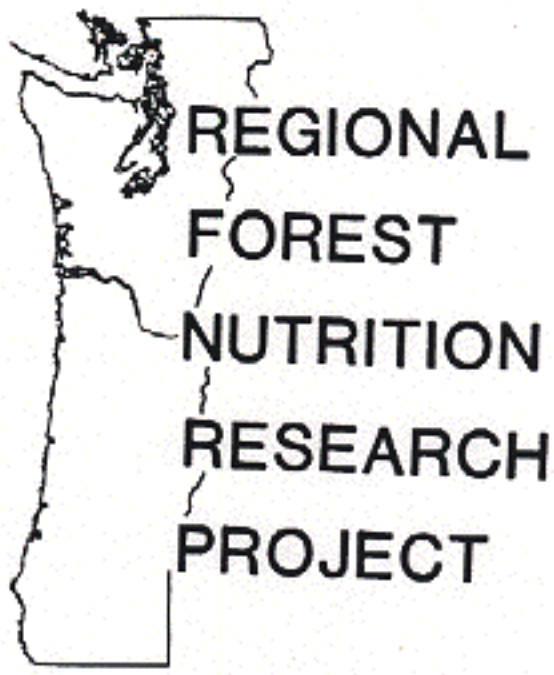

GROWTH RESPONSE TO SINGLE AND MULTIPLE APPLICATIONS OF N FERTILIZER OVER 16 YEARS IN UNTHINNED AND THINNED DOUGLAS-FIR STANDS IN THE PACIFIC NORTHWEST

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K. Stegemoeller and H.N. Chappell

SUMMARY

Basal area and volume growth response of thinned and unthinned second-growth Douglas-fir stands to single and multiple applications of nitrogen (N) fertilizer were estimated for eight 2-year periods. Installations originally included replicated treatments of 0, 200, and 400 lbs N/A applied as urea (46% N). A second fertilizer treatment of 200 lbs N/A was applied to one plot of each initial treatment before the fifth period, and a third application was made on those plots before the seventh period. The thinned installations were thinned to 60% of their original basal area at the time of installation establishment, and were lightly rethinned before the sixth period. Because treatment effects of the second refertilization cannot be distinguished from those of the first, the various treatment combinations are presented as management regimes. Also, because there is no longer any replication of treatments within installations, response estimates and trends are considered only on a regional scale.

Average responses to the initial fertilization and to both the second and third fertilizer applications, 8 and 12 years later, are statistically significant ($p < 0.05$). On thinned stands, duration of response to the initial treatment is approximately 8 years; unthinned stands continue to show significant volume growth response through 14 years, though basal area growth response decreases to non-significant levels between years 10 and 12. In both cases, the response to refertilization, while significant, is smaller than the

response to the initial fertilization. Two hundred lbs N/A applied after the eighth year, and a refertilization after the twelfth, on one initially untreated plot at each installation also produced significant growth responses.

INTRODUCTION

Few studies have addressed the effects of multiple N fertilizer applications on Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). The Regional Forest Nutrition Research Project (RFNRP) has completed two reports which include results of studies on the effect of multiple N fertilizer applications on growth response in unthinned and thinned Douglas-fir stands (Peterson and Heath 1986; Opalach et al. 1987). Barclay and Brix (1985) presented results on Douglas-fir growth response to multiple applications of N on a poor quality site.

Another 4 years of data have been collected on unthinned (Phase I) and thinned (Phase II) RFNRP installations since the last reports. The current study updates results and summarizes RFNRP growth response findings for its Phase I and Phase II second-growth Douglas-fir installations. Analyses of basal area and volume growth responses to single and multiple applications of N fertilizer (as management regimes) are included. Gross periodic annual increment over 2-year growth intervals also is presented to indicate response trends.

METHODS

Description of installations and data collection

Data were collected over a 16-year period from a total of 114 installations established in second-growth Douglas-fir stands in western Washington and Oregon by the RFNRP. Each installation is made up of six 0.1-acre or larger plots, with at least 80% of the basal area in Douglas-fir. Average initial stand conditions are summarized in Table 1.

Table 1. Approximate average stand conditions at the time of installation establishment.

	Unthinned	Thinned
Number of installations	80	34
Breast-height age (years)	31	30
Site index (feet, 50-year, King 1966)	118	114
Stems per acre	730	340
Basal area* (sq ft/A)	200	120
Volume* (cu ft/A)	6450	3790

* all stems $\geq$ 1.55 inches DBH

Thinned installations had 40% of their original basal area removed from below at the time of establishment. Initial fertilizer treatments at all installations consisted of two unfertilized plots (controls), two plots

treated with 200 lbs N/A as urea (46% N), and two plots treated with 400 lbs N/A as urea. Urea fertilizer was applied uniformly by hand to plots and surrounding buffer areas. After 8 years, one replicate of each treatment in each installation was refertilized with 200 lbs N/A. Rethinning of the Phase II installations was done from below after 10 years to increase growing space. The guideline for rethinning required reduction of plot relative density (Curtis 1982) to 40 and retention of at least 25 residual trees. All plots on all Phase II installations were subjected to this guideline. The number of trees on some plots prohibited them from being rethinned; therefore, the effect of rethinning on growth response was not estimated (appropriate "controls" do not exist).

Another 200 lbs N/A fertilizer treatment was applied after the twelfth year to those plots which received the second treatment. Six management regimes for both unthinned and thinned installations were thus defined. In the ensuing discussion they are referred to as:

0N or 0T	unfertilized (control)
2N or 2T	200 lbs N/A at time of establishment
4N or 4T	400 lbs N/A at time of establishment
0NR or 0TR	200 lbs N/A at 8 and 12 years after establishment
2NR or 2TR	200 lbs N/A at establishment + 200 lbs additional, 8 and 12 years later
4NR or 4TR	400 lbs N/A at establishment + 200 lbs additional, 8 and 12 years later,

where "N" indicates unthinned, "T" indicates thinned, and "R" indicates the refertilization regime. For more information about the treatment design, see Hazard and Peterson (1984).

Initial diameter at breast height (DBH) was measured for all trees greater than 1.55 inches in DBH on each plot. The heights of ten dominant and codominant trees also were measured to estimate volume (CVTS) using tarifs

(Turnbull et al. 1972); a sample of the height trees was used to estimate site index (King 1966). Diameter and height were remeasured at 2-year intervals following plot establishment.

Mensurational techniques

Fertilizer response has been partitioned into response due to improved nutrition (direct effects) and that due to altered stocking by fertilization in previous periods (indirect effects) (Comerford et al. 1980; Miller and Tarrant 1983; Auchmoody 1985; Opalach et al. 1987). Using basal area or volume at the beginning of each period as the covariate in an analysis of covariance model, the indirect effect is mathematically removed and direct fertilizer effects can be estimated. The emphasis here, however, is on determination of estimates of growth response to fertilization regimes rather than long-term response estimates. Hence combined direct and indirect effects of N fertilizer on total gross basal area PAI and total gross volume PAI were determined for each 2-year period using initial basal area or response as the covariate. Response is defined as in Peterson and Heath (1986):

growth response to fertilization regime	=	fertilized stand mean growth rate	-	unfertilized stand (control) mean growth rate

The general model used for the analysis of covariance is

$$Y_{ijk} = \mu + T_i + B_j + \beta(V_{ijk} - V...) + \epsilon$$

where

Y_{ijk}	=	volume (or BA) PAI of replication k, installation j, regime i
μ	=	mean volume (or basal area) PAI
T_i	=	main effect of regime i
B_j	=	block effect of installation j
β	=	regression coefficient
V_{ijk}	=	initial volume (or BA)
$V...$	=	mean volume (or BA) across all replications, installations, and regimes
ϵ	=	experimental error.

This model has been used in past RFNRP studies and has worked well for estimating growth response (Heath 1988). The model requires few assumptions about the relationship between the dependent and independent variables (Opalach and Heath 1988) and effectively reduces experimental error by blocking on installations.

Within the refertilization regimes, all plots were retreated after both the eighth and twelfth years; hence, response due solely to the N added after 12 years could not be partitioned from the 8-year refertilization response. Unless otherwise noted, responses were considered significant if $p \leq 0.05$.

RESULTS

Unthinned stands

Absolute and relative volume and basal area growth responses to single and multiple fertilizations for each 2-year period are illustrated in Figures 1 and 2. Gross volume increment for each treatment regime is plotted with the unfertilized plot increment levels in Figure 3, for comparison of treatment effects over a known level of control growth. Response estimates with standard errors and significance levels are given in Appendix Tables A and B, also by 2-year period.

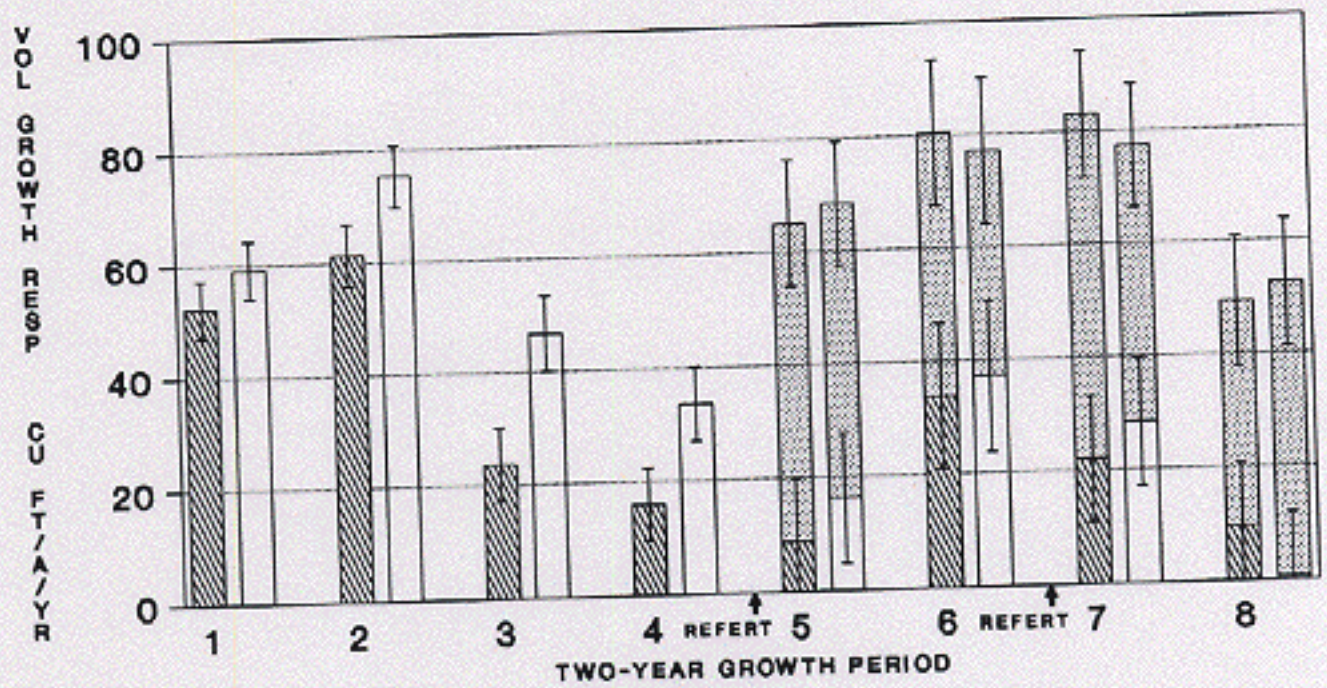
Initial applications of 200 and 400 lbs N/A produced significant growth responses both in terms of volume and basal area through four periods ($p < 0.05$). Volume response declined to non-significance in period five, but increased in period six and remained significantly greater than zero until period eight. Basal area response did not show the same trend in that it remained significant until period six, at which point it declined for both treatments, and only the 2N treatment response increased in periods seven and eight.

Refertilization between periods four and five produced significant basal area and volume responses through period six ($p < 0.001$). As opposed to the trend in response from the initial fertilization, where an increase in both basal area and volume growth was observed in the second period following application, response to refertilization appeared to continue increasing in the sixth period for volume only. The refertilization after period six succeeded in increasing response again, so that significant levels of growth response were maintained through the eighth measurement period. However, both

volume and basal area response declined in the second growth period after refertilization.

Growth responses to the addition of 200 lbs N/A on originally untreated (control) plots after period four (a delayed fertilizer treatment) were significant and were greater in magnitude than the responses to the 2N treatment in period one. Refertilization after period six resulted in the same kind of growth increase as seen for the other refertilization regimes, maintaining significance through the eighth period.

Figure 1. Total gross volume and basal area growth responses ± 1 standard error by 2-year growth period, for unthinned Douglas-fir stands.



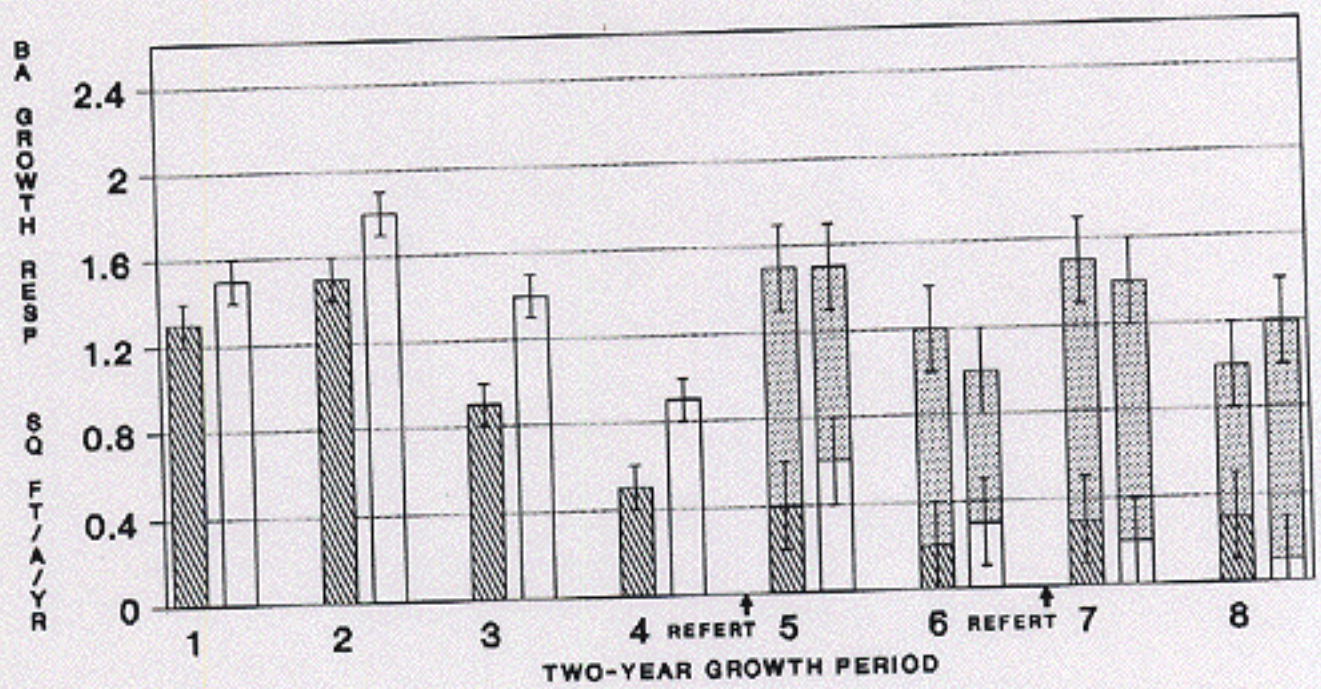


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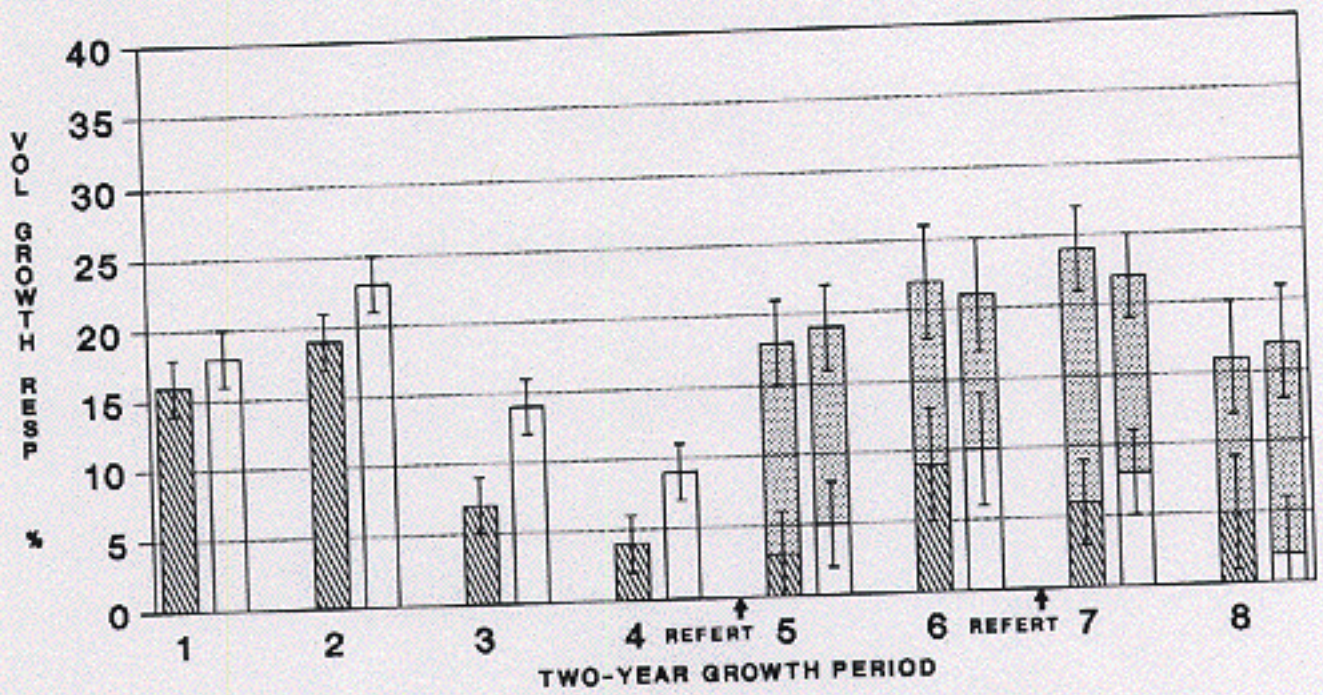
Figure 2. Relative volume and basal area growth response ± 1 standard error by 2-year growth period, for unthinned Douglas-fir stands.



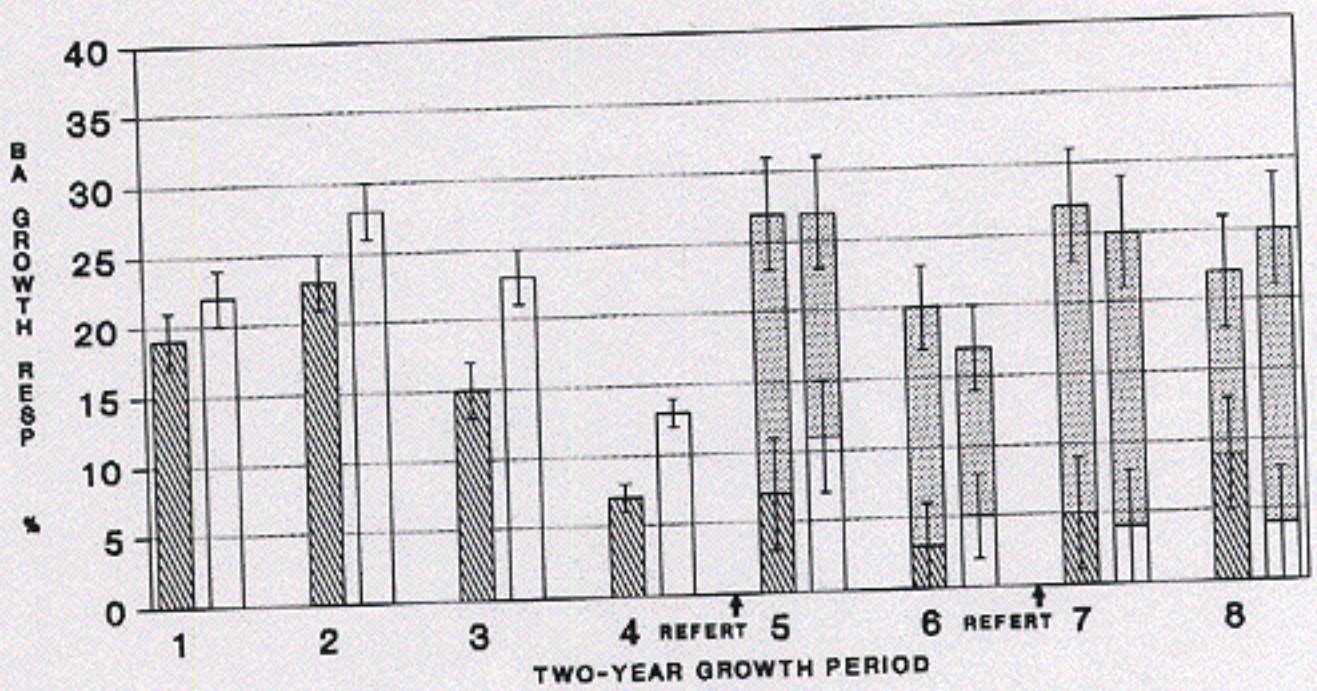


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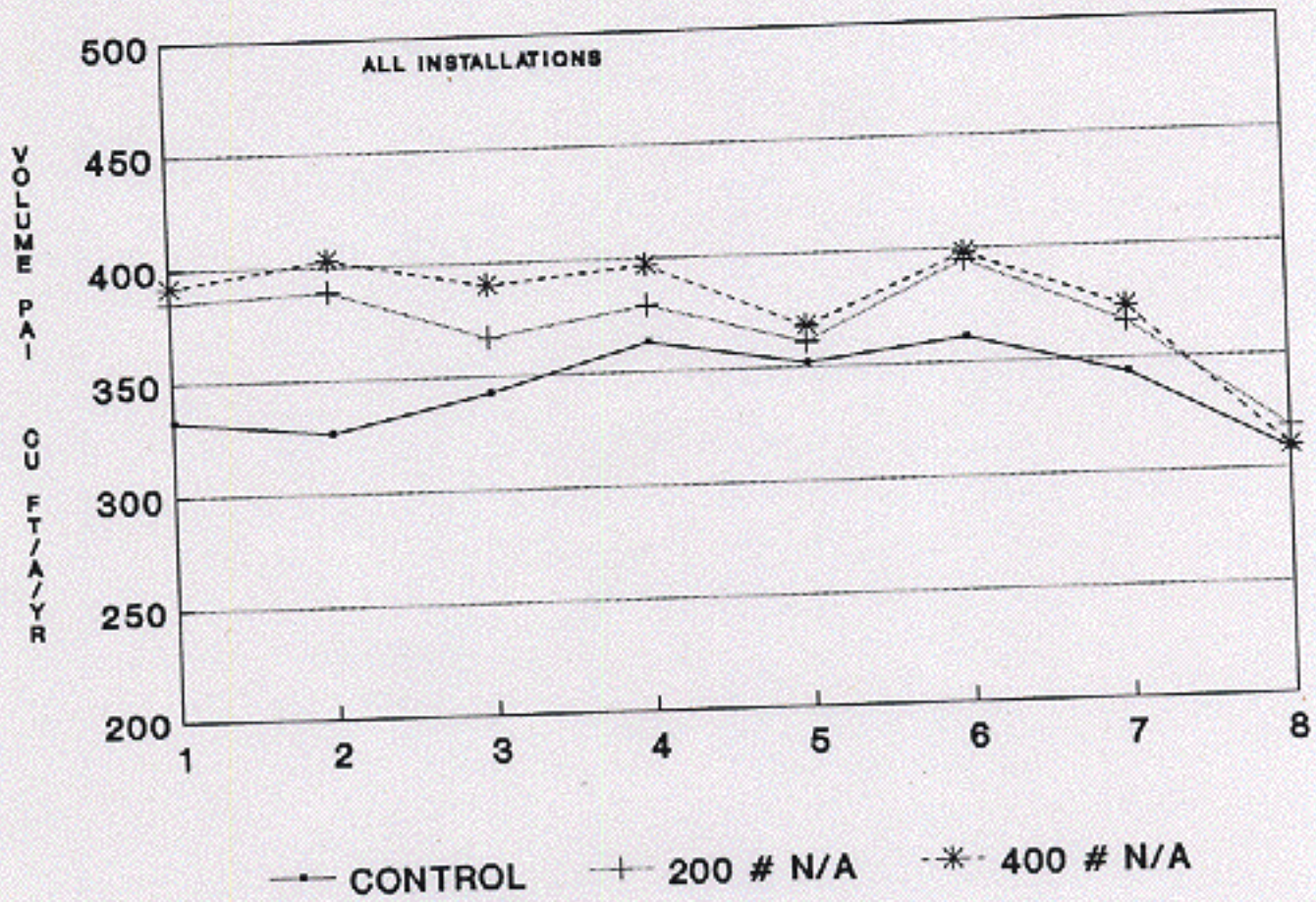
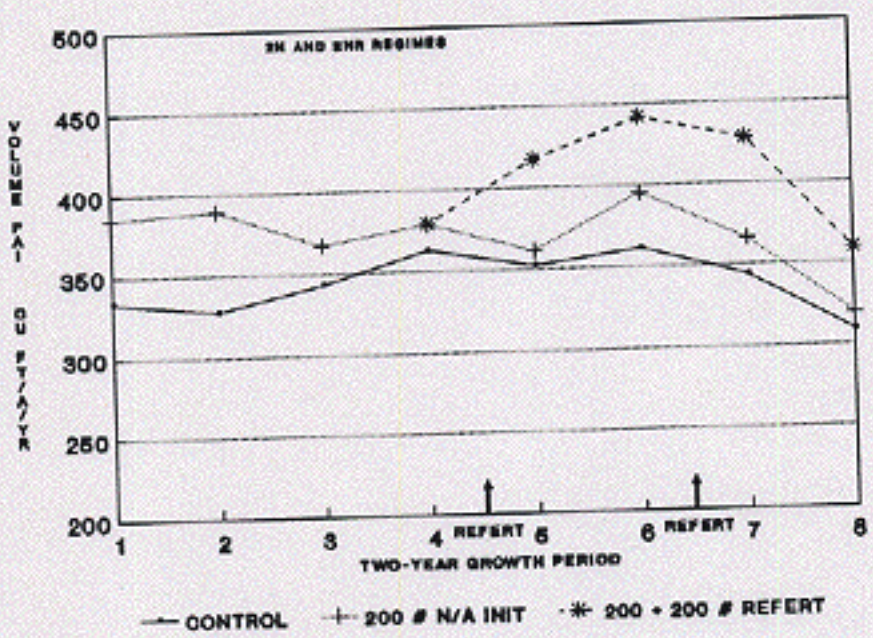
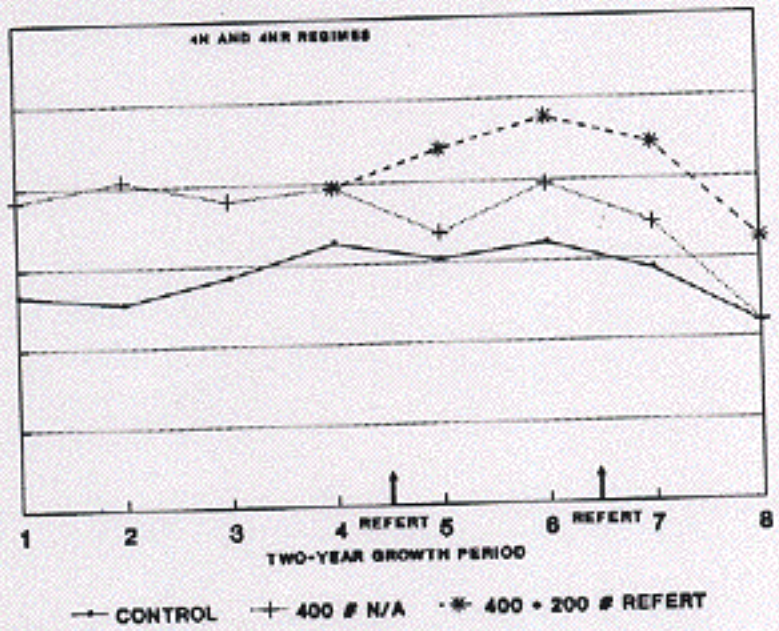
Figure 3. Gross volume PAI by 2-year growth period, for unthinned Douglas-fir stands.







Thinned stands

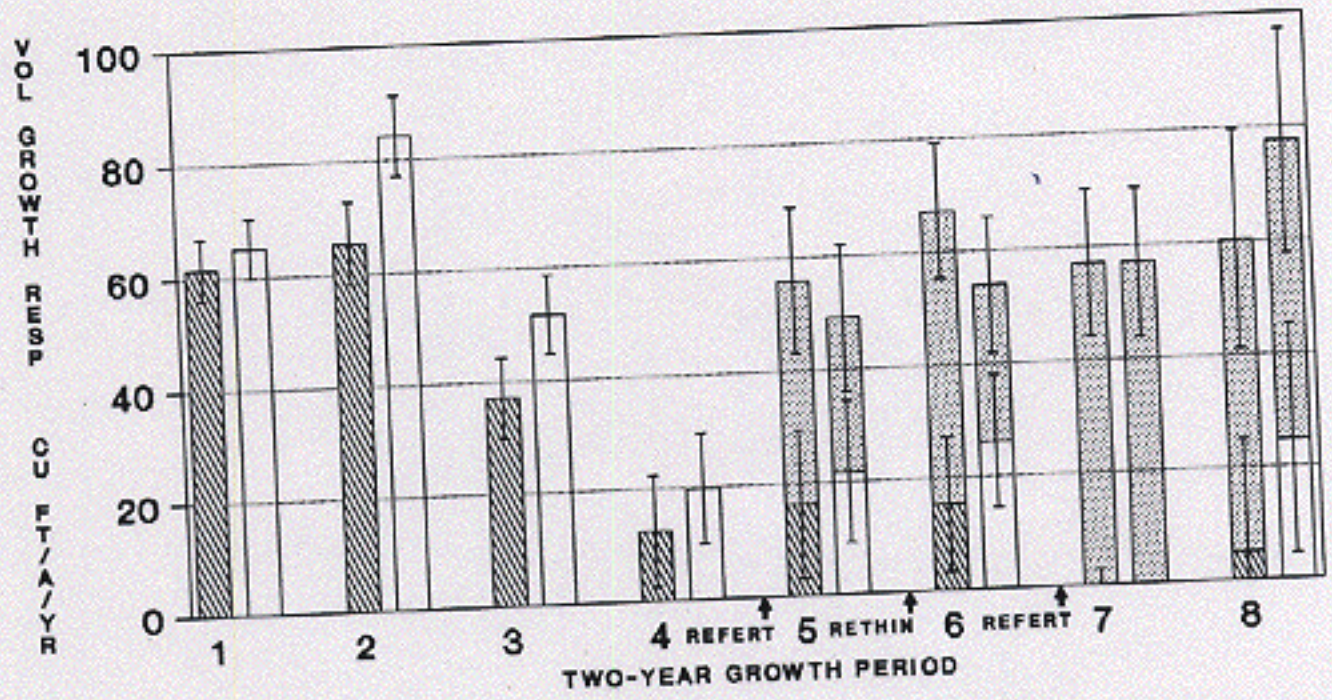
Volume and basal area responses to single and multiple fertilization for thinned stands are presented in Figures 4 and 5. The corresponding growth response estimates, standard errors and significance levels are included in the Appendix as Tables C and D. Figure 6 shows the gross volume increment for each treatment as it compares with the control plot increment.

Growth responses to both the 2T and 4T treatments on thinned installations were significant through three growth periods ($p < 0.001$), the 4T volume growth responses remaining so into the fourth period ($p < 0.05$). Responses of both 2T and 4T treatments increased slightly after period four, through period six -- the 400 lb treatment (4T) resulted in greater sustained response than the 200 lb treatment (2T) on these installations.

The first refertilization produced significant additional response beyond that carried over from the initial treatments, particularly the 2TR application. The second refertilization was applied before the effects of the first refertilization and/or rethinning had begun to decline, increasing the total growth response for both regimes, and maintaining significance through the eighth period ($p < 0.005$). These results were also seen with the 0TR fertilizer treatment.

Duration of growth response due to the multiple fertilization with thinning regimes must only be fully considered through period seven, as the period eight response values are only based on measurements from half of the thinned installations. Analyses on the full data set will be done after the remaining installation measurements are assimilated into the database.

Figure 4. Total gross volume and basal area growth response ± 1 standard error by 2-year growth period, for thinned Douglas-fir stands.



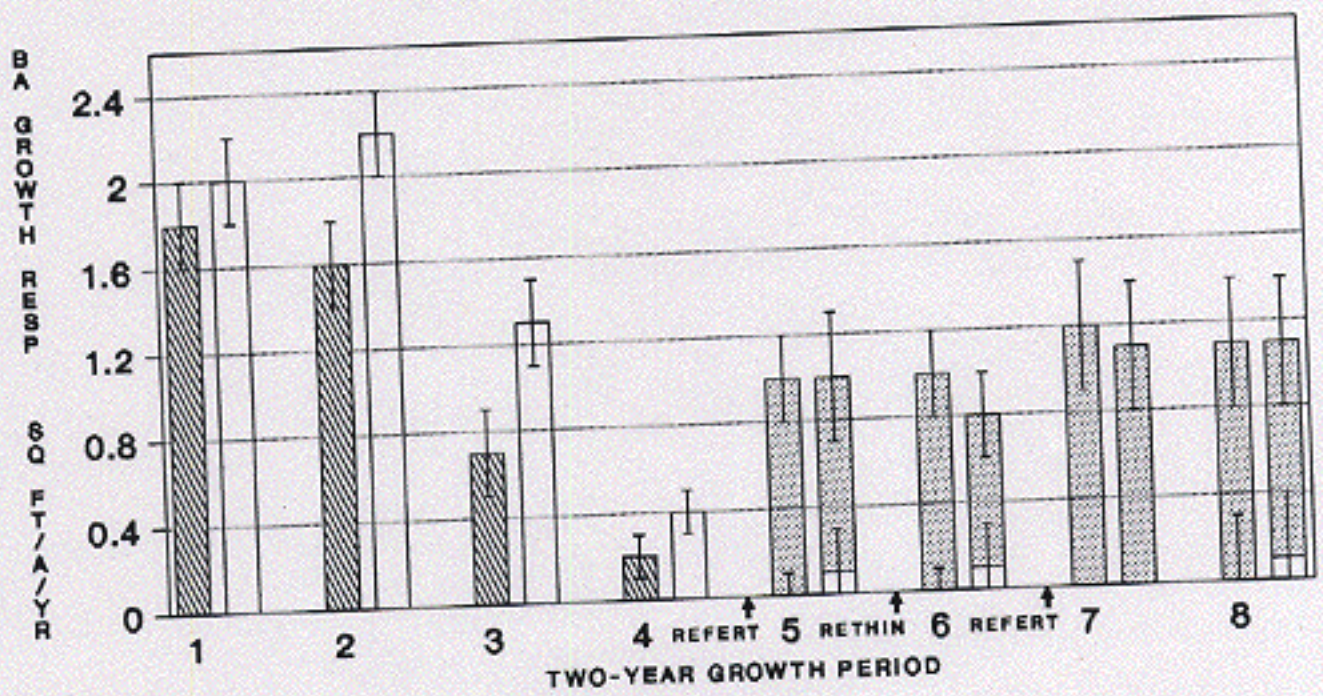


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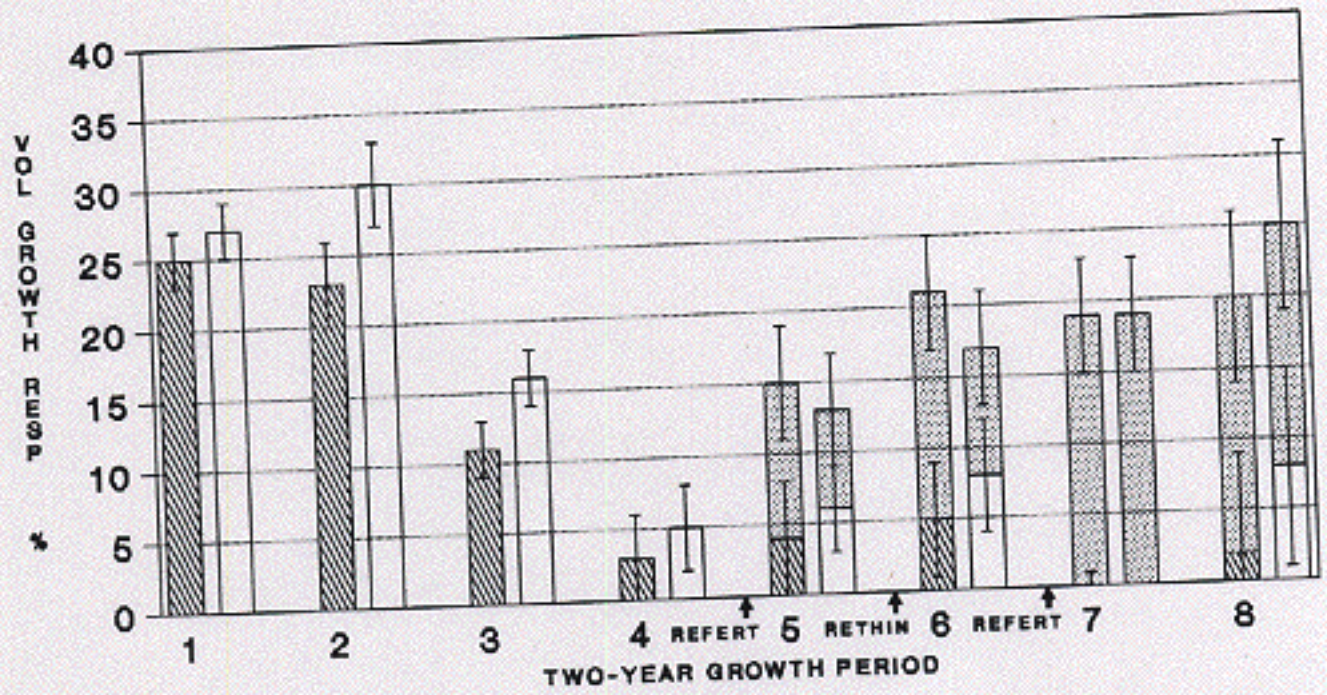
Figure 5. Relative volume and basal area growth response ± 1 standard error by 2-year growth period, for thinned Douglas-fir stands.



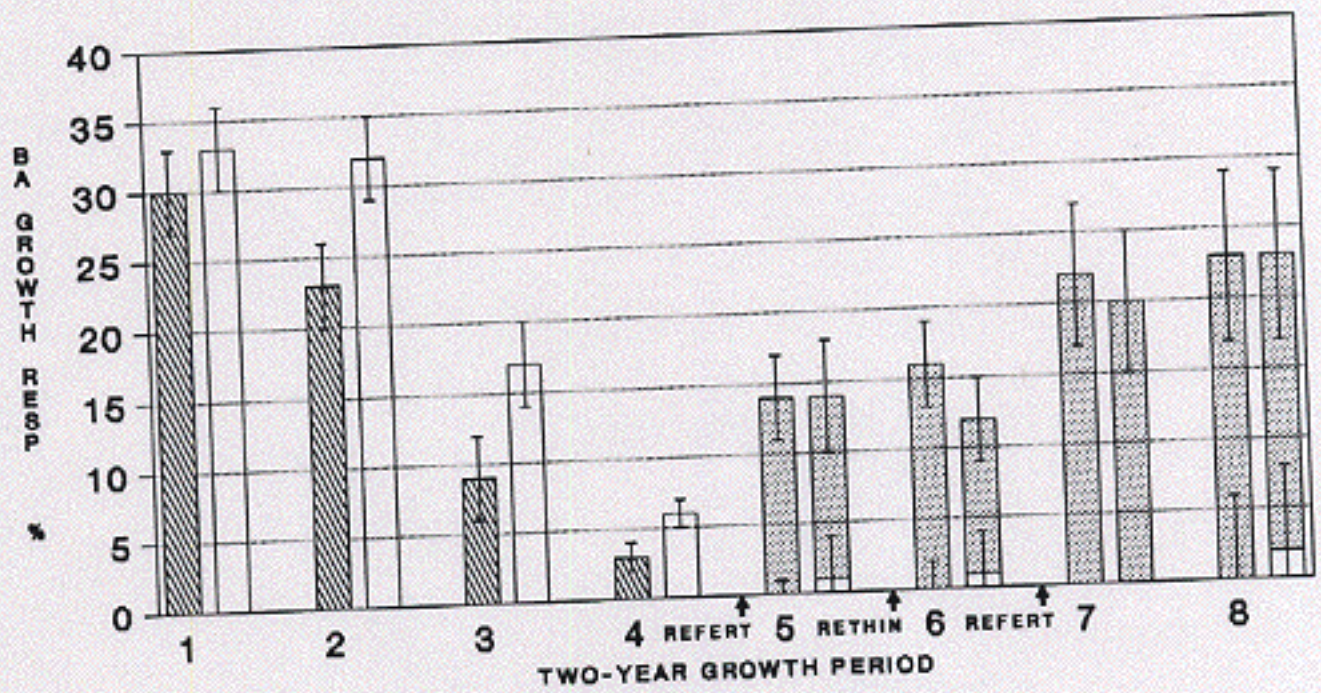


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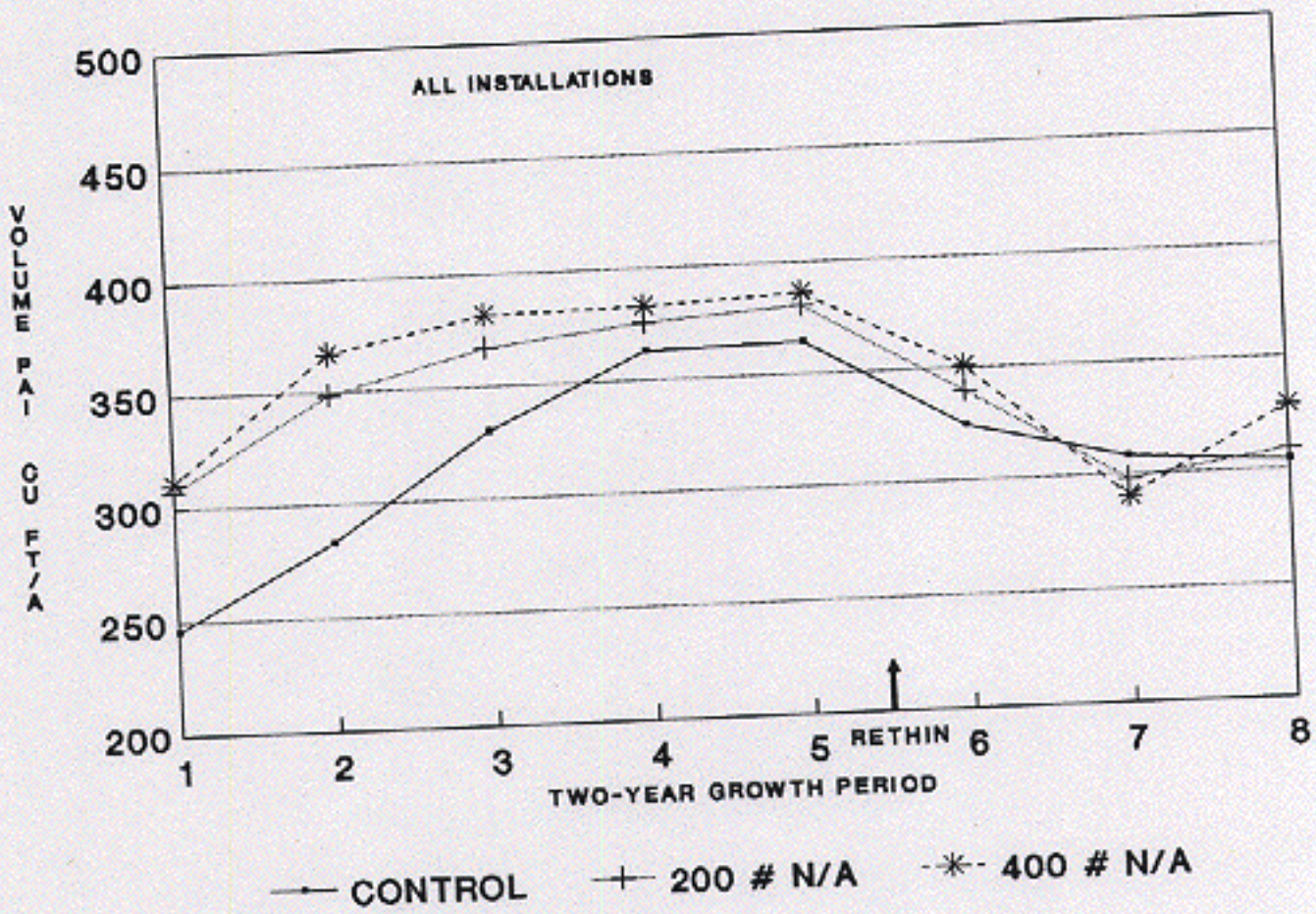
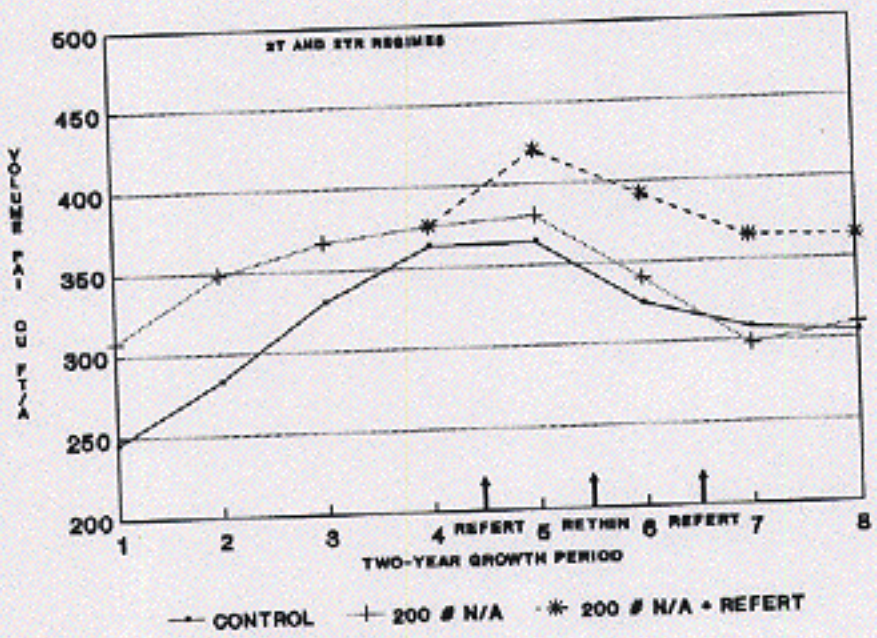
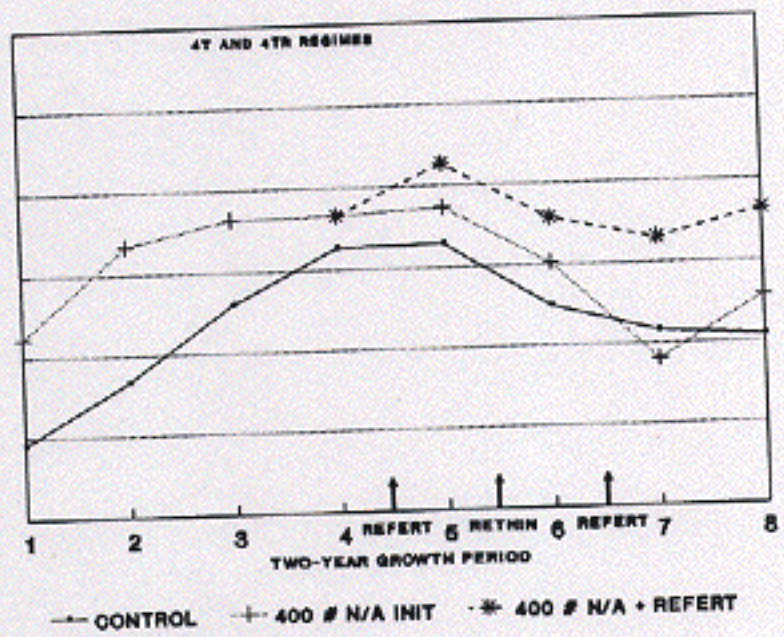
Figure 6. Gross volume PAI by 2-year growth period, for thinned Douglas-fir stands.







DISCUSSION

Growth response estimates presented here differ somewhat from those included in earlier RFNRP Reports (Peterson and Heath 1986; Opalach et al. 1987) for the first six 2-year growth periods. This is due in part to slight differences in the database used. Estimates may also have been affected by the final form of the analysis of covariance equation. Perhaps the greatest difference between this and the 1987 report, however, is that here the combined direct and indirect effects are presented, whereas only directs effects were presented at that time. Note that these changes do not cause the results and conclusions presented here to differ substantially from those found in past analyses.

Duration of response

Unthinned stands appear to respond to a single application of N fertilizer through 14 years. As reported in Peterson and Heath (1986), low volume growth response estimates for the fifth 2-year period seem to have been due to precipitation and temperature effects (U.S. Environmental Data Service 1969-1984), as the sixth period responses were even greater than those observed after four measurement intervals. This analysis indicates that volume response begins to decline in period seven becoming non-significant for the 4N treatment, and drops off to non-significant levels for the 2N treatment in period eight. Basal area growth response on these stands becomes non-significant in period six, and only the response to applications of the 2N treatment increases to a significant level in period seven.

Thinned stand responses reported to remain significant through 8 years

by Opalach et al. (1987) are confirmed here. Phase II installations were established 2 years after the Phase I installations were initially measured, therefore the same climatological effects which are thought to have impacted growth of the unthinned stands in their fifth growth period could also be responsible for the lesser growth of thinned stands in period four. Because there was no significant improvement in response after this decline, however, growth response is not as long-lasting for thinned stands as for unthinned.

Response to refertilization

Refertilization after the fourth period with 200 lbs N/A produced significant responses in both unthinned and thinned stands, regardless of the initial treatment level. The additional response on unthinned stands in the first 2 years following reapplication was comparable in magnitude to that achieved in the first 2-year period following the initial treatment, but declined in the next period. Fertilizing again after 12 years caused a similar increase in response in period seven, which declined in period eight.

The thinned stands did not respond as dramatically to the first refertilization as did the unthinned. After rethinning between periods five and six, however, both volume and basal area responses increased. After the second reapplication of N 2 years later, responses increased even more. As in the case of unthinned stands, the period eight responses were smaller than those in period seven.

Overall, retreatment responses associated with 200 lb initial treatments clearly were greater than those associated with 400 lb initial treatments. As noted in earlier RFNRP reports, this trend is opposite to that observed from the initial fertilization, and remains true for all the

retreatment management regimes through period seven (with the exception of the thinned regimes in period seven). In period eight the trend reverses itself. The suggestion that an unthinned or thinned stand's retreatment growth response may be inversely related to the amount of N fertilizer applied initially (Opalach et al. 1987) seems to hold for 2 to 4 years after reapplication. One would expect the trees treated under the 2NR (or TR) regime to be more responsive than those under the 4NR (or TR) regime since N was removed as a growth-limiting factor by applying the 4N treatment, and the effects of initial volume (or basal area) were eliminated by using the covariance model. Perhaps more important is the fact that both volume and basal area growth responses to fertilization with N as urea can be maintained at levels significantly greater than zero by retreatment applications.

CONCLUSIONS

The unthinned and thinned second-growth Douglas-fir data indicated that growth responses were significant for two fertilization management regimes which included N application at establishment, and after 8 and 12 years. There also was significant response to a delayed fertilization regime, where the initial application was not made until after the eighth growing season.

Retreatment growth response, when separated from the initial treatment response component, tends to be the larger of the two. It begins to decline in the second 2-year period after application, unlike the increased response in the second 2-year period after the initial application of fertilizer.

Unthinned and thinned stands exhibit significant growth response to application of N as urea, and continue to do so when refertilized periodically, through at least 16 years. Differences in response between plots initially treated with 200 lbs N and those treated with 400 lbs N become insignificant after the second refertilization. The possibility exists, however, that the 4NR regime would support more growth over more retreatments or longer intervals. In period eight, a tendency for response to be less on plots treated under this regime (as opposed to the 2NR regime) is reversed for basal area growth on unthinned stands. Continued analysis with 20-year growth data would be required to test this hypothesis.

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APPENDIX

CONTENTS

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Table A. Total gross (cu ft/A/yr) and relative (%) volume growth response estimates ± 1 standard error for unthinned stands, with levels of statistical significance, by 2-year growth period (min. DBH = 1.55").

Period	Response						
	2N-0N	4N-0N	0NR-0N	2NR-0N	4NR-0N	2NR-2N	4NR-4N
1	52.2±5.1 16 ± 2 p<0.001	59.1±5.2 18 ± 2 p<0.001	---	---	---	---	---
2	61.4±5.5 19 ± 2 p<0.001	75.2±5.6 23 ± 2 p<0.001	---	---	---	---	---
3	23.6±6.5 7 ± 2 p<0.001	46.6±6.7 14 ± 2 p<0.001	---	---	---	---	---
4	16.0±6.4 4 ± 2 p<0.025	33.6±6.5 9 ± 2 p<0.001	---	---	---	---	---
5	8.8±11.1 3 ± 3 p>0.250	16.3±11.5 5 ± 3 p<0.250	75.4±11.3 21 ± 3 p<0.001	65.0±11.2 18 ± 3 p<0.001	68.2±11.2 19 ± 3 p<0.001	56.2±12.5 16 ± 4 p<0.001	51.9±10.9 15 ± 3 p<0.001
6	33.8±12.9 9 ± 4 p<0.010	37.1±13.3 10 ± 4 p<0.010	87.3±13.1 24 ± 4 p<0.010	80.4±12.9 22 ± 4 p<0.001	77.0±13.0 21 ± 4 p<0.001	46.6±13.9 13 ± 4 p<0.001	39.9±13.0 11 ± 4 p<0.005
7	22.0±11.1 6 ± 3 p<0.050	28.4±11.3 8 ± 3 p<0.025	96.7±11.2 28 ± 3 p<0.001	83.0±11.3 24 ± 3 p<0.001	77.3±11.1 22 ± 3 p<0.001	61.1±12.2 18 ± 4 p<0.001	48.9±11.1 14 ± 3 p<0.001
8	9.6±11.2 3 ± 4 p<0.500	0.5±11.4 0 ± 4 p>0.500	63.3±11.3 20 ± 4 p<0.001	49.3±11.5 16 ± 4 p<0.001	52.5±11.3 17 ± 4 p<0.001	39.7±11.9 13 ± 4 p<0.001	52.1±11.0 17 ± 4 p<0.001

Treatment codes:
0N = control
0NR = 200 lbs N/A delayed
2N = 200 lbs N/A init.
4N = 400 lbs N/A init.
2NR = 200 + 2 * 200 lbs N/A refert
4NR = 400 + 2 * 200 lbs N/A refert

Table B. Total gross (sq ft/A/yr) and relative (%) basal area growth response estimates ± 1 standard error for unthinned stands, with levels of statistical significance, by 2-year growth period (min. DBH = 1.55").

Period	Response						
	2N-0N	4N-0N	0NR-0N	2NR-0N	4NR-0N	2NR-2N	4NR-4N
1	1.3±0.1 19 ± 2 p<0.001	1.5±0.1 22 ± 2 p<0.001	---	---	---	---	---
2	1.5±0.1 23 ± 2 p<0.001	1.8±0.1 28 ± 2 p<0.001	---	---	---	---	---
3	0.9±0.1 15 ± 2 p<0.001	1.4±0.1 23 ± 2 p<0.001	---	---	---	---	---
4	0.5±0.1 7 ± 1 p<0.001	0.9±0.1 13 ± 1 p<0.001	---	---	---	---	---
5	0.4±0.2 7 ± 4 p<0.010	0.6±0.2 11 ± 4 p<0.001	1.6±0.2 29 ± 4 p<0.001	1.5±0.2 27 ± 4 p<0.001	1.5±0.2 27 ± 4 p<0.001	1.0±0.2 18 ± 3 p<0.001	0.8±0.2 15 ± 3 p<0.001
6	0.2±0.2 3 ± 3 p<0.500	0.3±0.2 5 ± 3 p<0.250	1.3±0.2 22 ± 3 p<0.001	1.2±0.2 20 ± 3 p<0.001	1.0±0.2 17 ± 3 p<0.001	1.0±0.2 17 ± 3 p<0.001	0.7±0.2 12 ± 3 p<0.001
7	0.3±0.2 5 ± 4 p<0.050	0.2±0.2 4 ± 4 p<0.250	2.1±0.2 37 ± 4 p<0.001	1.5±0.2 27 ± 4 p<0.001	1.4±0.2 25 ± 4 p<0.001	1.2±0.2 21 ± 3 p<0.001	1.2±0.2 21 ± 3 p<0.001
8	0.3±0.2 7 ± 4 p<0.050	0.1±0.2 3 ± 4 p<0.500	1.4±0.2 30 ± 4 p<0.001	1.0±0.2 23 ± 4 p<0.001	1.2±0.2 26 ± 4 p<0.001	0.7±0.2 16 ± 4 p<0.001	1.0±0.2 22 ± 3 p<0.001

Treatment codes:
0N = control
0NR = 200 lbs N/A delayed
2N = 200 lbs N/A init.
4N = 400 lbs N/A init.
2NR = 200 + 2 * 200 lbs N/A refert
4NR = 400 + 2 * 200 lbs N/A refert

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Table C. Total gross (cu ft/A/yr) and relative (%) volume growth response estimates ± 1 standard error for thinned stands, with levels of statistical significance, by 2-year growth period (min. DBH = 1.55").

Period	Response						
	2T-0T	4T-0T	0TR-0T	2TR-0T	4TR-0T	2TR-2T	4TR-4T
1	61.6±5.4 25 ± 2 p<0.001	65.1±5.3 27 ± 2 p<0.001	---	---	---	---	---
2	65.5±7.3 23 ± 3 p<0.001	84.1±7.1 30 ± 3 p<0.001	---	---	---	---	---
3	37.1±7.1 11 ± 2 p<0.001	51.6±7.0 16 ± 2 p<0.001	---	---	---	---	---
4	12.4±10.0 3 ± 3 p<0.250	19.8±9.9 5 ± 3 p<0.050	---	---	---	---	---
5	16.3±13.2 4 ± 4 p<0.250	21.8±12.7 6 ± 3 p<0.100	61.8±12.4 17 ± 3 p<0.001	55.9±13.0 15 ± 4 p<0.001	49.1±13.0 13 ± 4 p<0.001	39.5±12.7 11 ± 3 p<0.005	27.4±12.5 8 ± 3 p<0.050
6	15.3±12.0 5 ± 4 p<0.250	26.3±11.8 8 ± 4 p<0.050	83.4±11.4 26 ± 4 p<0.001	67.2±11.9 21 ± 4 p<0.001	53.9±12.0 17 ± 4 p<0.001	51.8±11.4 16 ± 4 p<0.001	27.6±11.3 9 ± 3 p<0.025
7	-10.3±13.1 -3 ± 4 p>0.250	-17.7±13.2 -6 ± 4 p<0.250	85.6±12.8 28 ± 4 p<0.001	57.1±13.0 19 ± 4 p<0.001	57.0±13.2 19 ± 4 p<0.001	66.9±11.3 22 ± 4 p<0.001	64.4±11.2 21 ± 4 p<0.001
8	5.0±20.1 2 ± 7 p>0.500	24.8±20.4 8 ± 7 p<0.250	67.3±19.2 22 ± 6 p<0.005	60.3±19.3 20 ± 6 p<0.005	77.4±19.7 25 ± 6 p<0.001	55.3±20.6 18 ± 7 p<0.010	52.6±19.9 17 ± 7 p<0.010

Treatment codes:
0T = control
0TR = 200 lbs N/A delayed
2T = 200 lbs N/A init.
4T = 400 lbs N/A init.
2TR = 200 + 2 * 200 lbs N/A refert
4TR = 400 + 2 * 200 lbs N/A refert

Table D. Total gross (sq ft/A/yr) and relative (%) basal area growth response estimates ± 1 standard error for thinned stands, with levels of statistical significance, by 2-year growth period (min. DBH = 1.55").

Period	Response						
	2T-0T	4T-0T	0TR-0T	2TR-0T	4TR-0T	2TR-2T	4TR-4T
1	1.8±0.2 30 ± 3 p<0.001	2.0±0.2 33 ± 3 p<0.001	---	---	---	---	---
2	1.6±0.2 23 ± 3 p<0.001	2.2±0.2 32 ± 3 p<0.001	---	---	---	---	---
3	0.7±0.2 9 ± 3 p<0.001	1.3±0.2 17 ± 3 p<0.001	---	---	---	---	---
4	0.2±0.1 3 ± 1 p<0.250	0.4±0.1 6 ± 1 p<0.010	---	---	---	---	---
5	-0.2±0.3 -3 ± 4 p>0.500	0.1±0.2 1 ± 3 p>0.500	1.3±0.2 19 ± 3 p<0.001	1.0±0.2 14 ± 3 p<0.001	1.0±0.3 14 ± 4 p<0.001	1.2±0.2 17 ± 3 p<0.005	0.9±0.2 13 ± 3 p<0.005
6	-0.1±0.2 -1 ± 3 p>0.500	0.1±0.2 1 ± 3 p>0.500	1.5±0.2 23 ± 3 p<0.001	1.0±0.2 16 ± 3 p<0.001	0.8±0.2 12 ± 3 p<0.005	1.1±0.2 17 ± 3 p<0.001	0.7±0.2 10 ± 3 p<0.005
7	-0.3±0.3 -5 ± 5 p<0.500	-0.6±0.3 -11 ± 5 p<0.050	1.6±0.3 30 ± 5 p<0.001	1.2±0.3 22 ± 5 p<0.001	1.1±0.3 20 ± 5 p<0.001	1.4±0.2 27 ± 5 p<0.001	1.5±0.2 27 ± 5 p<0.001
8	0.0±0.3 0 ± 6 p>0.500	0.1±0.3 2 ± 6 p>0.500	1.2±0.3 25 ± 6 p<0.001	1.1±0.3 23 ± 6 p<0.001	1.1±0.3 23 ± 6 p<0.005	1.1±0.3 24 ± 7 p<0.001	1.0±0.3 21 ± 7 p<0.005

Treatment codes:
0T = control
0TR = 200 lbs N/A delayed
2T = 200 lbs N/A init.
4T = 400 lbs N/A init.
2TR = 200 + 2 * 200 lbs N/A refert
4TR = 400 + 2 * 200 lbs N/A refert