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Regional Variation in Growth Response of Coastal Douglas-Fir to Nitrogen Fertilizer in the Pacific Northwest

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ABSTRACT. Hypothesis testing for differences in growth responses among physiographic strata, thinning levels, and fertilizer dosage levels resulted in a set of empirical models for predicting volume increment response of even aged coastal Douglas fir to nitrogen fertilizer. Absolute and percent responses are estimated for stands both thinned and unthinned, as a function of dosage levels and physiographic provinces. Although not "highly" significant, the physiographic factor was retained in the models for purposes of refinement. FOR. SCI. 36(3):625–640.

ADDITIONAL KEY WORDS. Research, physiographic strata, thinning, fertilizer response, predictive models.

Nitrogenous fertilizer has been applied to second growth Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) on an operational basis in the Pacific Northwest since the early 1970s (Bengston 1979). A major source of information for this aspect of intensive management has been the Regional Forest Nutrition Research Project (RFNRP). The RFNRP, an applied research program administered by the University of Washington, was initiated in 1969 as a cooperative effort to provide information on the effects of fertilization in Douglas fir and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) stands in the Pacific Northwest. Since that time, the significant growth response to both 224 and 448 kilogrards of nitrogen per hectare on a regional basis has been thoroughly documented (e.g., Turnbull and Peterson 1976, RFNRP 1980, RFNRP 1982, Peterson et al. 1984, Miller et al. 1986). Although most of these reports contain a brief background of the project's origin and objectives, a complete documentation of research design, objectives, stand selection criteria, and analytical methods was recently published (Hazard and Peterson 1984) to provide a better understanding of RFNRP goals as scientific hypotheses, along with the analytical models utilized to achieve those goals.

The primary goal of the RFNRP was a comprehensive analysis of stand level growth response to urea nitrogen fertilizer for coast Douglas fir in western Washington and western Oregon. The analysis would include both thinned and unthinned

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stands, with subsequent refinement in the event that these responses differed among physiographic strata (subpopulations referred to as provinces) of the region. This manuscript presents and interprets the results of such a comprehensive analysis for Douglas fir. Results include model budding, point estimates of growth response, and prediction equations.

OBJECTIVES

In the past, RFNRP response estimates were commonly derived from a regression approach that utilized PAI (periodic annual increment) from each 0.04 ha plot as an independent observation. Although this method continues to be very useful in assessing regional growth and response to fertilizer application, some situations have arisen where ids mol=e advantageous to have growth response of the entire field installation, rather than the plot, as the experimental unit. Such stand responses have been used to "pair" with soils (Peterson et al. 1984) or foliar information (Turner et al. 1977), both of which are often expressed as averages. for an experimental site (installation in this case).

The primary objective of this study was to construct an empirical model (or set of models) for predicting volume growth stand response as a function of classification variables (province, thinning, and fertilizer dosage) and continuous variables (age, site index, basal area, and initial volume differences). In order to accomplish this goal, we have combined "plot" information at each field installation to more closely approximate the "stand" level of interest. That is, we consider growth response estimates based on uniform stand conditions from an area of 1 to 3 ha (field installation size), rather than 0.04 ha (plot size), to be more applicable for the practitioner's use. Furthermore, we are using the difference in PAls rather than PAI itself to formulate a more direct "in place estimate" of the growth response.

Values used for the continuous variables represented initial stand conditions at the time of fertilizer application. To build the model we needed to answer the following questions:

1. Do differences in fertilizer growth response exist among provinces?
2. Do differences in fertilizer growth response exist between thinned and unthinned stands?
3. Do differences in fertilizer growth response vary according to levels of fertilizer application?
4. Do interactions exist among these factors (province, thinning, fertilizer), or between these factors and the initial stand conditions?

Based on answers to the above questions, one or more predictive equations were developed.

METHODS

A brief description of the experimental design and analytical methods is presented for the reader. For a more detailed documentation of the RFNRP, see Hazard and Peterson (1984).

The target populations of the study were uniform even aged second growth Douglas fir stands of natural origin, which were fully stocked (80% to 110% "normal") according to USDA Bulletin 201 McArdle et al. 1930). The candidate stands were stratified into six subpopulations called "provinces," distinct Douglas-fir strata' in western Washington and Oregon (Figure 1) that are similar to the physiographic areas delineated by Franklin and Dyrness (1973). They were arrayed into breast height age classes of 10 to 50 years, and site index classes 1 through 4 (King 1966), within each province. Stands in which to locate the field installations were then randomly selected from this matrix.

In the original sample of Douglas fir, a major objective was to select relatively pure stands (at least 80% by basal area stocking). Post establishment computations of tallied information showed that some installations were placed in stands which were less than 80% Douglas fir (the other species component tended to be western hemlock). Since this represented an error in selecting target stands "by eye," we decided to base the final model on all data, with some indication of how the final response estimate might change if the predictive models are based solely on installations which are greater than 80% Douglas fir. Thus, the final estimates are still influenced by relatively pure stands of Douglas-fir, and should not be construed as being equally valid for stands in which Douglas-fir does not comprise at least 80% stocking by basal area.

Thinned and unthinned treatments were randomly assigned within provinces, as initial conditions for each field installation. "Unthinned" stands were those not thinned at the time of fertilizer application, whereas thinned stands were those in which the average basal area at each field installation was reduced by 40% just prior to fertilizer application. In this way, the basal area after thinning was uniform among plots within an installation, albeit varied from installation to installation. At each installation, three treatments of 0 (controls), 224, and 448 kilograms of nitrogen per ha, replicated twice, were assigned at random, totaling six 0.04-ha plots or larger per installation. Throughout this manuscript, we will use ON, 224N, and 448N as notation for those respective levels of fertilizer application.

ANALYTICAL MODEL

The experimental design model (without covariance variables) used in the analysis was a split plot model:

$$Yijkm = \mu + Pi + Tj\,PTij + Ik(ij) + [Fm + PFim + TFjm + PTFijm + eijkm]$$

where the portion in brackets is the split plot portion of the model and:

1 There are actually nine RFNRP physiographic provinces, six of which are Douglas-fir. The three remaining provinces (3, 5, and 9) are western hemlock.

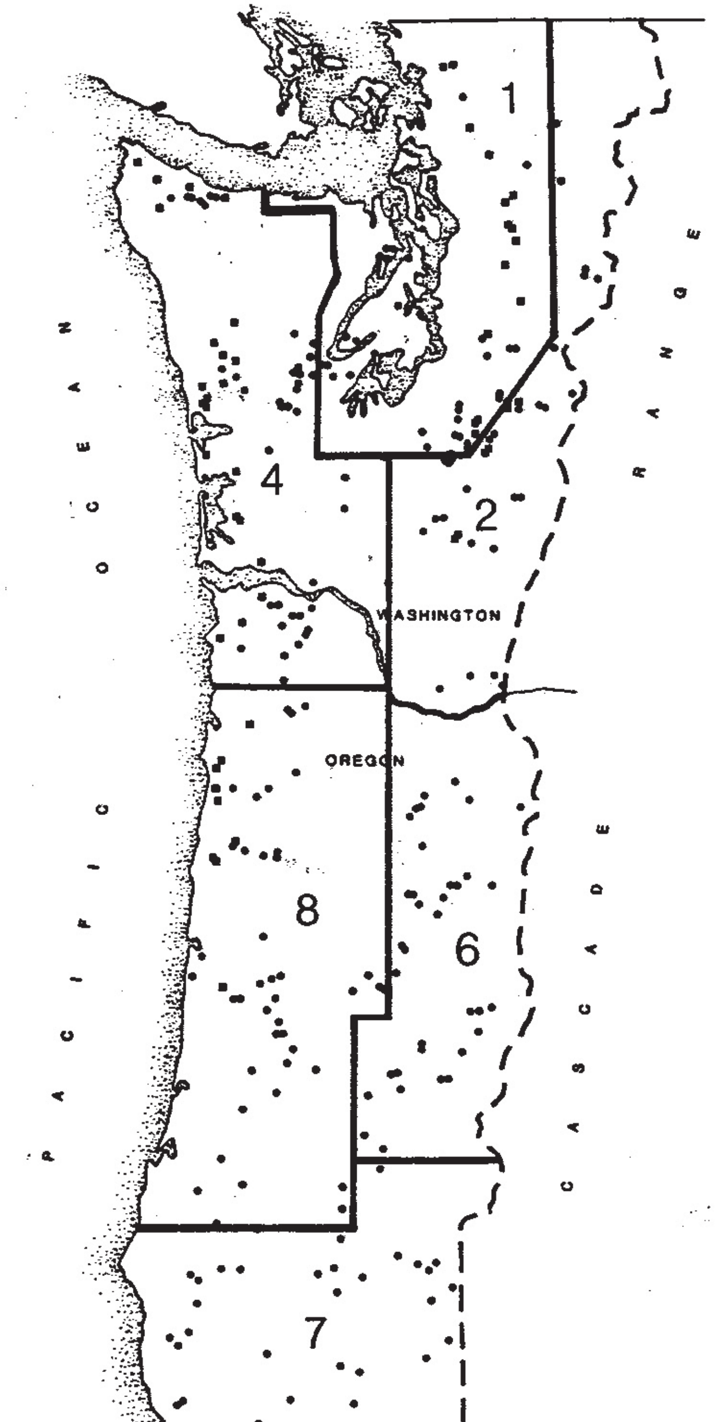

FIGURE 1. Regional stratification of western Washington and westem Oregon into six Douglas-fir provinces (1, 2, 4, 6, 7, and 8).

Yijkm =	the response to the *m*th fertilizer level of the kth installation within the *j*th thinning level within the *i*th province,
μ =	the effect due to the overall mean,
Pi =	the province effect (*i* = 1,2,4,6,7,8),
Tj =	the thinning effect; *j* = 1 (thinned) = 2 (not thinned),
PTij =	the province × thinning interaction effect,
Ik(*il*) =	the effect of installations within thinning and provinces,
Fm =	the split plot fertilizer effect; *m* = 1 (224N) = 2 (448N),
PFim .=	the province × fertilizer interaction effect,
TFjm =	the thinning × fertilizer interaction effect,
PTFijm =	the province × thinning × fertilizer interaction effect, and
eijkm =	the random variation among installations within the split plot design.

The model is a split lot experimental design model because the installations (experimental units for provinces and thinning) are split into fertilizer treatment subunits. Growth responses to fertilizer are measured on each split-plot experimental unit. Covariance variables were introduced into this model at the split-plot level. Thus only one regression was used for adjusting growth responses. In addition to the individual covariate effects, interactions between covariates and classification variable effects were added to the general model.

CHOICE OF VARIABLES

(1) Response

At each field installation, stand response to 224N and 448N was computed directly from 4-year total gross volume[2] PAI (period annual increment) by subtracting average PAI of the controls from the average PAI of the fertilized plots. Both absolute response and percent response were computed, since the potential users of the results are interested in both formulations. The final determination of a province effect was, however, based on variation in *percent* response, as we thought percent provided the best statistical base for testing. The computations produced two unbiased estimates of growth response, symbolized as Δ224 and Δ448, for the respective fertilizer applications at each field installation. Recall that the six plots were an objective sample at each field installation, and that fertilizer treatments were randomly assigned to those plots.

The primary reason for choosing the first four years following fertilizer application was that this 4 year interval represented the period of highest annual

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[2] Tree volume was estimated using tarifs (Turnbull et al. 1972); diameter at breast height was measured initially and at 2-year intervals on all trees; total height was measured initially and at 2-year intervals, on a subsample of trees for site index and tarif.

growth response (Regional Forest Nutrition Research Project 1978). The preference for at least a couple remeasurements on permanent sample plots to reduce the chance for any measurement or data entry errors was also a consideration. The average observed values for 4-year volume increment response are given in Tables 1 and 2, for respective unthinned and thinned stands. The same mean responses, collected according to fertilizer level, thinning level, and province, are depicted graphically in Figures 2 and 3, for absolute and percent values, respectively.

(2) Covariates

Four continuous variables of initial stand conditions were considered as covariates in this study. These include breast height age, King's (1966) 50 year site index, basal area, and difference between treatments in initial volume, symbolized as *AGAR*, *SBAR*, *BBAR*, and *VDIFF*, respectively. Average values of the age, site index, and basal area variables were calculated for the Δ224 and Δ448 treatments at each installation. For example, average age for Δ224 is age averaged across control plots and plots receiving 224N plots. On the other hand, average *VDIFF* corresponding to Δ224 is average initial volume of plots receiving 224N minus average initial volume of controls.

The average values of the covariates along with the number of sampled installations (observations) are presented in Tables 3 and 4 according to province number and fertilizer dosage for both unthinned stands and thinned stands. The

TABLE 1.

Average unadjusted 4-year volume PAI (periodic annual increment) response (minimum, maximum in parentheses) for unthinned Douglas-fir stands.

	Fertilizer application			
	224 kg N ha^{-1}		448 kg N ha^{-1}	
Province	m^3 · ha^{-1} · yr^{-1}	%	m^3 · ha^{-1} · yr^{-1}	%
1	5.2 (−3.7,14.0)	0.32 (−.12,.91)	6.2 (−3.6,14.6)	0.36 (−.12,.91)
2	6.0 (0.8,9.5)	0.30 (.03,.68)	4.8 (−2.5,12.5)	0.27 (−.08,.81)
4	2.5 (−2.0,8.6)	0.12 (−.08,.51)	3.8 (−4.2,8.9)	0.18 (−.13,.50)
6	4.3 (−5.7,14.3)	0.22 (−.14,.67)	4.1 (−6.2,11.9)	0.22 (−.15,.68)
7	2.9 (−7.8,9.0)	0.24 (−.24,1.38)	3.9 (−1.3,9.4)	0.27 (−.06,.56)
8	3.5 (−4.1,8.4)	0.18 (−.19,.67)	5.0 (−3.6,12.7)	0.26 (−.17,.83)
ALL	3.9 (−7.8,14.3)	0.22 (−.24,1.38)	4.6 (−6.2,14.6)	0.25 (−.17,.91)

TABLE 2.

Average unadjusted 4-year volume PAI (periodic annual increment) response (minimum, maximum in parentheses) for thinned Douglas-fir stands.

	Fertilizer application			
	224 kg N ha^{-1}		448 kg N ha^{-1}	
Province	$m^3 \cdot ha^{-1} \cdot yr^{-1}$	%	$m^3 \cdot ha^{-1} \cdot yr^{-1}$	%
1	3.6 (−5.7,11.2)	0.29 (−.19,.73)	6.8 (3.7,11.2)	0.42 (.20,.73)
2	2.4 (−3.2,7.8)	0.14 (−.14,.43)	2.3 (−2.8,5.7)	0.13 (−.12,.32)
4	4.1 (0.4,8.1)	0.24 (.04,.45)	4.9 (1.8,8.6)	0.31 (.08,.63)
6	6.3 (3.6,8.4)	0.48 (.17,1.35)	7.9 (4.2,11.0)	0.58 (.28,1.43)
7	5.9 (1.8,10.1)	0.54 (.10,.84)	5.1 (4.5,5.7)	0.50 (.41,.59)
8	4.6 (1.5,8.2)	0.28 (.06,.60)	5.7 (1.9,9.4)	0.36 (.08,.93)
ALL	4.4 (−5.7,11.2)	0.31 (−.19,1.35)	5.4 (−2.8,11.2)	0.36 (−.12,1.43)

larger sample for Δ224 estimates in all provinces is because installations estabfished in later years retained the 224N treatment, while sacrificing the 448N treatment in favor of other treatments (Hazard and Peterson 1984). That decision was influenced by region wide acceptance of 224 kilograms nitrogen per ha as

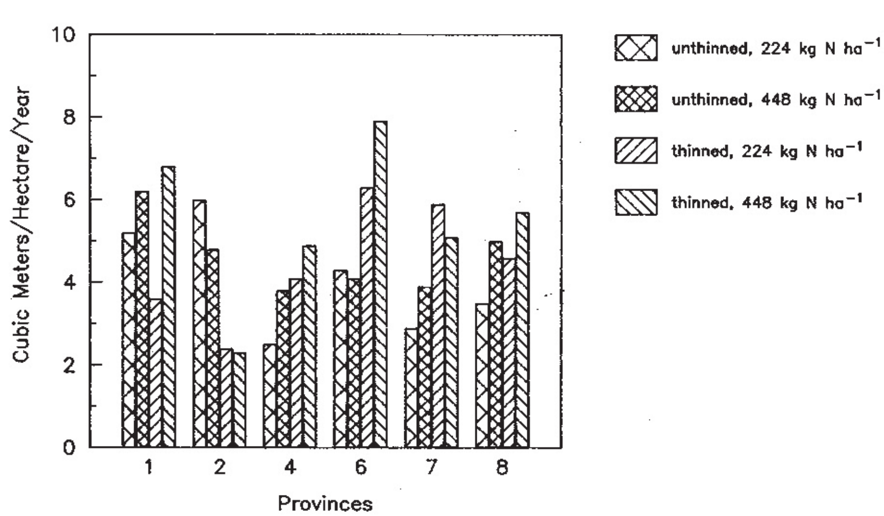

FIGURE 2. Observed average absolute (m^3/ha/yr) 4-yr volume PAI (periodic annual increment) response of Douglas-fir to N-fertilizer, by province.

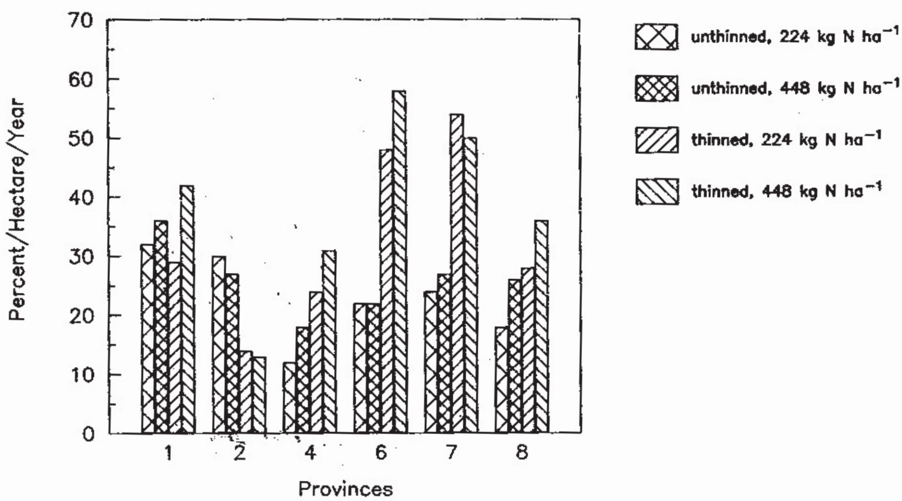

FIGURE 3. Observed average % 4-yr volume PAI (periodic annual increment) response (ha/yr) of Douglas-fir to N-fertilizer, by province.

near some "optimal" level[3] for operational application, and thus a low priority was attached to further treatments which might include levels above 224N. A consequence of this earlier decision may be that the sample for an estimate of Δ448 for province. 7 is insufficient for thinned stands and minimal for unthinned stands.

RESULTS AND DISCUSSION

MODEL BUILDING

The approach to model building was to start with the full model as defined above, plus the four covariates and the covariate × factor (classification variable) interactions. Initially, a test of significance was made to determine which of the covariates (*ABAR*, *SBAR*, *BBAR*, or *VDIFF*) should be in the predictive model. Since estimation was the primary consideration, the covariates were reordered first in the model to determine their effect, independent of the rest of the full model. All four covariates were considered significant ($P \leqslant 0.05$), and thus were included in all subsequent analyses, with the exception of *VDIFF*. Although *VDIFF* was used as a covariate, it was eventually dropped as a predictor variable because it was impractical to use.

The covariate × factor interactions were then tested for heterogeneity of slopes. The intent was to have the capability of individual covariate slopes for different combinations of provinces, thinning levels, or fertilizer treatments. If slopes were homogeneous, the covariate interaction terms would be dropped from the model. All covariate × factor interactions were considered nonsignificant ($P > 0.05$), and thus those interaction terms were dropped from the model for

[3] RFNRP Internal Report Series No. 1, 1984, on file at the College of Forest Resources, University of Washington, Seattle, Washington.

TABLE 3.

Average initial stand conditions (minimum, maximum in parentheses) for unthinned Douglas-fir stands.

	Fertilizer application									
	224 kg N ha^{-1}					448 kg N ha^{-1}				
Province	n	B.H. age (yr)	50-yr site index (m)	Basal area (m^2 ha^{-1})	*Vdiff* (m^3 ha^{-1})	n	B.H. age (yr)	50-yr site index (m)	Basal area (m^2 ha^{-1})	*Vdiff* (m^3 ha^{-1})
1	20	29 (4,53)	32 (20,41)	38 (1,58)	16 (−69,93)	15	36 (23,52)	31 (19,40)	37 (32,55)	5 (−174,142)
2	14	30 (11,47)	36 (23,42)	46 (14,66)	9 (−168,149)	13	31 (12,46)	36 (24,41)	47 (14,60)	−19 (−81,59)
4	20	29 (4,46)	37 (27,44)	43 (4,62)	21 (−69,124)	18	31 (15,45)	38 (27,43)	48 (23,64)	33 (−24,207)
6	23	30 (9,50)	34 (23,42)	43 (6,61)	2 (−136,262)	22	30 (9,51)	34 (23,42)	43 (6,63)	−13 (−155,86)
7	20	41 (17,81)	25 (18,32)	41 (6,73)	−8 (−218,130)	9	37 (27,55)	26 (16,32)	41 (26,56)	0 (−59,43)
8	21	29 (10,47)	38 (25,46)	46 (20,81)	−5 (−107,101)	20	30 (10,48)	36 (23,46)	47 (23,78)	11 (−90,143)
ALL	118	31 (4,81)	34 (18,46)	43 (1,81)	6 (−218,262)	97	32 (9,55)	34 (16,46)	45 (6,78)	4 (−174,207)

developing a prediction equation and for all subsequent analyses. The significance of province and thinning main effects was obscured with the presence of a significant province × thinning interaction (Table 5). This seemed to be supported by the raw data means in Figures 2 and 3, which suggest that if response to fertilizer varies from province to province, the change in magnitude or direction is not the same for both thinned and unthinned stands (e.g., note response in province 2). Consequently, we decided that the data should be partitioned by thinning level and reanalyzed for province effects.

The *PTtj* interaction term was omitted from the model. The model was then fitted separately to data from thinned stands and unthinned stands, for testing the province main effect. The result was that average percent response did not differ significantly among provinces for either thinned stands ($P = 0.12$) or unthinned stands ($P = 0.21$). At this point, we had determined that:

1. The choice of fertilizer dosage level could affect the average percent volume growth response.
2. The variation in average percent response for all stands across provinces (i.e., *PT* interaction) appears to be influenced less by which province the stand is in, than whether the stand has been thinned or unthinned.

Although a significant province effect was not detected for either thinned or unthinned stands, the effect of unbalancedness or void cells in a split plot covariance analysis needed to be addressed as a source for possible spurious results.

TABLE 4.

Average initial stand conditions (minimum, maximum in parentheses) for thinned Douglas-fir stands.

	Fertilizer application								
	224 kg N ha^{-1}				448 kg N ha^{-1}				
Province	n	B.H. age (yr)	50-yr site index (m)	Basal area (m^2 ha^{-1})	*Vdiff* (m^3 ha^{-1})	n	B.H. age (yr)	50-yr site index (m)	Basal area (m^2 ha^{-1})	*Vdiff* (m^3 ha^{-1})
1	11	22 (5,43)	33 (26,38)	17 (1,37)	4 (−32,42)	6	32 (20,43)	32 (27,36)	25 (11,37)	12 (−13,45)
2	8	26 (11,48)	34 (28,40)	27 (14,36)	1 (−14,22)	7	28 (14,47)	33 (28,40)	29 (14,35)	−14 (−41,18)
4	10	28 (4,45)	37 (31,43)	26 (2,43)	3 (−29,32)	8	34 (14,45)	37 (33,43)	31 (17,42)	−1 (−28,28)
6	9	22 (12,42)	36 (30,41)	21 (10,33)	−.4 (−20,23)	7	25 (11,42)	36 (31,41)	23 (10,32)	−4 (−27,11)
7	6	30 (17,50)	26 (21,32)	19 (10,35)	6 (−27,44)	2	32 (20,45)	22 (20,24)	25 (15,35)	6 (1,11)
8	12	25 (7,45)	38 (29,44)	24 (2,39)	−7 (−55,15)	11	27 (7,45)	38 (29,44)	25 (3,39)	3 (−13,15)
ALL	56	25 (4,50)	35 (21,44)	22 (1,43)	1 (−55,44)	41	29 (7,47)	35 (20,44)	27 (3,42)	−1 (−41,45)

That is, potential bias can exist in the sources of variation and ultimately in the estimates themselves, since estimates will be weighted more heavily by the treatments which are full (balanced). If void cells arise in treatment combinations for which the computed means are quite different from the true mean for that

TABLE 5.

Full model ANCOVA where dependent variable is 4-yr percent volume response.

Source	df	F-value	p-value
* Covariates	3		
P	5	2.73	0.0227
T	1	2.96	0.0910
PT	5	3.35	0.0076
* I(PT)	162		
F	1	3.68	0.0573
PF	5	<1	0.5056
TF	1	<1	0.5038
PTF	5	<1	0.9595
* Split plot error			

* Tests of covariates, covariate X factor interactions, and error terms have been omitted from this table. Model explanation is given in text under *Analytical Model* section.

treatment, then means formed from combinations of that treatment with others will not reflect this difference and will be biased. This is not an uncommon situation and arises with almost all unbalanced situations.

On the other hand, the situation may not introduce bias at all. We do know that if the number of void cells is small relative to other treatments, the influence should be small because the marginal means will be missing only a small amount of information. In order to determine the extent of this bias, we chose to run various subanalyses on subsets of the data looking at the results with and without the void cells.

In addition to analyzing the full model with and without covariates, we ran the whole plot and split plot analyses separately with and without covariates, and with and without province 7 (the province with most of the void cells). We also ran separate subanalyses for Δ224 unthinned, Δ224 thinned, Δ448 unthinned, and Δ448 thinned, to test province effects on percent response at each thin level and fertilizer level. In this way, all of these subanalyses were balanced (i.e., did not involve a split plot). The results showed a significant effect for provinces in three of four cases (*P*-values of 0.0023, 0.0291, 0.0226, and 0.0988 respectively) when all data were included. The exception where province was less important occurred with the 448-kilogram application to thinned stands. Removal of province 7 did not affect the general outcome, in that the effect for provinces was stiff important in three of four cases (*P*-values of 0.0164, 0.0128, 0.2200, and 0.0647, respectively). Without province 7, however, province effect was less important with the 448-kilogram application to unthinned stands.

These results suggested that four separate estimating equations might be needed. However, further analysis showed that the significance of province on percent growth response in each of the individual equations was not always due to the same provinces. That is, for unthinned stands, the largest province differences for both Δ224 and Δ448 in Figure 3 are between province 1 and 4. Furthermore, the response to Δ224 in province 2 is greater than response to 0448 in the same province. In contrast, the largest province differences of thinned stands are between province 2 and 6 for Δ448 and between province 2 and 7 for Δ224. Since we cannot biologically justify that a land manager can expect response to 224N to be greater than response to 448N in province 2, we decided against two separate whole plot models for the unthinned situation. For thinned stands, the uncertainty of response estimates is clearly reduced by not splitting what is a much smaller sample size relative to the sample of unthinned stands:'
Overall, we found all subanalyses supported our full model analyses and conclusions for thinned and unthinned subsets. We do not believe there is any substantial bias in our final analyses. Regarding province 7, one could question as to whether or not the initial stand conditions sampled in that province (southern Oregon) are typical of those in the remaining provinces. In the model building analyses, the removal of province 7 data did not affect the significance of main effects or interactions of classification variables. However, compared to the average and range of site indices sampled elsewhere in the region, the sample average site index in province 7 is substantially lower, and range much narrower, for both unthinned and thinned stands (Tables 3 and 4). The smaller sample of installations in province 7 also reflects the difficulty in finding candidate stands in that area which could meet the selection criteria (e.g., stands which are uniform and weft stocked).

Thus, the decision to keep the province variable in the model represents a refinement by "judgment" on the "significance" of provinces, and in doing so should not incur management problems.

The biggest impact of this decision is on unthinned stands in province 2. Since the models will reflect the majority of situations in which response to 448N is greater than response to 224N, our estimates of response in that situation will be less than observed for 224N and more than observed for 448N. As stated above, this "compromise" is probably a more realistic expectation for a manager in that province.

PREDICTIVE MODELS

The final equations for estimating both absolute and relative 4-year volume PAI response of thinned and unthinned stands are given in Table 6. The resulting point estimates by thinning and fertilizer levels for each province are provided in Table 7, and graphically in Figures 4 and 5.

We also used these models to generate the smoothed values in "look-up" tables provided for RFNRP cooperators in an internal report; an example is given in Table 8. Response for province 7 was not, however, estimated for site indices above 32 m. Recall that site index at sampled locations in province 7 (Tables 3 and 4) did not exceed 32 m. "Higher site quality" stands of Douglas fir which might meet the selection criteria were not found in province 7. Consequently, even though stands sampled in the remaining provinces covered this void, we decided it would be inappropriate to estimate response for site indices above 32 m in province 7. In fact, the comparability of site index across all provinces could be of

TABLE 6.

Final estimating equations for 4-yr volume PAI (periodic annual increment) response of Douglas-fir to N-fertilizer, both absolute ($m^3 \cdot ha^{-1} \cdot yr^{-1}$) and percent.

	Unthinned stands		Thinned stands	
	Absolute	Percent	Absolute	Percent
Parameters				
Intercept	13.3	1.006	12.0	1.006
ABAR	0.0664	0.00695	0.0269	0.00616
SBAR	−0.2120	−0.00519	−0.1895	−0.00424
BBAR	−0.0641	−0.00174	0.0092	−0.00251
FERT Δ224	−0.7	−0.037	−0.9	−0.073
Δ448	0.0	0.000	0.0	0.000
PROV #1	−0.1	−0.021	−1.4	−0.102
#2	1.1	0.059	−3.8	−0.224
#4	−0.9	−0.061	−1.0	−0.061
#6	−0.7	−0.052	1.5	0.152
#7	−4.2	−0.256	−1.7	−0.027
#8	0.0	0.000	0.0	0.000
n	215	215	97	97
MSE	3.72	0.202	2.72	0.214
R^2	0.177	0.329	0.304	0.381

TABLE 7.

Four-year estimates of absolute ($m^3 \cdot ha^{-1} \cdot yr^{-1}$) and relative (%) annual total gross volume increment response of Douglas-fir to fertilizer applications of 224 and 448 kg N ha^{-1} by thinning level and province.

Province	Unthinned stands 224 N	Unthinned stands 448 N	Thinned stands 224 N	Thinned stands 448N
1	5.3 (32%)	6.2 (37%)	4.2 (32%)	5.6 (37%)
2	5.1 (32%)	5.7 (35%)	1.9 (10%)	2.8 (17%)
4	2.9 (13%)	3.4 (16%)	3.9 (24%)	5.1 (30%)
6	3.9 (21%)	4.6 (25%)	6.6 (48%)	7.5 (55%)
7	3.1 (23%)	3.7 (27%)	5.7 (51%)	6.7 (59%)
8	3.9 (20%)	4.5 (24%)	4.8 (28%)	5.6 (36%)

TABLE 8.

An example of values generated from predictive models: estimated absolute 4-year volume PAI (periodic annual increment) response to N-fertilizer in second-growth stands of Douglas-fir in Province 1 (total $m^3 \cdot ha^{-1}\ yr^{-1}$ per year, minimum dbh = 3.8 cm).

		Unthinned stands			
		50-year site index (m)			
B.H. Age	kg N ha^{-1}	26	32	38	44
15	224	5.2	3.9	2.6	1.3
	448	5.9	4.6	3.3	2.0
25	224	5.9	4.6	3.2	2.0
	448	6.5	5.2	3.9	2.6
35	224	6.5	5.2	3.9	2.6
	448	7.2	5.9	4.6	3.3
45	224	7.2	5.9	4.5	3.3
	448	7.8	6.5	5.2	3.9
		Thinned stands			
		50-year site index (m)			
B.H. Age	kg N ha^{-1}	26	32	38	44
15	224	5.4	4.2	3.0	1.8
	448	6.3	5.1	3.9	2.7
25	224	5.7	4.5	3.3	2.0
	448	6.6	5.4	4.1	2.9
35	224	5.9	4.7	3.5	2.3
	448	6.8	5.6	4.4	3.2
45	224	6.2	5.0	3.8	2.6
	448	7.1	5.9	4.7	3.5

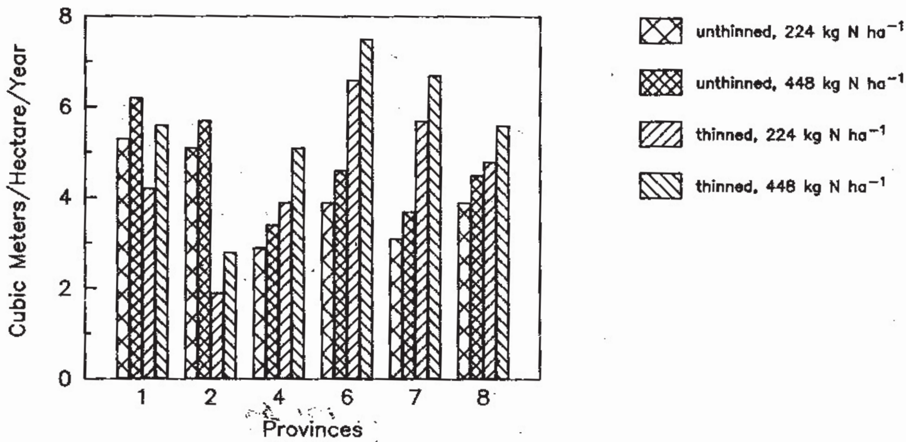

FIGURE 4. Estimated average absolute (m^3/ha/yr) 4-yr volume PAI (periodic annual increment) response of Douglas-fir to N-fertilizer, by province.

some concern, since it has often been noted that the climate (e.g., temperature and/or precipitation) in that province is more akin to "east-side" (east of the Cascade Mountains) conditions than the remaining "west-side" provinces. That is to say, if site index in province 7 is characterized by drought, far example, more than nitrogen deficiency, then we would not necessarily expect stands of low site quality (e.g:, less than 30 m) in province 7 to respond to nitrogen fertilizer either in kind or to the same degree as those stands of similar site index in the remaining provinces. Fertilizer response information specific to southwest Oregon is given elsewhere (Miner et al. 1987).

CONCLUSIONS AND RECOMMENDATIONS

Variation in both absolute and percent growth response to fertilizer appears to be influenced more by the presence or absence of thinning than by the physiographic

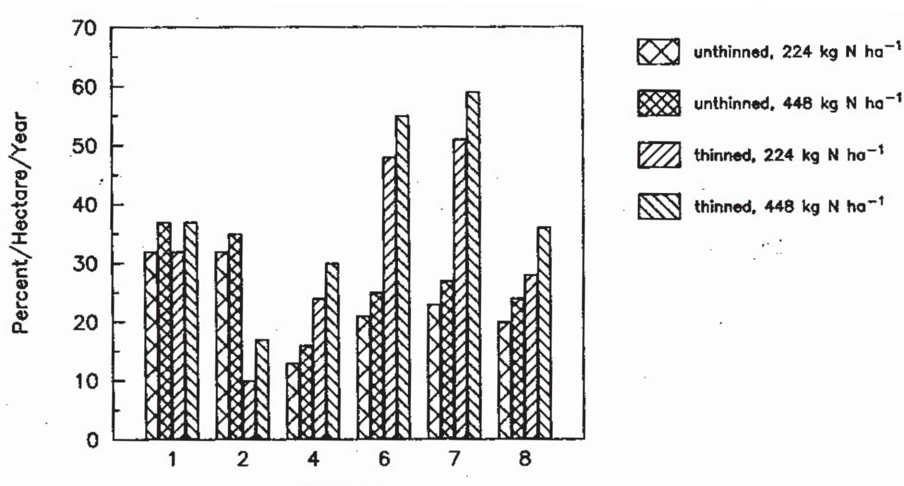

FIGURE 5. Estimated average % 4-yr volume PAI (periodic annual increment) response (ha/yr) of Douglas-fir to N-fertilizer, by province.

province in which the stand is located. Although a "significant" ($P \leqslant .05$) effect of province was not detected, we decided to include it in the model for purposes of refinement.

Some results should be examined more closely. For example, in province 7, the larger fertilizer response obtained for thinned stands relative to unthinned stands could be a function of the small sample taken in thinned stands, and should it be substantiated with additional information prior to assuming that such an increase is operationally attainable. Likewise in province 2, the low fertilizer response in thinned stands, relative to the response in unthinned stands, should be studied further.

Finally, in addition to volume increment response, this same comprehensive analysis should be done for other response variables (e.g., basal area increment), and for total PAI itself. Similar analyses could, for example, be conducted using soil or foliar information at each installation, in place of site index and stand variables as covariates. By conducting more of these comprehensive analyses of the existing data, the collective results might give us a better understanding (and estimate) of the variability in forest growth and response among these physiographic areas. In this way, the time and effort invested in such analyses would likely identify future information needs for managers to effectively forecast responses of forests to silvicultural practices such as thinning and fertilization, alone and in combination.

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