2	3	7	11	19	11	24	26	52	423
50-60	0	15	33	19	16	4	33	9	13	47	95	
	T	5	8	4	3	1	2	0	0	10	13	165
60	0	19	19	13	27	10	27	5	15	47	88	
	T	6	10	9	6	0	0	0	0	15	16	166
All	0	126	231	125	232	139	317	133	258	523	1038	
	T	76	98	72	93	66	109	68	112	282	412	2255
Totals		531		522		631		571		2255		

[a] TMT = treatment; 0 = unthinned or unfertilized; T = thinned; F = fertilized.

Table 15—Variables used in SWOR equations

Treatment variable[a]	0	F	T	T+F
P.a.i. and response equations				
A	x		x	x
A^{-1}			x	x
A^{-2}	x			x
SI	x	x	x	x
SI^{-2}		x		
Ln (SI)				x
dT^{-1}		x		
dT^{2}		x		
$(dT+2)^{-1}$			x	x
$(dT+2)^{-2}$				x
Ln (N+1)		x		x
Ln (RD)	x			
IRD		x		
Ln (IRD)		x		
TRD			x	
Ln (TRD)			x	
d/D				x
$SI * A^{-1}$	x	x	x	
$(dT + 2) * SI^{-2}$			x	
$Ln (SI) * dT^{-1}$		x		
$SI * dT * A^{-1}$				x
$IRD * TRD^{-1} * (d/D)^{-1}$			x	x
Relative density equations				
A	x			
A^{-1}	x			
A^{-2}	x			
Ln (A)			x	
SI	x		x	
Ln (SI)	x			
$SI * A^{-1}$	x			
IRD			x	

[a] See "Abbreviations and Definitions" in the appendix.

Abbreviations and Definitions

A - Stand age, breast height (4.5 feet above ground) at midpoint of growth period (beginning age + 1/2 year).

CVTS -Cubic-foot volume of total stem including stump and tip.

d/D -Quadratic mean diameter of cut trees divided by quadratic mean stand diameter before thinning.

Dg -Diameter at breast height of tree of average basal area.

dT - Time (years) since treatment.

Gross p.a.i. - Actual growth per acre of all trees 1.6 inches d.b.h. and larger included at start of period and not reduced by mortality.

IRD -Relative density immediately before treatment; IRD is constant for subsequent growth periods. (See RD for method of computing.)

Ln – Natural logarithm (to base e).

N - Pounds of nitrogen applied per acre divided by 10.

Net p.a.i. - Net periodic annual increment of all trees 1.6 inches d.b.h. and larger during a specified period after reduction for mortality losses.

P.a.i.- Periodic annual increment in cubic feet per acre during a specified period. (See also gross p.a.i. and net p.a.i.)

RD - Relative density of untreated stands at the beginning of a growth period. Computed as stand basal area divided by square root of quadratic mean stand diameter of all stems 1.6 inches and larger.

SI -Site index (base age at 50 years b.h.).

TAD - Relative density immediately after thinning; TRD is constant for subsequent growth periods. (See RD for method of computation.)

dV - Periodic annual increment in cubic feet per acre during a specified growth period. (See also gross p.a.i. and net p.a.i.) .

Y_f - Annual response in gross volume growth in fertilized but unthinned stands.

Y_t - Annual response in gross volume growth in thinned but unfertilized stands.

Y_{ft} -Annual response in gross volume growth in stands concurrently thinned and fertilized.

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From data for 114 thinning and fertilizing trials in forests of southwestern Oregon and northern California with 5 or more years of observation, we produced equations to estimate gross cubic volume growth of 10 to 70-year-old Douglas-fir stands. These equations use stand descriptors (breast-height age, site index, and relative density) and treatment descriptors to estimate annual gross volume growth during a 10-year period for untreated and treated (fertilized or thinned, or both) stands.

These predictions (SWOR) were compared with other growth predictions including DFSIM, a simulation model based on a broader, regionwide data base. Our predictions consistently showed greater gross and net growth of untreated Douglas-fir in this subregion than does DFSIM and generally showed greater volume gains from nitrogen fertilization of unthinned stands, especially on poor quality sites and in young stands. SWOR forecasts reduced gross volume growth during the 10-year period after thinning and predicts faster recovery after early thinning on good sites than on poor. Our data indicated that nitrogen fertilization could increase wood production in about 70 percent of unthinned and thinned Douglas-fir forests in this subregion. Gains in gross growth in a 10-year period after fertilization of 20-year-old site 85 stands with 200 lb of nitrogen per acre were estimated as 800 and 650 cubic feet per acre, respectively, for unthinned and thinned stands.

Keywords: *Pseudotsuga menziesii,* forest fertilization, thinning, silviculture, stand density, growth models.

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