REGIONAL FOREST NUTRITION RESEARCH PROJECT

BIENNIAL REPORT

1986 - 1988

January 1989

College of Forest Resources
University of Washington
Seattle, Washington 98195

METRIC EQUIVALENTS

1 inch (in) = 2.540 centimeters (cm)

1 foot (ft) = 0.3048 meter (m)

1 square foot (ft^2) = 0.0929 square meter (m^2)

1 acre (ac or A) = 0.4047 hectare (ha)

1 cubic foot (ft^3) = 0.02832 cubic meter (m^3)

1 square foot/acre (ft^2/A) = 0.2296 square meter/hectare (m^2/ha)

1 cubic foot/acre (ft^3/A) = 0.06997 cubic meter/hectare (m^3/ha)

1 pound (lb) = 0.4535 kilogram (kg)

1 pound/acre (lb/A) = 1.12 kilograms/hectare (kg/ha)

EXECUTIVE SUMMARY

Fertilization of forest stands continues to be an important silvicultural tool in the Pacific Northwest. Nitrogen fertilization is an ongoing practice on both private and public timberlands, primarily for stands of Douglas-fir. Using regional information available on potential growth responses to fertilization, many forest management plans for western Washington, Oregon, and British Columbia include various levels and timings of fertilizer applications.

Multiple applications of fertilizer have been or will be employed by forest land managers in the region. Volume and basal area growth responses to such treatment regimes were found to be significant on both unthinned and thinned Douglas-fir stands, with similar responses in the first 2-4 years after the initial fertilization and after fertilizer reapplication. Analysis of long-term response to a single application of N on thinned stands indicated that growth of treated stands is still 14% greater than untreated stand growth after 12 years. The difference in growth is mostly due to altered stocking brought on by increased growth in previous growing seasons (indirect effect) as opposed to the direct effect of improved nutrition. Reapplication of fertilizer is, therefore, one way to maximize the potential response of a stand.

Part of an effort to improve selection criteria for Douglas-fir fertilization prescriptions included an analysis of the response of young stands to treatment with 200 lbs N per acre. Relative volume growth for unthinned and thinned plots was 16% and 20% greater, respectively, after fertilization than for control plots. Using response surface methodology, stands of intermediate basal area were shown to produce the greatest growth response, although response was lower for stands with higher site index. A study of forest floor and soil influence was also conducted; forest floor C/N ratio appeared as the dominant variable in explaining response variation among sites. Other site specific growth analyses are currently underway.

Fertilization trials on species other than Douglas-fir have been initiated in the past two years. Results are summarized for 6-year growth response of four installations in precommercially thinned western hemlock stands and 8-year response of three western larch stands. Initial results from sixteen screening trials established in young stands of noble fir and Pacific silver fir are reviewed; first-year foliar N concentration and 2-year basal area growth increased significantly for fertilized trees.

This Biennial Report includes summaries and abstracts of RFNRP projects accomplished during the past two years. Also included is a compilation of RFNRP reports and presentations over the past 20 years. More detailed information on the results presented in this report is available in the references listed.

CONTENTS

RESEARCH SUMMARIES AND PROGRESS REPORTS

ABSTRACTS

FOREWORD

S. P. Gessel

The passage of forty years brings a Douglas-fir tree into the prime of its life. Forty years represents almost the total productive years of a professional career for an individual such as this writer. Therefore, this report, marking 20 years of operation of the Regional Forest Nutrition Research Project, provides an opportunity for reflection and an assessment of where we have been and where we are going. This report contains many interesting articles and reviews of RFNRP developments over the past two years. I will attempt to depict from a broader viewpoint the occurrences of the past and the climate for the future.

Productivity of forest land, at one time a difficult concept for foresters, is now vigorously discussed by people in all walks of life. Environmentalists, however the category is defined, use the word in a different sense than foresters, but often to condemn the present land managers. This condemnation is based on the view that the present custodians of the land are rapidly destroying its productivity, or have already. As a result, many organizations including the U.S. Forest Service have published goals to maintain and enhance productivity.

Most of the heated debates and broad statements are not endowed with many facts, but are blessed with many opinions. For instance, there is very little factual information or data to make comparisons of productivity over time periods, even if we agree on using wood production as a quantitative expression of forest productivity. When the definition of productivity is generalized to include all elements of the ecosystem, an objective, quantitative base is lost.

Forty years ago, productivity of forest land was an even more elusive concept. Factors which influence productivity of trees under forest conditions were very poorly understood. Research emphasis on forest tree nutrition at the University of Washington, beginning in 1948, developed the general awareness that forest trees in the Pacific Northwest were as susceptible to nutrient deficiencies as agricultural crops. Man's potential influence on this aspect of productivity was explored, resulting in programs to supply essential elements in low supply to forest lands.

Since the early years, those programs have taken many forms, but on a large scale are represented by aerial application of nitrogen to forest areas. Environmentalists first welcomed these programs as a means to concentrate timber production on fewer areas and leave the rest for other purposes. Public opinion has evolved, however, with one extreme perhaps best expressed in the November 1988 letter to the Seattle Times headlined "Forests Can't be Improved; They are Perfect as They Are."

Against this backdrop of changing public philosophy, the Regional Forest Nutrition Research Project has worked for 20 years refining our ability to quantify forest productivity, improving our abilities to recognize and define elemental deficiencies in forest trees and to correct them when they do exist. Work on improvement in these areas has been directed to ecological as well as economic components of forest fertilization treatments.

When we look beyond the Pacific Northwest, we realize that the rest of the forestry world has also been very busy in the nutritional and fertilization aspect of forestry. Countries which depend on plantations of exotic tree species have found that elemental deficiencies limit the ability of trees to develop their size potential over large areas of planted forests. Numerous examples in Australia, New Zealand, Chile, Brazil, and large areas in Africa could be cited. Large areas of forest land throughout Europe also have nutritional deficiencies; however, some aspects of this are now being confused in the acid rain debate.

The next question pertains to the future of programs such as the RFNRP in light of present arguments and debate. This program was originally established to answer some simple questions in a restricted time period. We have answered the original questions and many more in twenty years; in fact, much more has been accomplished than was ever expected. Valid research questions remain, however, and the answers will make the task of managing forests more rewarding and the net result more valuable. Acquisition of baseline information on aspects of forest productivity is of great importance. We must retain the base we now have and expand it in order to deal effectively with the management issues which will face us in the future.

INTRODUCTION

The Regional Forest Nutrition Research Project will embark on its twentieth year of operation in 1989, a milestone that merits reflection on the accomplishments of the program. In 1969, fertilization was a practice in the earliest stages of acceptance in North America as a potentially viable means to enhance forest growth. Forest fertilization research programs had been underway for some time in Europe, and a few researchers in the Pacific Northwest (PNW) and the southeastern U.S. had explored fertilization for a number of years. Because of the promising results from this work and the need for more information to carry out cost-effective fertilization programs, organizations involved in forest management and research came together to form cooperative programs in the Douglas-fir and southern pine regions of the country. The quality of these research programs and their stability through time have produced results that form the basis for operational fertilization programs in two important forest regions. More recently established research programs have emulated these cooperatives in other forest regions.

The Regional Forest Nutrition Research Project continues to be an internationally recognized leader in forest nutrition research. Operational programs in western Washington and Oregon, based on results from the RFNRP and related PNW research projects, have treated about 3,000,000 acres of timberland with one or more applications of fertilizer. About 150,000 to 200,000 acres are fertilized annually in the region; at the time the RFNRP was initiated, a cumulative total of less than 50,000 acres had been fertilized in the PNW.

Because of the broad base of support for the RFNRP, continuity and quality control in data collection and management have been provided in a stable, focused effort. Research direction provided by cooperating organizations has ensured the program is responsive to changing needs, reflecting both the increases in the information base and the changes in the character of commercial timberlands. The cooperative was initiated with the primary objective of providing forest managers with information on growth and response to N fertilization of second-growth stands of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). RFNRP results have documented growth increases for fertilized Douglas-fir stands, and Project work has continued on a number of consequent objectives. PNW forest management emphasis is shifting from naturally-regenerated second-growth stands to plantations of the third forest, and cooperative emphasis has concomitantly evolved with efforts to improve site-specific response estimates and evaluate responses in young managed stands.

Measurement, maintenance, and treatments continued on the extensive base of RFNRP field trials during 1986-1988. As of June 1988, there were 135 active field installations distributed throughout western Oregon and Washington. Currently remeasured installations include a subset of the oldest plots, now approaching the twentieth growing seasons since initial treatment, as well as new single-tree screening trials in higher elevation stands. Remeasurement and treatment intervals have been extended on many trials. The substantial data base generated by the long-term measurements has been continually updated and edited.

The focus of current data analysis is guided by objectives set forth in the current 5-year plan. Exploitation of the data base is directed toward monitoring and evaluating long-term studies and development of site-specific response information. Future analyses will increasingly recognize effects of management regimes on stand growth and development, demonstrating the long-term nature of available growth data. Fieldwork and analyses will also reflect the partnership with the Stand Management Cooperative in evaluating effects of interacting treatments. Although most RFNRP research centers on Douglas-fir responses, this report also highlights analyses for western hemlock, western larch, noble fir, and Pacific silver fir.

As in previous biennial reports, summaries are presented for research completed in the past two years, and progress is reported for several ongoing projects. Results from Project studies are available to cooperators before general publication, through presentations and an internal report series. RFNRP Reports now number eleven, with more in preparation. Also included in this Biennial Report is a listing of RFNRP publications and presentations from 1969 through 1988. The list encompasses publications and reports dealing with forest fertilization by Project faculty, staff, and graduate students, and those resulting from research by collaborating scientists utilizing RFNRP installations and data. The role of RFNRP collaborators is clearly demonstrated here -- the cooperative provides a synergistic link to other research projects through shared field plots and data. An excellent example is the recently completed analysis of thinning and fertilization in southwestern Oregon, combining RFNRP measurement data with other plot data from the subregion. Other research summarized in this report and tallied in the literature list demonstrates the breadth of forest fertilization topics covered by the RFNRP.

Operational fertilization practice in the Pacific Northwest has proceeded ahead of research results in terms of information available for multiple fertilizer applications, targeting the most responsive stands, fertilization responses in plantations established at wide spacings, and other questions. Principal research direction for the future continues to be improvement of site specific response estimates and predictions, and providing information on growth and yield of stands where several interacting treatments have been applied. In particular, better information is needed on the quantity and quality of wood produced by management regimes combining stand density control with fertilization; similarly, information on interactions with other intensive management practices needs definition. The significant role of fertilization in PNW forests will continue, and necessitating further research and development to provide accurate prediction of responses and to enhance the forest manager's ability to increase effectiveness of fertilizer investments.

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

K. Stegemoeller and H. N. Chappell

Few studies have addressed the effects of multiple N fertilizer applications on Douglas-fir. The Regional Forest Nutrition Research Project has completed two reports which include results of studies on these effects in unthinned and thinned Douglas-fir stands (Peterson and Heath 1986; Opalach, Heath and Chappell 1987). Another 4 years of data have been collected on these RFNRP installations since those reports. The current study updates results and summarizes growth response findings for RFNRP Phase I and Phase II second-growth Douglas-fir installations (unthinned and thinned, respectively). Analyses of basal area and volume growth responses to single and multiple applications of N fertilizer (as management regimes) are included.

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.

Effects of N fertilizer on total gross basal area and volume PAIs were determined for each 2-year period, with response defined as in Peterson and Heath (1986):

$$\text{growth response to fertilization regime} = \text{fertilized stand mean growth rate} + \text{unfertilized stand mean growth rate}$$

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.

Table 1 outlines the average stand conditions of the Phase I and Phase II installations at the time of establishment. Figures 1 and 2 show the total gross volume and basal area growth responses ±1 standard error by 2-year growth period for these stands. Treatment codes used in these figures reflect the fact that multiple applications of fertilizer have resulted in treatment combinations which are now considered management regimes. The codes are:

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.

Table 1. Approximate average stand conditions at 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† (ft^2/A)	200	120
Volume† (ft^3/A)	6450	3790

† all stems ≥ 1.55 inches DBH

LITERATURE CITED

Opalach, D., L.S. Heath, and H.N. Chappell. 1987. Growth response to single and multiple nitrogen fertilizer applications in thinned Douglas-fir stands. RFNRP Report No. 8 (unpublished). College of Forest Resources, Univ. of Washington, Seattle. 23 p.

Peterson, C.E., and L.S. Heath. 1986. Volume growth and volume growth response after fertilization of unthinned Douglas-fir stands. RFNRP Report No. 6 (unpublished). College of Forest Resources, University of Washington, Seattle. 22 p.

* *Summarized from Stegemoeller and Chappell (1988).*

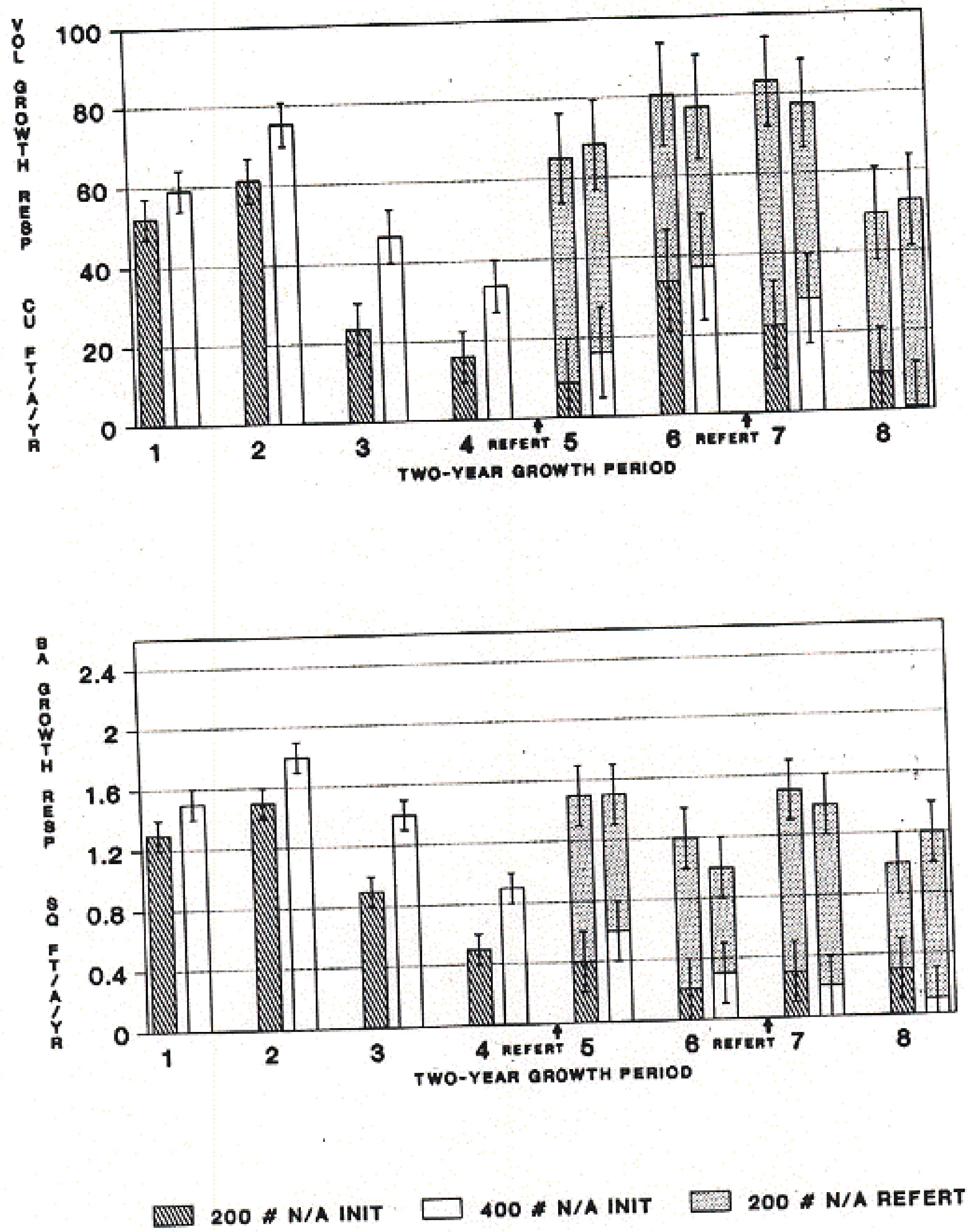

Figure 1. Total gross volume and basal area growth responses ± 1 standard error by 2-year growth period, for unthinned Douglas-fir stands.

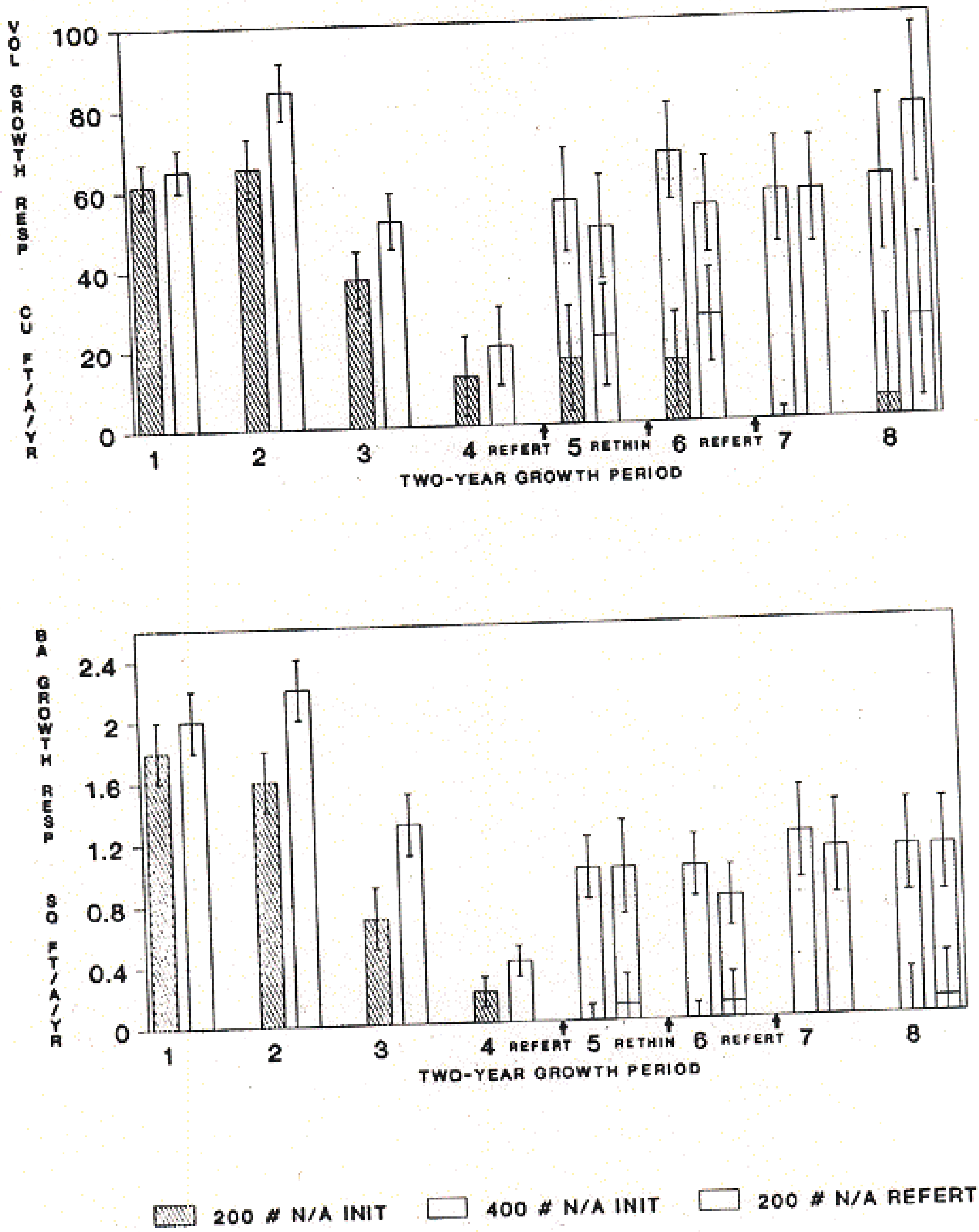

Figure 2. Total gross volume and basal area growth responses ± 1 standard error by 2-year growth period, for thinned Douglas-fir stands.

VOLUME GROWTH RESPONSE TO FERTILIZATION IN YOUNG DOUGLAS-FIR STANDS *

L. Heath

Volume growth response to one application of 200 lbs nitrogen per acre in unthinned and thinned Douglas-fir stands of breast height age 25 years or less is estimated for one 6-year growth period. Regional mean fertilizer response is 50.3 ± 7.8 $ft^3/A/yr$ in unthinned stands and 44.3 ± 4.5 $ft^3/A/yr$ in thinned stands. These translate into relative growth responses of 16% and 20%, respectively.

Response surface methodology is used to examine trends of volume growth response across basal area and site index. Response behavior is illustrated using contour diagrams (Figures 3 and 4). Response trends are similar for unthinned and thinned stands. Response is affected by an interaction of basal area and site index. It is greatest at intermediate basal areas, 50-160 ft^2/A in unthinned stands, and 40-110 ft^2/A in thinned stands. Site index has an increasingly inverse effect as basal area increases. Response varies little over site index in regions of low basal area, decreases moderately as site index increases in the intermediate region, and decreases fairly rapidly in the high basal area region.

Response trends across basal area and Steinbrenner's soil-site index are also examined. The trends are not the same for unthinned and thinned stands, and they do not conform to existing theories of response. Because the RFNRP soil variables were not collected for the purpose of using Steinbrenner's equations to predict soil-site index, a few variables are missing. The predicted soil-site indices tend to be of average value. It is concluded that soil-site index as computed in this paper is not a good substitute for site index.

In the past, response trends have been overlooked because they were not statistically significant in the standard RFNRP statistical analysis. Response surfaces provide for a solid exploration of underlying trends which can then be incorporated into statistical models.

* *Summarized from Heath (1988).*

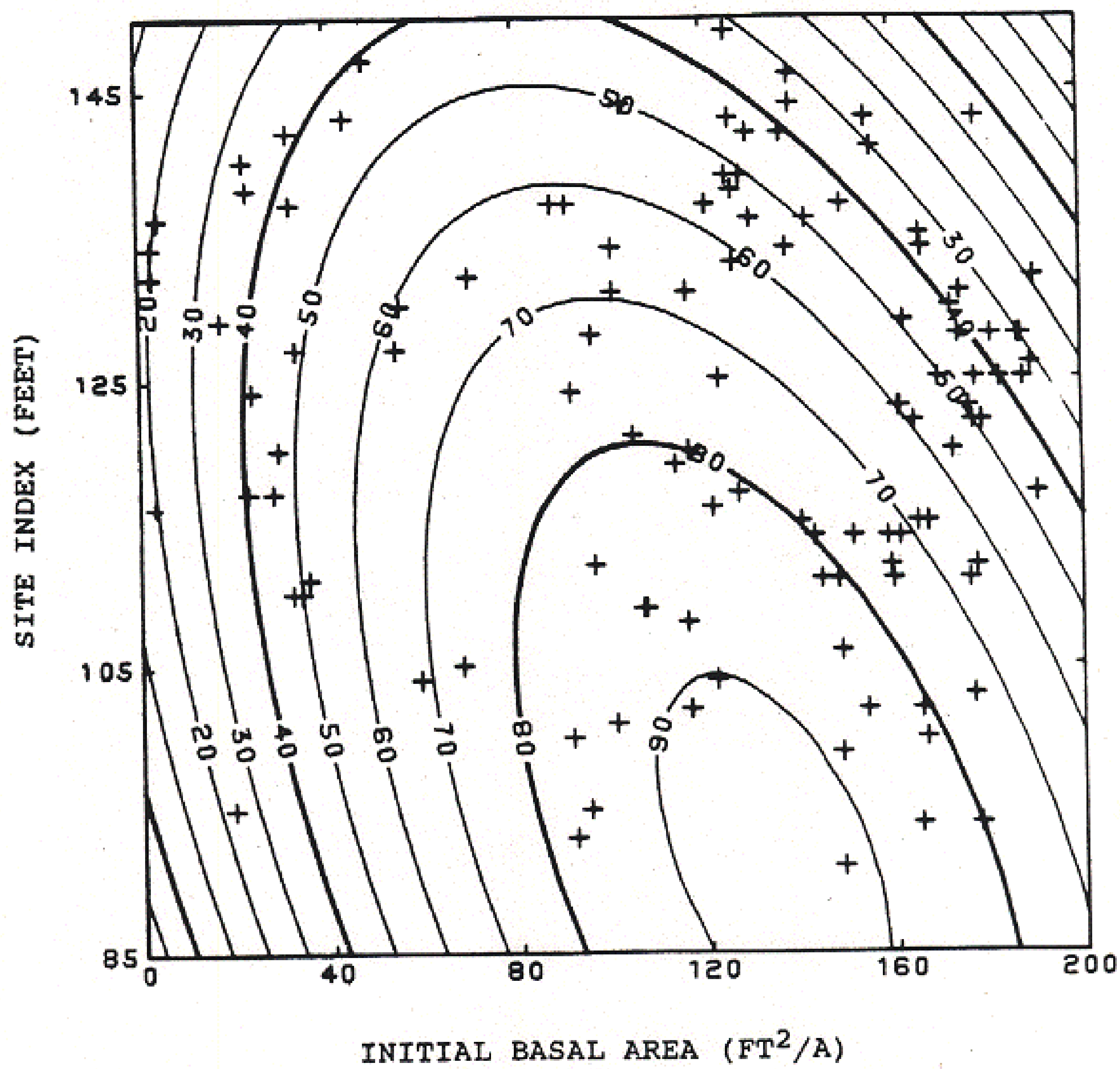

Figure 3. A contour diagram of estimated response (ft^3/A/yr) in gross CVTS volume PAI over a six-year period in unthinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and site index. The plus symbol (+) represents a data point (not a response value) in the basal area-site index plane.

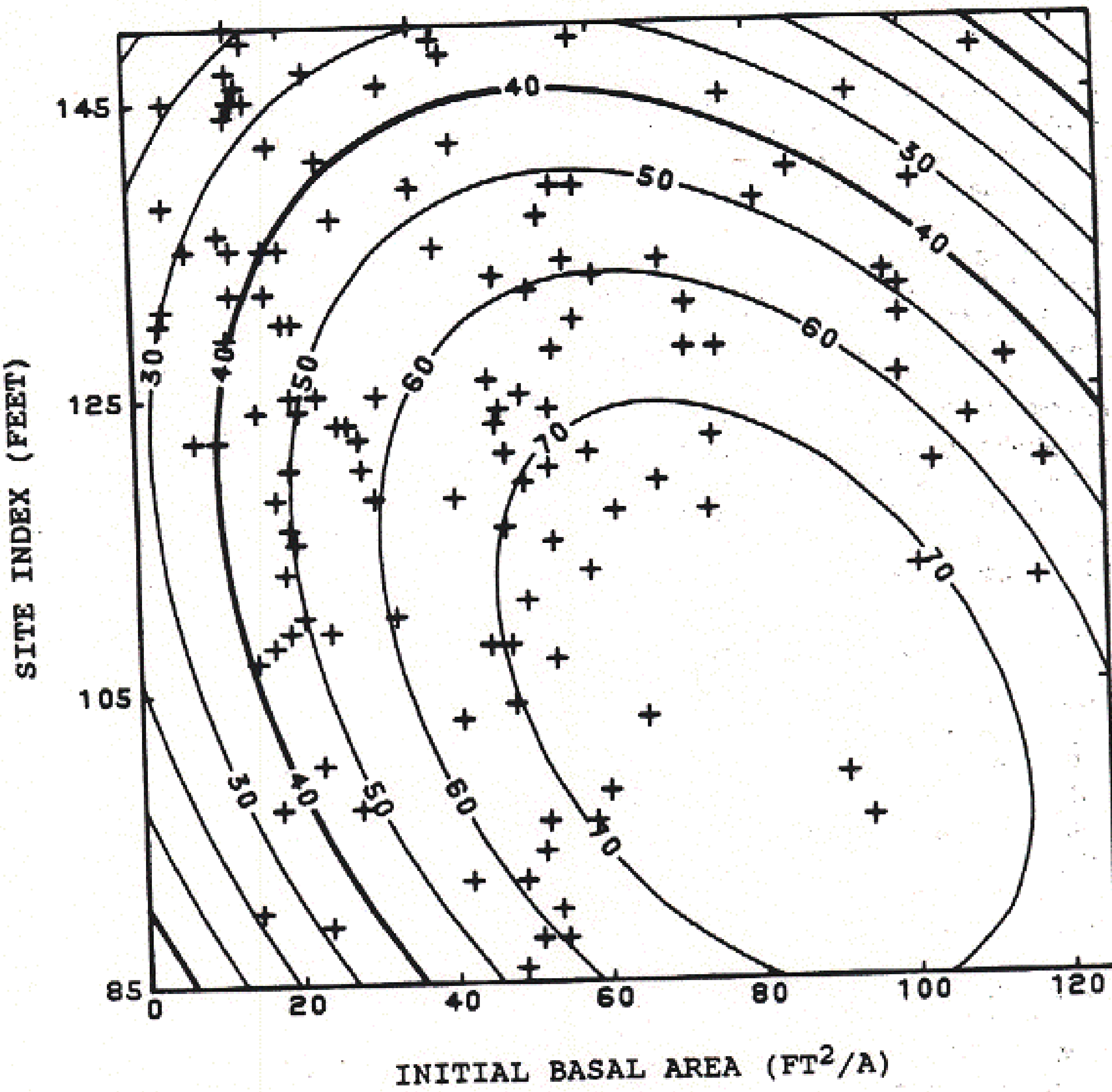

Figure 4. A contour diagram of estimated response ($ft^3/A/yr$) in gross CVTS volume PAI over a six-year period in thinned Douglas-fir stands fertilized with 200 lbs N/A by basal area and site index. The plus symbol (+) represents a data point (not a response value) in the basal area-site index plane.

EVALUATION OF LONG-TERM FERTILIZER RESPONSE *

D. Opalach and L. Heath

This paper describes a method that can be used to evaluate long-term fertilizer response. Emphasis is placed on how response behaves over time and the partitioning of response into direct and indirect effects. The direct effect is that part of the response due to improved nutrition; the indirect effect is the remaining portion of the response due to altered stocking brought on by fertilizer in previous growing seasons. Recent publications on long-term N fertilizer response in Douglas-fir have dealt with direct effects (Peterson *et al.* 1986), combined effect of direct and indirect components (Barclay and Brix 1985), and discussion of both (Miller and Tarrant 1983).

Remeasurement data from 34 research installations established in thinned second-growth Douglas-fir stands are analyzed and results presented to supplement the discussion. Analysis of covariance is used to estimate response and direct effect for each growth period. Two separate analyses are required for each period (except the first): one to determine response and one to determine direct effect. The general model for volume PAI or basal area PAI is

$$Y_{ijk} = \mu + T_i + B_j + \beta(S_{ijk} - S...) + \epsilon_{ijk}$$

where Y_{ijk} = PAI of replicate k, installation j, treatment i
- μ = mean PAI
- T_i = main effect of treatment i
- B_j = block effect of installation j
- β = regression coefficient
- S_{ijk} = initial stocking or current stocking covariate
- $S...$ = mean stocking
- ϵ_{ijk} = error

The covariate S_{ijk} plays an important role in the estimation of treatment effects. If the covariate is initial stocking, then T_i is the response to treatment i. This covariate is used to adjust treatment effects for differences in initial stocking that existed at the time of fertilization. If the covariate is current stocking, then T_i is the direct effect of treatment i. In addition to adjusting for initial stocking differences, this covariate adjusts treatment effects for differences in current stocking brought on by fertilizer in previous growing seasons.

Estimates of responses and direct effects for each growth period are plotted relative to mean control volume PAI to reveal the response pattern (Figure 5). Results for these data indicate that stands fertilized with 200 lbs N per acre continue to grow faster (14%) than control stands 12 years after fertilization. At this time, the increase in growth is mostly due to altered stocking brought on by the fertilizer in previous growing seasons (indirect effect). Very little of the response 12 years after fertilization is due to the improved nutritional status of these stands (direct effect).

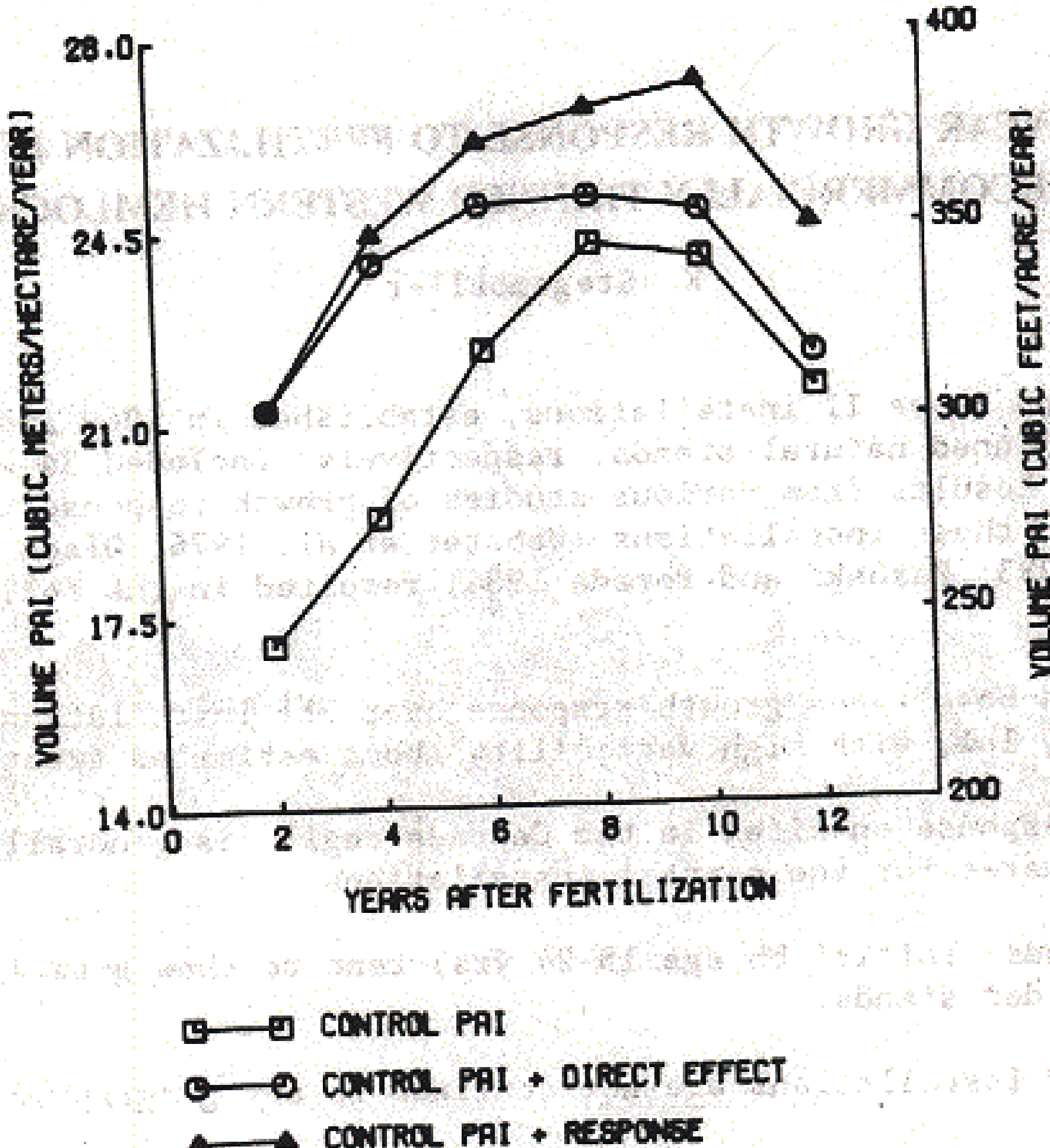

Figure 5. Response pattern for second-growth thinned Douglas-fir stands. Although the direct effect is no longer significant ($p > 0.10$) six years after fertilization, the response is still significant ($p < 0.01$) 12 years after fertilization.

LITERATURE CITED

Barclay, H. J., and H. Brix. 1985. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 12-year growth response. Canadian Forestry Service, Pacific Forestry Centre, Information Report BC-X-271.

Miller, R. E., and R. F. Tarrant. 1983. Long-term growth response of Douglas-fir to ammonium nitrate fertilizer. Forest Science 29:127-137.

Peterson, C.E., S.R. Webster, P.R. Barker, and R.E. Miller. 1986. Using nitrogen fertilizer in management of coast Douglas-fir: II. Future informational needs. p. 304-309 *In*: C.D. Oliver et al, eds., Douglas-fir: Stand management for the future. Proc. Sympos. held June 18-20, 1985, Seattle. Inst Forest Resources Contrib. No. 55. University of Washington, Seattle.

* *Summarized from Opalach and Heath (1988).*

6-YEAR GROWTH RESPONSE TO FERTILIZATION IN YOUNG PRECOMMERCIALLY THINNED WESTERN HEMLOCK STANDS

K. Stegemoeller

RFNRP Phase I and Phase II installations, established in 1969 and 1971 in unthinned and thinned natural stands, respectively, included 34 western hemlock sites. Results from various studies of growth response to N fertilization on these installations (Webster *et al*. 1976; Olson *et al*. 1980; Radwan *et al*. 1983; Zasoski and Porada 1984) resulted in the following general conclusions:

1. Volume and basal area growth response over all installations is relatively low, with high variability about estimated treatment means.

2. Average response on sites in the Cascade region is generally greater than estimates for the coastal installations.

3. Young stands (initial bh age 15-24 yrs) tend to show greater response than do older stands.

4. Responding installations are not confined to any geographic location.

Emphasis in recent years has switched from growth response analysis of older stands to that of young stands which have indicated greater potential for positive response. Therefore, an analysis of growth response of young, precommercially thinned (RFNRP Phase IV) western hemlock installations was undertaken.

Data for the analysis of 6-year growth response of western hemlock to N fertilization consist of measurements from four experimental installations in western Washington, each with six plots (Table 2). Three of the six plots had 200 lbs N/A applied as urea; the other three were left untreated. One of the four installations has an additional six plots included for evaluation of growth response due to application of phosphorous (P) alone and in addition to N. Three of these six plots were treated with 200 lbs P/A as dicalcium phosphate, the other three with 100 lbs N/A and 200 lbs P/A. This installation and one of the others are considered "coastal" in comparison with the other two sites, located on the west slope of the Cascades. All four installations had been precommercially thinned to 300 stems per acre, and initial average breast height age at all sites was less than 25 years. Site productivity is believed to be similar at all four locations, though the site index values available are questionable due to young stand ages.

Table 2. Initial conditions of young, precommercially thinned (RFNRP Phase IV) western hemlock installations.

	Cascades		Coast		Overall Average
	234	236	253	263	
B.H. Age	7.0	23.3	14.2	9.2	13.5
Stems/acre	290.0	300.0	300.0	295.0	296.3
Site index	115.0	115.0	115.0	105.0	112.5
Basal Area	15.4	59.3	33.4	20.6	32.2
Volume	166.2	882.0	478.7	234.8	440.4

where
- Site index - feet, base age 50 years (Wiley 1978)
- Basal Area - ft^2/A, stems > 1.55 in. dbh
- Volume - CVTS, ft^3/A, stems > 1.55 in. dbh

OBJECTIVES AND ANALYSIS PLAN

The primary objectives of this analysis were to determine the gross volume periodic annual increment (PAI) response to N-fertilization in precommercially thinned, young western hemlock stands for one, 6-year growth period, and to draw conclusions and make recommendations as to the future status of these installations. Other objectives to be accomplished by this analysis included estimation of basal area (BA) growth response to N application, comparison of response between coastal and Cascade sites, and investigation of effects of P fertilization, both with and without concurrent N application, on growth responses.

The general model used to estimate regional growth response is similar to that used in previous RFNRP Douglas-fir stand analyses (Heath 1988); area and installation were used as blocking factors to examine the effect of geographic location:

$$Y_{ijk} = \mu + T_i + B_j + \beta(X_{ijk} - X_{...}) + \epsilon_{ijk}$$

where
- Y_{ijk} - volume or BA PAI of plot k, area or installation j, treatment i
- μ - mean volume PAI
- T_i - main effect of treatment i
- B_j - block effect of area or installation j
- β - regression coefficient
- X_{ijk} - initial volume or BA
- $X_{...}$ - mean volume or BA across all plots, areas or installations, and treatments
- ϵ_{ijk} - error

The P fertilization plots were established at one of the coastal installations to examine the hypothesis that lower levels of P on coastal sites (relative to the Cascades) might contribute to reduced growth responses to N fertilization (Gill 1981; Radwan *et al.* 1983; Radwan and Shumway 1983; Zasoski and Porada 1985). Growth estimates were determined independently for this installation, to note if P application alone had any effect on growth rate, and if the N + P treatment interaction had any further effect.

RESULTS

The regional estimate of volume growth response to 200 lbs N/A applied to these sites is 29.8 ± 13.4 ft^3/A/yr, a relative response of 15% ($p=.04$, $R^2=.61$). Inclusion of the area classification variable to differentiate between coastal and Cascade sites did not affect the R^2 value. The significance of the area term overwhelmed the treatment differences so that response to fertilization treatment was no longer significant. Estimates were, therefore, calculated by area so that response due to treatment would not be confounded by geographic differences. P-values for these showed that response was not significant (at $p=.10$) for either Cascade or coastal sites. Installation 236 has the greatest response and is the most influential factor in the regional model's significance. Variability between the two Cascade installations and within coastal sites is great. These findings corroborate those from earlier western hemlock growth response studies: high variability across regions and installations exists, and treatment response is somewhat greater in the Cascades. These four installations do not provide conclusive evidence of regional hemlock volume growth response to N fertilization.

Gross BA growth response analysis showed the same trends. The regional model estimated significant growth response to 200 lbs N/A, at 1.9 ± .6 ft^2/A/yr, or 19% relative response ($p=.01$, $R^2=.60$). Examination of Tables 3 and 4 suggests that installation 236 is, again, primarily responsible for the significant response to treatment.

Table 3. Adjusted total gross volume (CVTS) growth and response estimates (± 1 s.e.) of young, pre-commercially thinned western hemlock stands for one 6-year growth period, with relative response and levels of statistical significance, by installation and by area.

Installation	PAI	Volume growth response		
	----- ft^3/A/yr	-----	(percent)	
<u>Cascades</u>				
234	198.0	-7.6 ± 16.7	(-4 ± 8)	p = .68
236	205.9	68.7 ± 9.4	(40 ± 6)	p = .01
area avg.		36.1 ± 22.0	(19 ± 12)	p = .15
<u>Coastal</u>				
263	265.2	30.9 ± 35.8	(12 ± 14)	p = .45
253	187.7	2.7 ± 23.3	(1 ± 13)	p = .92
area avg.		16.5 ± 35.8	(8 ± 27)	p = .79

Table 4. Adjusted total gross basal area growth and response estimates (± 1 s.e.) of young, pre-commercially thinned western hemlock stands for one 6-year growth period, with relative response and levels of statistical significance, by installation and by area.

Installation	PAI	BA growth response		
	----- ft²/A/yr -----		(percent)	
<u>Cascades</u>				
234	11.0	.1 ± 1.0	(1 ± 9)	p = .92
236	9.2	4.1 ± 0.2	(56 ± 3)	p = .00
area avg.		1.7 ± 1.1	(19 ± 12)	p = .16
<u>Coast</u>				
253	12.3	.9 ± 1.2	(9 ± 12)	p = .50
263	10.5	1.3 ± 1.7	(11 ± 14)	p = .52
area avg.		2.5 ± 3.6	(23 ± 32)	p = .50

Analysis of P and N+P data from installation 253 resulted in no significantly different ($p=.10$) mean gross volume increment (Table 5). The overall model was significant ($p=.04$) and had an $R^2 = .72$, however, the covariate of initial volume was the only factor that explained a significant portion of response variability ($p=.02$). Conclusions concerning western hemlock growth response to P and N+P applications cannot be reached based on one installation; information gained from these plots must be considered tentative, though adding to our western hemlock knowledge base.

Table 5. Gross volume (CVTS) growth PAI estimates adjusted for initial volume by treatment, for installation 253, for one 6-year growth period.

Treatment	Volume PAI
	(ft³/A/yr)
ON	269.9
2N	306.2
OP	271.9
2P	289.3

where
ON = no fertilizer applied
2N = 200 lbs N/A as urea
OP = 200 lbs P/A as dicalcium phosphate
2P = 100 lbs N/A + 200 lbs P/A

CONCLUSIONS

In the past it has been unclear whether N fertilization of western hemlock stands is truly effective, and whether other factors are influencing the growth response of this species (e.g. P deficiency). This analysis focused on the first of these questions with a look at some possible explanations for the second. Although there was some positive growth response at these installations, the variability between and within installations does not allow the effectiveness of N fertilization on western hemlock to be judged any more clearly than in the past. Also, the effects of P application cannot be established from analysis of installation 253. Therefore, maintenance of these installations appears unwarranted, particularly on a 2-year remeasurement schedule. If determination of western hemlock growth response to N fertilization is still of interest, a remeasurement in four years could provide data for perhaps a more conclusive analysis.

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GROWTH RESPONSE TO NITROGEN FERTILIZATION AFTER EIGHT YEARS FOR THREE WESTERN LARCH STANDS IN NORTHEASTERN WASHINGTON

H. N. Chappell and D. Opalach

In 1978 the RFNRP established three forest fertilization field trials in mixed conifer stands dominated by western larch (*Larix occidentalis* Nutt.) in northeastern Washington. The objective of the study was to evaluate stand growth after nitrogen fertilization for selected soils on the Colville National Forest.

Installations for this trial were established in uniform, unthinned natural stands of western larch (larch > 80% SBA). Each installation comprised six 0.2 acre plots, with two plots left as untreated controls, two plots fertilized with 200 lbs N/A, and two fertilized with 400 lbs N/A. Treatments were assigned randomly and urea fertilizer was uniformly broadcast by hand in treated plots and surrounding buffers. Standard RFNRP measurement procedures were followed with a 2-year remeasurement interval.

Initial stand conditions (1978) were:

	Installation		
	223	224	225
Mean b.h. age (years)	47	46	50
Site index (50 yr basis, ft)	60	74	51
Stand density (stems/A)	1320	167	204
Basal area (ft^2/A)	176	91	56
Volume (CVTS, ft^3/A)	4200	2670	1210
Mean diameter (in.)	4.9	10.0	7.1

GROWTH RESPONSE TO FERTILIZATION

Response for this analysis is defined as

$$\text{Response} = \text{mean growth rate of fertilized plots} - \text{mean growth rate of control plots}$$

After eight years, gross basal area growth response on the three installations ranged from 0.5 to 1.7 ft^2/A/yr, and gross volume growth response ranged from 22 to 67 ft^3/A/yr (Table 6). Relative response estimates are large for all installations when compared to relative responses for Douglas-fir stands in western Washington. Responses to the 200 and 400 lbs N/A application rates were similar. Trends in 2-year periodic annual increments indicate that the fertilizer effect is diminishing at each installation, and absolute differences in PAI are small after eight years.

Mortality appeared to be related to treatment in installation 223, with slightly greater mortality in fertilized plots. Inspection of individual tree measurements revealed that mortality was confined to the smallest diameter classes in all installations.

Table 6. Gross basal area response and gross volume response to N fertilizer for three western larch installations in NE Washington. Numbers in parentheses express response relative to growth in control plots.

Response	Installation 223	Installation 224	Installation 225
Basal area (ft^2/A/year)			
200 lbs N/A	1.7 (57%)	1.1 (92%)	0.6 (24%)
400 lbs N/A	0.7 (27%)	0.5 (42%)	1.2 (47%)
Volume (CVTS, ft^3/A/year)			
200 lbs N/A	67 (50%)	48.5 (67%)	20.2 (23%)
400 lbs N/A	39 (29%)	32.5 (45%)	32.5 (38%)

GROWTH RESPONSE FOUR YEARS AFTER FERTILIZATION WITH UREA AND TRIAMINOTRIAZINE-UREA FERTILIZERS FOR THREE DOUGLAS-FIR STANDS IN WESTERN WASHINGTON AND OREGON

K. Stegemoeller

Nitrogen fertilization is a well-demonstrated means to increase growth of coast Douglas-fir stands in the Pacific Northwest. Results from the Regional Forest Nutrition Research Project and other field trials have shown that 200 lbs N/A applied as urea is a silviculturally and economically sound practice for increasing growth in Douglas-fir stands over a wide range of site and stand conditions.

Urea (46% N) has been the preferred N source for PNW fertilization projects because of its high N content and low susceptibility to leaching losses. Nitrogen loss due to NH_3 volatilization may occur after urea fertilization under warm, dry conditions, and N immobilization in forest soils is a factor for any N fertilizer application. Slow release N fertilizers may increase fertilizer use efficiency by mitigating strong immobilization of soluble N in forest soils, and by limiting volatile N losses. Growth responses equal to or greater than response from urea application using a lower rate of N from a slow release source may be possible. A study to test the effects of slow release N fertilizer application on growth response in young Douglas-fir stands was undertaken in 1984 by the RFNRP. Triaminotriazine (2,4,6-triamino 1,3,5-triazine; 66% N), a slow release N source, in mixture with urea was provided by MCI AgSystems (MCI 55-0-0, a 50:50 combination of triamino-triazine and urea) and was tested against N applied as urea.

Objectives of this study included comparisons between applications of MCI fertilizer and urea for (1) basal area growth response, (2) volume growth response, and (3) response duration, for each measurement interval and for the entire period.

Three installations were established in 1984 for use in achieving these goals. Standard RFNRP methods for plot establishment, measurement and treatment were followed. Treatments applied included:

N source	Application rate	Treatment code
	lbs N/acre	
control	0	C
urea	100	1N
urea	200	2N
MCI	100	1M
MCI	150	1.5M
MCI	200	2M
MCI + urea	100+100	N+M

All treatments were not applied at each site due to limited area available to install 5 replicates of each treatment.

ANALYSIS AND RESULTS

The unbalanced nature of the experimental design limited the scope of the overall analysis to include only those treatments common to all installations (control, 2N, and 1M). ANCOVA (analysis of covariance) was used to obtain BA and volume growth estimates for these treatments over the combined installations using the general model:

$$Y_{ijk} = \mu + T_i + B_j + \beta(X_{ijk} - X_{...}) + \epsilon_{ijk}$$

where Y_{ijk} = BA or volume PAI of replicate k, installation j, treatment i,
μ = mean BA or volume PAI,
T_i = main effect of treatment i,
B_j = block effect of installation j,
β = regression coefficient,
X_{ijk} = initial BA or volume, and
$X_{...}$ = mean BA or volume over all replicates, installations, and treatments
ϵ_{ijk} = error

Each site was also analyzed separately using this model without the installation blocking factor.

Average untreated gross total basal area and volume growth rates over the four-year measurement period were:

		Installation 267	268	269
Basal Area	(ft^2/A/yr)	9.4	10.2	4.8
Volume	(ft^3/A/yr)	285	321	97

Response estimates for treated plots are based on comparison with these values from control plots. In the following discussion, estimates are considered significant at p=0.20.

Adjusted gross BA growth response over all three installations was significantly greater than the control for the 2N treatment (1.7 ± 0.4 ft^2/A/yr, a 21% increase), but not so for the 1M treatment (0.4 ± 0.4 ft^2/A/yr; 5%). On a site-by-site basis, all treatments resulted in significantly greater BA growth rates at installation 267, 2N and 2M were significant at installation 268, and none of the treatments were significantly different from the control at site 269. R-squared for the model ranged from .59 to .90, with p-values of .0001 to .0029. Analysis of response by 2-year periods indicated the same tendencies.

Adjusted gross volume (CVTS) growth response across all installations was also significant for the 2N treatment and not significant for the 1M treatment, based on 4-year growth and by 2-year intervals. R-squared values for the overall volume PAI model were .76 to .96 (p=.0001). At installation 267, all six treatments resulted in growth rates significantly greater than the control, for each growth period analyzed. Installation 268 had much less pronounced volume growth response, and again, site 269 showed the least response. Relative 4-year volume growth response estimates for all treatments are summarized in Figure 6 for all installations.

Results from these three trials indicate that application of 100 lbs N/A as MCI fertilizer does not induce significant gross BA or volume growth response after four growing seasons for these Douglas-fir stands, but that 200 lbs N/A applied as urea does increase growth over that on untreated plots. Analysis results by installation exhibit a fairly consistent trend for response to be greatest on plots fertilized with 200 lbs N/A as urea, and least on those with 100 lbs N/A applied as MCI fertilizer. Plots fertilized with higher rates of MCI fertilizer generally performed better, though still not as well as the 2N treatment plots. The N+M mixture did not consistently increase growth rates above those from the other treatments on the installations where it was used. Duration of fertilizer effect was fairly consistent; where response was significant in the first 2-year period it tended to also be significant in the second.

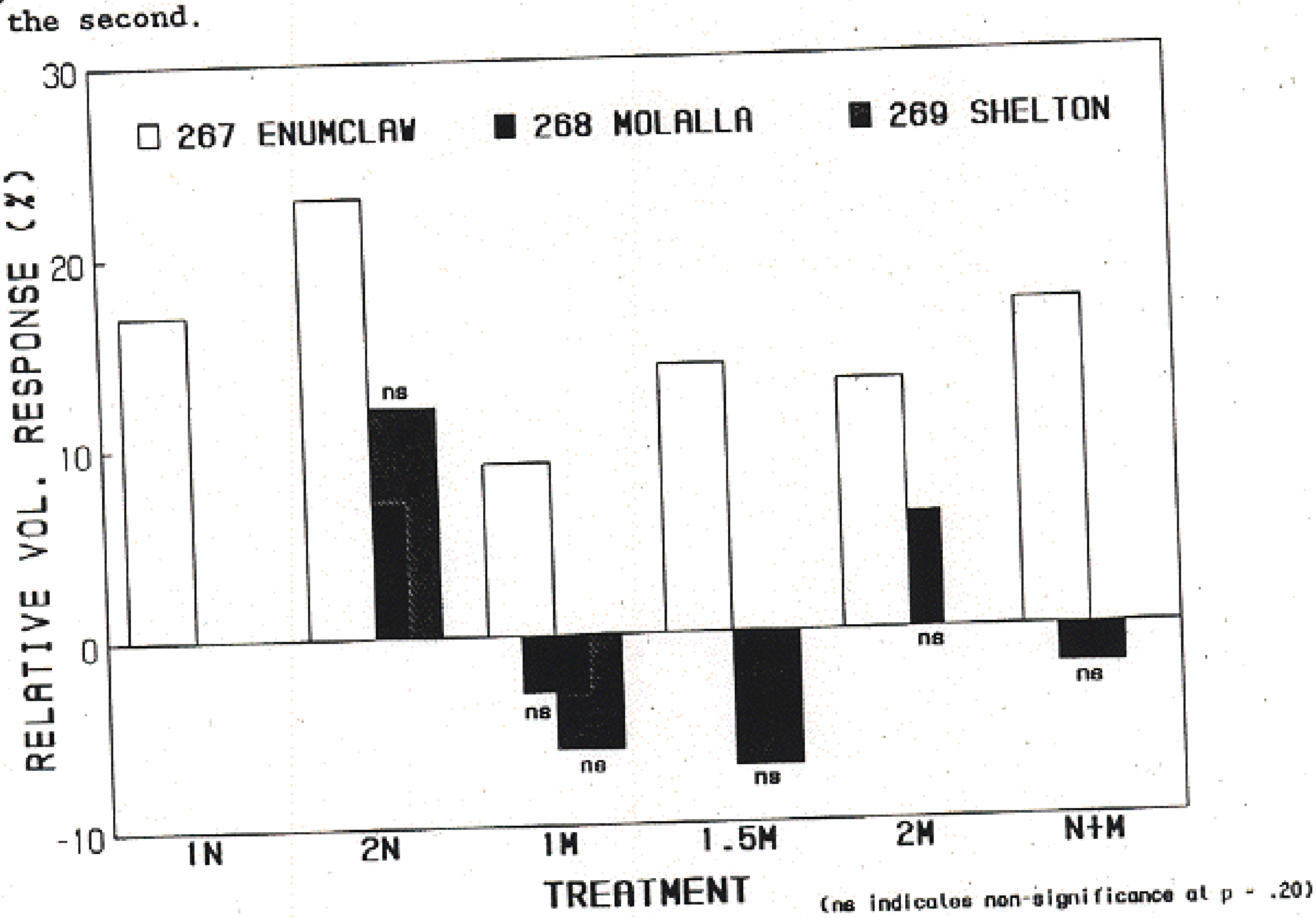

Figure 6. Relative gross (CVTS) volume growth response to fertilizer on three installations, adjusted for initial volume, over one 4-year growth interval.

FERTILIZATION SCREENING TRIALS IN NOBLE FIR AND PACIFIC SILVER FIR STANDS IN THE CASCADE RANGE OF WASHINGTON AND OREGON: PROGRESS REPORT

H. N. Chappell and W. S. Bennett

Because of successful fertilization programs in Douglas-fir and increased management of upper-slope Cascade forests, interest has developed for information on potential fertilization responses in upper-slope forest types. In a recent survey, Regional Forest Nutrition Research Project cooperators characterized 12% of their timberland ownership in the true fir/hemlock forest type. The importance of this forest type must be considered in any attempt to improve productivity of Pacific Northwest forests. In addition to questions on potential growth and response of true fir stands to fertilizer application, there are also basic questions on growth and yield of managed forests in the Pacific silver fir zone.

These fertilization screening trials were established in young stands of noble fir (*Abies procera* Rehd.) and Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) in the Pacific silver fir zone as defined by Franklin and Dyrness (1973). Study objectives were:

1. To evaluate growth responses of managed stands in the Pacific silver fir zone to nitrogen fertilization.

2. To examine differences in growth and response after fertilization with urea and ammonium nitrate.

3. To examine growth responses to application of other nutrient elements (P,S) in combination with N.

METHODS

Study Areas   Plantations and naturally regenerated even-aged stands selected for this study were as uniform as possible with respect to species composition, stocking and spacing, age, competing vegetation, and site productivity. Noble fir or Pacific silver fir trees comprised at least 60% of stems per acre. Stands were evenly spaced and well-stocked (500-600 stems/acre minimum), and trees were free to grow above the influence of competing woody vegetation. Ten noble fir and six Pacific silver fir trials were established in 1986 and 1987 on commercial forest land in the Cascade Range in Washington and Oregon, and results from these trials are reported here; six additional trials were established in 1988, expanding the north-south geographic scope. Stands selected were 6 to 19 years b.h. age and spanned an elevation range of 3200-4400 feet.

Experimental Procedure For the two species examined in these trials, a randomized complete block design was used with 10 sample trees in each of seven treatments. Fertilization rates, nutrient sources, and treatments were:

Treatment	Nutrient rate and source
1. Control	
2. 200 AN	200 lb N/A as ammonium nitrate (NH_4NO_3)
3. 400 AN	400 lb N/A as ammonium nitrate
4. 200 Urea	200 Urea: 200 lb N/A as urea ($CO(NH_2)_2$)
5. 400 AN + P	400 AN + 200 lb P/A as dicalcium phosphate ($CaHPO_4$)
6. 400 AN + S	400 AN + 50 lb S/A as elemental S + 50 lb S/A as $MgSO_4$
7. Complete	400AN + P + S + 100 lb K/A as KCl + 8 lb/A FTE 503

Individual noble fir or Pacific silver fir trees were selected in stands meeting the criteria established above. Sample trees were tagged, mapped, and measured. Treatments were randomly applied to sample trees at each location. Fertilizer was uniformly applied by hand in a 10 ft radius around the stem.

At the end of one growing season following fertilization, height and diameter were remeasured and current foliage was sampled from the second whorl of each sample tree. Samples were dried, needles were removed from the twigs, and subsamples counted and weighed to determine mass/100 needles. Total N and P was determined for each sample.

Responses to fertilization were evaluated for foliage mass, foliage N concentration and content, and height and diameter growth for each species. Graphical techniques described by Timmer and others (1978), Carter and Klinka (In Press), and others were used to interpret changes in needle mass, concentration, and content. Analyses of data from single trees were limited to ranking responses to fertilizer applications as a basis for determining sampling strata for further studies; extrapolation of growth responses to a per acre basis is not possible.

RESULTS

Basal area growth was significantly increased by fertilizer treatments for both species, with the exception of the urea treatment for Pacific silver fir (Table 7 and Figure 7). Fertilizer treatments had little influence on height growth for either species. Addition of other nutrients did not significantly increase growth above the level of N-only treatments.

Foliar nitrogen concentrations were significantly increased by fertilizer treatments for both species (Table 7). Treatments including 400 lb N/A as ammonium nitrate had the greatest effect; the urea treatment produced little or no effect. Ammonium nitrate treatments significantly increased needle mass for both species. Pacific silver fir foliar N and P levels were highest for the N + P treatment; foliar levels for noble fir followed a similar trend, although differences were nonsignificant.

Vector analyses of foliar N responses indicated initial N levels were limiting growth. All fertilizer treatments produced a positive response. Ammonium nitrate treatments yielded approximately equivalent responses that were significantly greater than response to urea.

Table 7. Growth and foliar responses of Noble fir and Pacific silver fir trees to fertilizer treatments. Means followed by the same letter are not significantly different from each other at the .05 level. Basal area and height growth means are adjusted for initial basal area and height, respectively.

Treatment	2-year Basal Area Growth	2-year Height Growth	Total N	Total P	Foliage Mass
	in^2/tree	ft	%	ppm	g/100 needles
NOBLE FIR					
Complete	7.20 a	3.81 a	2.16 bc	2097 a	1.20 a
400 AN+S	7.09 ab	3.64 ab	2.07 c	2035 ab	1.17 a
400 AN+P	7.06 ab	3.64 ab	2.31 a	2098 a	1.18 a
400 AN	6.83 ab	3.58 ab	2.28 ab	2056 ab	1.14 a
200 AN	6.50 bc	3.67 ab	1.78 d	1979 bc	1.14 a
200 Urea	5.99 c	3.45 ab	1.38 e	1982 bc	1.03 b
Control	4.67 d	3.31 b	1.20 f	1901 c	1.04 b
PACIFIC SILVER FIR					
400 AN + S	5.57 a	2.62 ab	2.11 b	1655 b	1.48 a
400 AN	5.43 ab	2.89 a	2.10 b	1729 ab	1.40 abc
200 AN	5.09 ab	2.69 ab	1.81 c	1655 b	1.43 ab
Complete	5.04 ab	2.62 ab	2.18 b	1716 ab	1.48 a
400 AN + P	4.97 ab	2.66 ab	2.42 a	1769 a	1.39 abc
200 Urea	4.72 bc	2.53 ab	1.31 d	1662 b	1.33 bc
Control	3.99 c	2.33 b	1.12 d	1658 b	1.31 c

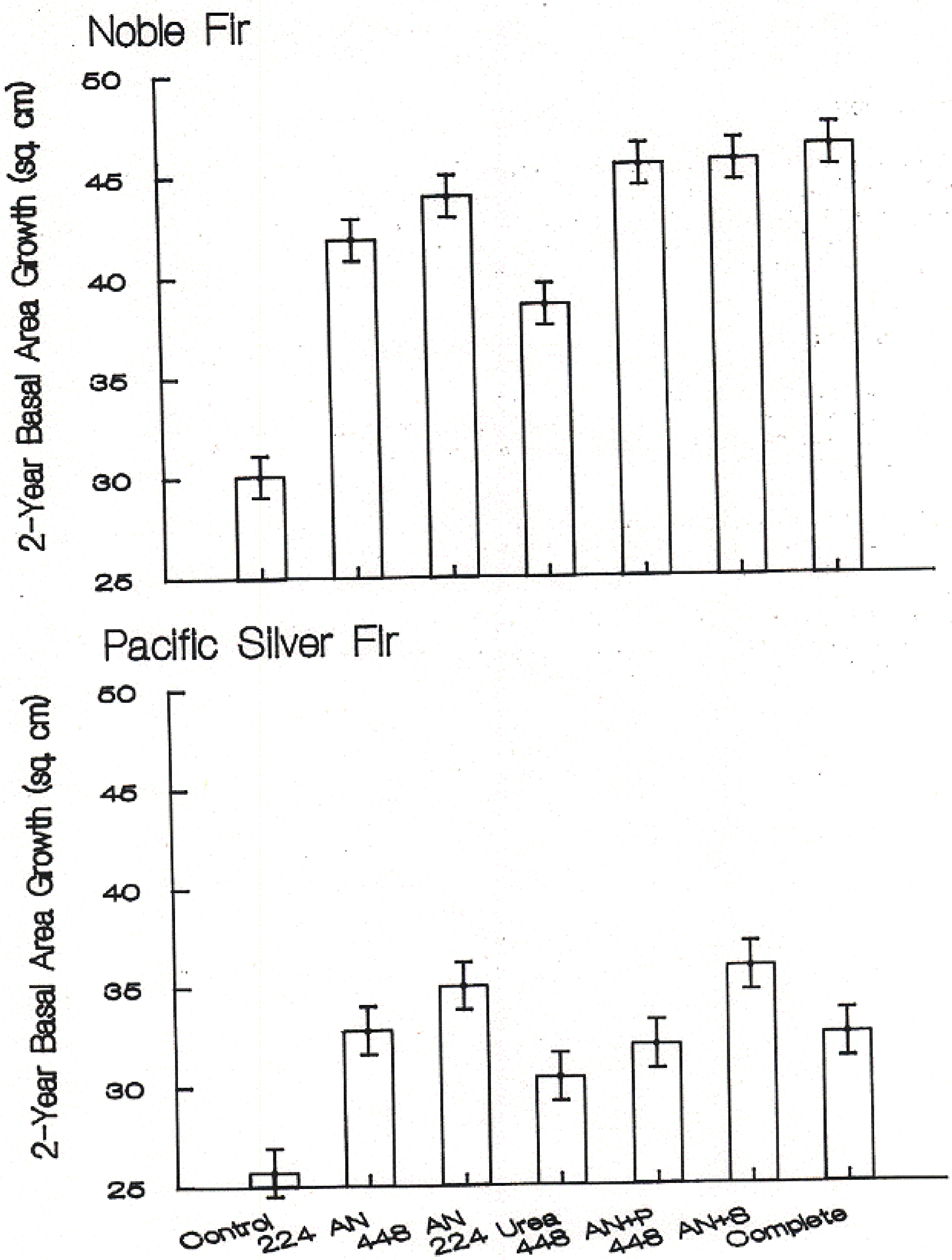

Figure 7. Mean 2-year basal area growth ± 1 s.e. for individual noble fir and Pacific silver fir trees for six fertilizer treatments. Means adjusted for initial basal area.

CONCLUSIONS

Nitrogen fertilizer treatments increased basal area growth, foliar N concentration, and needle mass for noble fir and Pacific silver fir trees. Ammonium nitrate consistently produced greater responses than urea for both species. Addition of other nutrients did not significantly increase responses over N-only treatments for either species.

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FOREST FLOOR AND SOIL INFLUENCE ON RESPONSE OF DOUGLAS-FIR TO UREA *

R. L. Edmonds and T. Hsiang

Data from the Regional Forest Nutrition Research Project in Washington and Oregon were analyzed to improve stand-specific prediction of Douglas-fir response to urea fertilization. The response variable (relative difference in volume growth between fertilized and control plots 4 yr after fertilization with 448 kg N/ha) was regressed against the 28 stand and site variables shown in Table 8 using stepwise multiple regression analysis. Data from 120 Phase I and II installations were stratified by thinning level (thinned or unthinned), geographic location (provinces), and site quality (site index and class). Forest floor C/N ratio was the dominant variable related to response as shown in Table 9. The relationship between forest floor C/N ratio and volume response was better in thinned installations (r^2=0.44, Figure 8B) than unthinned installations (r^2=0.18, Figure 8A). In thinned installations of high site quality (site classes I and II), 60% of variation in response was explained by the forest floor C/N, and 75% of the variation in response was explained with inclusion of surface soil exchangeable K (Table 9). In thinned, low site quality stands, response was not as well related to forest floor C/N. Analysis of the data by province indicated that S may be limiting in southwest Oregon and P in coastal Washington (Table 9).

* *Summarized from Edmonds and Hsiang (1987).*

Table 8. Forest floor (FF), composite soil (CS, 0-15 cm), total installation (TI), and other variables used in regression analysis against response. Analytical procedures and sample sizes are also shown.

Variable	Measurement	Procedure	Sample size
1. SITE INDEX	Site index, m at 50 yr	King (1966)	120
2. AGE	Stand age, yr	Breast height	120
3. SLOPE	Slope, %	Abney level	120
4. ELEV	Elevation, m	Topography map	120
5. PPT	Precipitation, mm yr⁻¹	Nearest weather station	95
6. $\%C_{FF}$	C, %	LECO combustion (†)	119
7. CW_{FF}	C weight, kg ha⁻¹		119
8. $\%N_{FF}$	N, %	Kjeldahl method (‡)	119
9. NW_{FF}	N weight, kg ha⁻¹		120
10. TW_{FF}	Total weight, kg ha⁻¹	See Metnods Section	120
11. C/N_{FF}	C/N ratio		119
12. $\%C_{CS}$	C, %	LECO combustion (†)	119
13. CW_{CS}	C weight, kg ha⁻¹		116
14. $\%N_{CS}$	N, %	Kjeldahl method (‡)	119
15. NW_{CS}	N, kg ha⁻¹		116
16. C/N_{CS}	C/N ratio		119
17. AVP_{CS}	Available P, mg kg⁻¹	Bray no. 2 extract. (§)	120
18. $TOTP_{CS}$	Total P, mg kg⁻¹	$HClO_4$ digestion (§)	120
19. AVS_{CS}	Available S, mg kg⁻¹	K_2HPO_4 extraction (¶)	120
20. $EXCA_{CS}$	Exch. Ca, $cmol_c$ kg⁻¹	1 *M* NH_4OAc extract. (§)	120
21. EXK_{CS}	Exch. K, $cmol_c$ kg⁻¹	1 *M* NH_4OAc extract. (§)	119
22. $EXMG_{CS}$	Exch. Mg, $cmol_c$ kg⁻¹	1 *M* NH_4OAc extract. (§)	120
23. CEC_{CS}	CEC, $cmol_c$ kg⁻¹	1 *M* NH_4OAc extract. (§)	119
24. $BSAT_{CS}$	Base saturation, %		119
25. pH_{CS}	pH	1:1 soil-water susp.	119
26. DEP_{CS}	Soil depth, cm	Soil pits and augers	117
27. CW_{TI}	C, kg ha⁻¹		116
28. NW_{TI}	N, kg ha⁻¹		116

† Nelson and Sommers (1982).
‡ Bremmer and Mulvaney (1982).
§ Jackson (1958).
¶ Ensminger (1954).

Table 9. Equations for multiple regression analyses for percent volume response over control 4 yr after fertilization with 448 kg urea-N/ha (dependent variable) with stand and site variables.

Data set	N	Equation†	Adj-R^2
		Unthinned	
All	85	$4.99 + 1.50\ C/N_{FF}$ (17) $- 1.15$ SITE INDEX (7) $- 0.29$ SLOPE (4)	0.27
Province 1, 2, 6	39	$-72.6 + 2.44\ C/N_{FF}$	0.26
Province 4	18	$-15.1 + 1.83\ C/N_{CS}$ (39) $- 128.32\ \%N_{CS}$ (14) $+ 0.025\ TOTP_{CS}$ (14) $- 8.26\ EXMG_{CS}$ (5)	0.72
Province 7, 8	28	$79.53 - 4.37\ AVS_{CS}$ (27) $+ 0.98$ SITE INDEX (10)	0.37
Site class 1, 2	46	$-10.96 + 1.34\ C/N_{CS}$ (11) $- 1.68\ AVS_{CS}$ (7)	0.18
Site class 3, 4, 5	39	$-232.9 + 2.84\ C/N_{FF}$ (17) $+ 2.41\ \%C_{FF}$ (8) $- 1.71\ AVP_{CS}$ (7) $- 0.29$ ELEV (6) $+ 15.63\ pH_{CS}$ (5)	0.43
		Thinned	
All	35	$-107.0 + 2.63\ C/N_{FF}$ (41) $+ 25.22\ EXK_{CS}$ (11) $+ 29.97$ SITE INDEX (5)	0.57
Province 1, 2, 6	19	$-111.73 + 3.68\ C/N_{FF}$	0.52
Province 4, 7, 8	16	$+6.99 - 116.5\ \%N_{CS}$	0.34
Site class 1, 2	16	$-94.22 + 2.63\ C/N_{FF}$ (60) $+ 30.77\ EXK_{CS}$ (15)	0.75
Site class 3, 4, 5	19	$+109.26 - 0.345\ NW_{FF}$	0.37

† Percent portion toward total degrees of freedom adjusted R^2 value is given in parentheses after each independent variable.

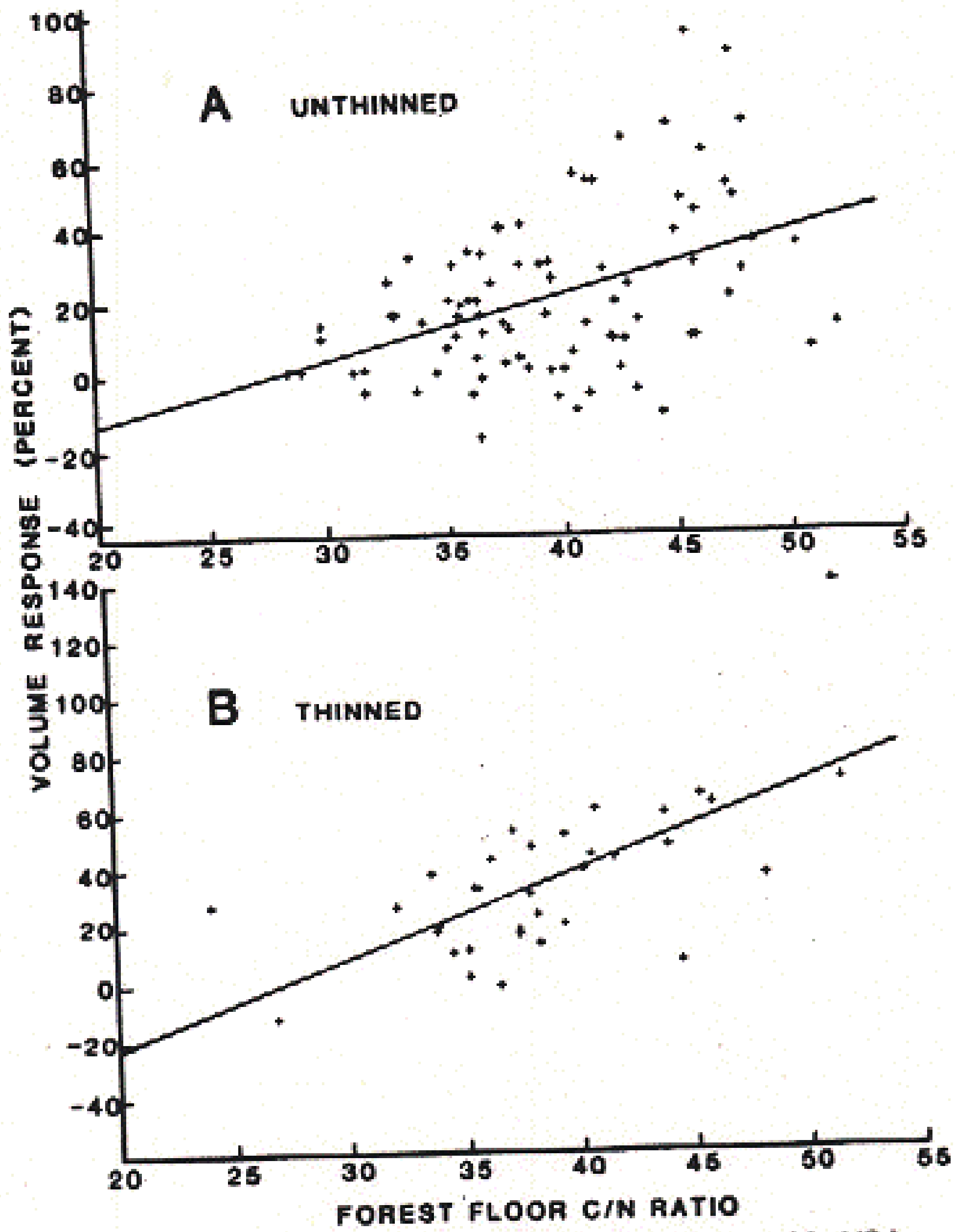

Fig. 1. Percent volume response 4 yr after fertilization with 448 kg urea-N/ha in relation to forest floor C/N ratio: (A) unthinned installations, (B) thinned installations. Slopes for the regression lines are 1.69 and 2.97, respectively, and the critical forest floor C/N ratios as defined by the *x*-intercepts are 27.9(A) and 27.5(B), respectively.

Figure 8. Percent volume response 4 yr after fertilization with 448 kg urea-N/ha in relation to forest floor C/N ratio: (A) unthinned installations, (B) thinned installations. Slopes for the regression lines are 1.69 and 2.97, respectively, and the critical forest floor C/N ratios as defined by the x-intercepts are 27.9 (A) and 27.5 (B), respectively.

SULFUR NUTRITION RESEARCH UPDATE

INTRODUCTION

Sulfur nutrition of forest trees has received considerable interest in recent years. Earlier work in the Pacific Northwest developed relationships between S and N concentrations in soil and foliage and tree and stand responses to N fertilization, and recent studies have included S fertilizer applications to test those relationships. Field trials including S fertilization treatments have produced inconsistent results, contributing to uncertainty about the place of S in fertilization programs, particularly for coast Douglas-fir stands. In the fall of 1987, the Regional Forest Nutrition Research Project Technical Advisory Committee discussed S fertilization results from recent RFNRP trials, and proposed an informal meeting to summarize work in the region and to outline future needs.

The workshop on Sulfur Nutrition and Fertilization of Western Conifers was held March 30-31, 1988 at the University of Washington Pack Demonstration Forest near Eatonville, Washington. Participants included researchers actively involved in forest nutrition research. Each participant was requested to provide a summary of research projects and results; additional information, reprints, and notes were welcomed. The two-day workshop included individual presentations of status reports on research projects and participation in one of two discussion groups. Workshop proceedings compiled status reports and summaries of the two discussion sessions (Chappell and Miller 1988). The document is not intended to be a thorough scientific review of S nutrition of forest trees, but rather is a status report of research in the PNW and a resource for planning additional trials and analyses.

RESPONSES TO SULFUR IN NITROGEN FERTILIZED DOUGLAS-FIR STANDS

One of the field trials reported on at the workshop was the N+S fertilization study initiated in 1980 (Blake 1985) supported by the Sulfur Development Institute of Canada (SUDIC), Weyerhaeuser Company, and RFNRP. Five Douglas-fir stands were selected which had potential for additional response to N+S applications when compared to N alone. Initial study objectives were to characterize the potential volume gain from N+S fertilization and determine if methods used to establish critical levels of S availability were consistent with the site-specific growth responses (Blake 1985). A refertilization regime was initiated in an attempt to monitor foliar concentration/content changes in relation to growth response to annual N and S fertilization.

Five installations were established in 1980 and 1981 in western Oregon and Washington (Table 10). All installations received fertilizer treatments at establishment. Treatments were (1) control, (2) 200 lbs N/A applied as urea, and (3) 200 lbs N/A + 100 lbs S/A, as ammonium sulfate + urea. The refertilization regime began in Spring 1984 by repeating the initial treatments. In Spring 1985 and 1986, 100N and 100N+50S was applied to (2) and

(3), respectively. DBH of all stems and total height on a subsample was measured annually from establishment through 1987. Foliage samples were taken before initial treatment and in Fall 1981, 1982, 1984, and 1985.

Basal area and volume growth responses to fertilizer treatments were analyzed for two growth periods: (1) the 3 or 4 years after initial fertilization, and (2) the 3 years in the refertilization regime. Generally the pattern of response for each installation in both periods was similar, however, response between installations was quite variable. Not all installations showed a significant response to N fertilization (N alone and N+S versus Control). Analysis of N alone versus N+S was inconclusive; however, in most cases there was no indication of additional growth from the application of N+S over N alone.

Foliar analysis using a graphical diagnostic technique (Timmer and Stone 1978, Weetman and Fournier 1982) seems to substantiate these growth response conclusions. Analysis of N at all installations except McKenna indicated luxury consumption which would suggest that a response from application of additional N is unlikely. S analysis shows almost complete utilization of SO_4-S reserves at all locations, again with the exception of McKenna. S concentration and content was essentially the same for both N and N+S treatments, possibly indicating loss/sorption in soil or no uptake of applied S.

Plans for these installations include completion of supplemental soil sampling and analysis, and completion of foliage sample analysis. The growth and response analysis will be completed in early 1989, and a manuscript is in preparation reporting results from these installations.

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Table 10. Initial stand characteristics and treatments for five nitrogen and sulfur fertilization field trials.

	Installation Number				
	227	228	229	230	231
Location	McKenna	Molalla	Sutherlin	Forest Grove	Elkton
State	WA	OR	OR	OR	OR
Origin	Planted	Planted	Natural	Planted	Planted
B.H. Age †	17	16	26	22	12
Site Index (meters) ‡	36	41	32	38	45
Basal Area (m^2 ha^{-1})	26	32	24	28	24
Replications	5	5	3	6	5
Plot Size (hectares)	0.062	0.062	0.083	0.062	0.062
Established	Mar 1980	Feb 1980	Jan 1980	Mar 1981	Mar 1981

† Ave. age determined at breast height on dominant or co-dominant individuals.
‡ Ave. height of dominant or co-dominant trees at base age 50 (King, 1966).

FINE ROOT AND HYPHAL GROWTH IN DOUGLAS-FIR STANDS: RESPONSE TO NITROGEN STRESS *1

A. L. Friend, S. M. Ohmann, and T. M. Hinckley

The roles of N stress and soil microenvironment N availability on fine root and hyphal ingrowth were examined in Douglas-fir forests. Plastic mesh ingrowth bags containing 50 g of horticultural vermiculite (verm.) with 0.02, 1, or 9 mg N/g verm. as ammonium nitrate were installed in a fertilized (75 kg N/ha/yr over 15 yrs) plot and an unfertilized (N stressed) plot in December, 1986. After 6 months, greater root (2x) and hyphal (3x) ingrowth had occurred in the unfertilized compared to the fertilized plot. Root ingrowth was positively correlated with total N of the ingrowth medium ($r^2 = 0.82$) on the unfertilized but not on the fertilized plot. The N stressed plot exhibited compensatory root growth responses to N availability, i. e., an accelerated growth in high N microenvironments. Both of the observed responses to N stress, high total fine root growth and compensatory root growth in high soil microenvironments, are possible mechanisms for tolerating N stress.

SOIL SULFATE-SULFUR AND GROWTH RESPONSES OF NITROGEN-FERTILIZED DOUGLAS-FIR TO SULFUR *2

J. Blake, S. R. Webster, and S. P. Gessel

Two studies were conducted to determine the growth response of N-fertilized Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) to S supplements. The relationship between response and soil SO_4-S extracted with Morgan's solution, 1.22 M NaOAc + 0.53 M HOAc (pH 4.8), was used to establish critical levels for S. Douglas-fir seedlings were grown in the greenhouse in the surface mineral layer (0 to 0.15 m) of 20 forest soils from western Washington and Oregon. On the average, significant increases in total dry weight (17.5%), stem diameter (10.1%), and height (6.9%) occurred when soils were fertilized with N and S in comparison to N alone. Using the Cate-Nelson procedure, growth responses to N and S were most likely to occur when soil SO_4-S was below 14 mg S kg^{-1}. Twenty eight installations were established in the field containing five N treatments, three rates of N as urea, and one plot of 336 kg N ha^{-1} with P, K, Ca, and S. Differences in percent basal area growth between N alone and N with P, K, Ca, and S were significantly related to soil SO_4-S. Over the initial 5-yr period, response over N alone was improved by 74% when soil SO_4-S was <20 mg S kg^{-1}. When the N with P, K, Ca, and S were retreated with only N and S, responses over the next 3 yr was more than doubled compared with N alone. Identification of S responsive stands was improved by the inclusion of stand age weighted subsoil SO_4-S concentrations.

*1 *From Friend, Ohmann, and Hinckley (1987)*

*2 *From Blake, Webster, and Gessel (1988)*

VOLUME GROWTH AND RESPONSE TO THINNING AND FERTILIZING OF DOUGLAS-FIR STANDS IN SOUTHWESTERN OREGON *3

R. E. Miller, G. W. Clendenen, and D. Bruce

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 descriptions (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 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 following 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.

NITROGEN REQUIREMENTS IN YOUNG DOUGLAS-FIR IN THE PACIFIC NORTHWEST *4

J. Turner, M. J. Lambert, and S. P. Gessel

A series of fourteen Pacific Northwest Douglas-fir installations, ranging in age from 6 to 26 years were analyzed with respect to site factors, foliage nutrients, and growth response to applied fertilizer. Unfertilized basal area increment ranged from 1.2 to 3.1 $m^2ha^{-1}yr^{-1}$ with no apparent relationship with soils, stand age or site index. Basal area increment was correlated with foliage N and a critical level for N was calculated as 1.7%. Application of 220 kg N ha^{-1} as urea increased growth between 0 and 95% of the unfertilized basal area growth, with an average of 24.9%. Response could be predicted from foliage N and unfertilized basal area increment. When the same relationships were applied to previously older stand data, results were more variable as elements such as B and S showed evidence of being limiting.

*3 *From Miller, Clendenen, and Bruce (1988)*

*4 *From Turner, Lambert, and Gessel (1988)*

FIELDWORK AND INSTALLATION OVERVIEW

During 1986-88, measurements and treatments continued on the extensive base of RFNRP field trials. In 1989, a number of installations will complete 20 growing seasons after initial treatment and have been fertilized a total of four times. Scheduled remeasurements for many RFNRP installations have been extended to 4-year intervals; other RFNRP installations are measured on 2-year intervals.

RFNRP trials have been established in a number of phases, and reference to these phases is common practice to identify a particular subset of the field installations. Additional permanent plots have been established in supplemental and contract studies. RFNRP phases are:

Phase I — Natural, unthinned stands of Douglas-fir and western hemlock; established 1969-70.

Phase II — Natural, thinned stands of Douglas-fir and western hemlock; established 1971-72.

Phase III — Young thinned plantations of Douglas-fir and western hemlock; low site quality stands of Douglas-fir; established 1975.

Phase IV — Precommercially thinned plantations of Douglas-fir and western hemlock; Douglas-fir stands of naturally low stocking; established 1980.

The fertilization schedule for Phase I and II Douglas-fir installations is summarized below. Other installations are on similar refertilization schedules, depending on phase or study objectives; thinned installations may be scheduled for further stand density control.

Douglas-fir Phase I & II Fertilization Schedule

Plot	Initial fertilization	After 8 growing seasons	After 12 growing seasons	After 16 growing seasons
	------------	lbs N/acre as urea	---------------	
1	0	0	0	0
2	0	200	200	200
3	200	0	0	0
4	200	200	200	200
5	400	0	0	0
6	400	200	200	200

STATUS OF FIELD TRIALS

The RFNRP has established nearly 300 research installations since 1969. Six to 35 permanent growth plots make up an installation, for experimental designs used in Phases I-IV and contract installations. Recent screening trials established in the Pacific silver fir (PSF) zone are on individual trees. Active RFNRP trials are listed below; other installations are inactive (no remeasurements are scheduled) or dropped (no further measurements are possible, e.g. plots have been logged, windthrown, etc.). Remeasurement of all western hemlock trials has been discontinued.

Establishment Year	Installation Type	Number Established	Number Active 6/88
1969	Phase I	57	13
1970	Phase I	60	12
1971	Phase II	16	9
1972	Phase II	27	22
1973	Contract (BLM)	6	0
1975	Phase III	29	22
1975	Contract (USFS)	4	0
1976	Contract (USFS)	1	0
1977	Contract (USFS, BLM)	17	0
1978	Contract (USFS)	4	0
1979	Contract (SUDIC)	3	3
1980	Phase IV	34	24
1980	Contract (SUDIC)	2	2
1983	Contract (MCI)	3	3
1984	Contract (USFS)	3	3
1985	Phase V PSF	6	6
1986	Phase V PSF	10	10
1987	Phase V PSF	6	6
	TOTALS	288	135

GRADUATE STUDENTS

Hans Porada earned the Ph.D. degree in 1987 after completing his dissertation entitled "The effect of aluminum on the growth and mineral composition of Douglas-fir and western hemlock." Hans returned to New South Wales, Australia, where he is now working in forest research with the N.S.W. Forestry Commission. Alex Friend completed his Ph.D. dissertation in 1988 and accepted a post-doctoral position at Oak Ridge National Laboratory. Part of Alex's research made use of RFNRP field plots; his dissertation is entitled "Nitrogen stress and fine root growth of Douglas-fir." Abstracts of both dissertations are included at the end of this section.

Linda Heath is putting the finishing touches on her dissertation entitled "Stand-level decisionmaking under risk." She will begin a post-doctoral appointment in January in the economics project at the PNW Station in Portland. Dan Opalach plans to complete the requirements for his Ph.D. program in June 1989. Dan has a research faculty appointment at Oregon State University and is working with CRAFTS on the small tree modeling project. Jim McCarter began his graduate program at UW in September and will be working on stocking relationships in managed stands.

THE EFFECT OF ALUMINUM ON THE GROWTH AND MINERAL COMPOSITION OF DOUGLAS-FIR AND WESTERN HEMLOCK

Hans J. Porada

Soil properties such as high exchangeable Al, high Al saturation, and low base status are a major deterrent for plant growth in strongly acid soils. Yet these properties are notable features of the coastal forest soils of Oregon and Washington, and there have been suggestions that for these soils Al may be an important contributor to the erratic growth response by the coastal forests from N applications. Consequently, two studies were initiated to determine the potential effect of Al on the growth and nutrient composition of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), the two most common tree species on these soils. The first study was an in situ seedling fertilization trial designed to investigate the growth response of both species to N, P, and N+P applications, and to examine the fertility status of those soils to determine whether Al had an impact on growth response to fertilizer application. The study revealed that these soils had high P sorption capacity (>93%) and were dominated by Al on the soil exchange sites. For Douglas-fir there was a consistent positive growth response to P application, while for western hemlock growth response was erratic, and high N applications depressed growth, particularly on burnt sites. Foliar analysis revealed that only P was below the reported optimum level for Douglas-fir. For western hemlock, application of N or P had no significant effect on foliar levels of these elements. Slash burning appeared to reduce dramatically western hemlock's foliar N and Zn to below critical levels and part of this species' erratic response is attributed to a Zn deficiency on burnt sites. Slash burning also appeared to have a marked effect on western hemlock foliar Al and Ca levels--Al levels were higher and Ca levels lower on burnt sites. Two years after planting western hemlock had twice the foliar Al levels of Douglas-fir.

Because of the high P sorption and low base status of these soils, a second study was initiated, using solution culture techniques, to determine the effect of pH, and varying Ca:Al, P:Al, and OH:Al mole ratios on Douglas-fir and western hemlock root growth and tissue concentrations. Both species were extremely tolerant of low pH and high levels of Al relative to crop plants; western hemlock was more tolerant of low pH compared with Douglas-fir and there is evidence suggesting that western hemlock may be more tolerant of Al at low pH and low Ca levels compared with Douglas-fir. Increasing the Ca:Al and OH:Al ratios ameliorated the toxic effects of Al on root growth, especially for Douglas-fir; for Ca this was attributed mainly to its physiological role rather than its effect on Al activity in solution. However, increasing the P:Al ratios depressed root growth due to the decrease in solution pH as P additions increased. Tissue analysis revealed that while Douglas-fir generally had the highest P and Zn levels, western hemlock had the highest Al, Ca, Mg, Mn, and Fe levels.

NITROGEN STRESS AND FINE ROOT GROWTH OF DOUGLAS-FIR

Alexander L. Friend

Fine root growth in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) seedlings and stands was examined to determine: (1) if nitrogen (N) stress resulted in increased carbon and dry weight partitioning to fine roots, (2) if N stress altered the proliferation of fine roots in high N soil environments, and (3) the physiological processes that might explain the results from (1) and (2).

Studies of carbon-14 and dry weight partitioning in seedlings demonstrated that under severe N stress, fine root:foliage dry weight ratio increased up to four-fold. Less severe, but still sub-optimal nitrogen regimes decreased overall growth, but did not necessarily increase the partitioning of assimilates into roots relative to foliage. Several experiments verified this result. These studies also demonstrated that assimilate partitioning to roots is affected by factors other than N stress, such as shoot growth phenology and seedling ontogeny.

In contrast to the increased assimilate partitioning to the entire fine root system under very low N regimes, the growth of isolated individual roots from both seedlings and stands was stimulated in localized areas of very high N regimes. In a range of seedling and stand experiments, root dry weight growth was greater in high compared to low N microenvironments containing less than one tenth of the root system (range: two- to seven-fold increase). This proliferation response to high N microenvironments was greatest when the remaining seedling or stand was N-deficient. Thus, N stress resulted in the entire root system receiving a greater proportion of assimilates, and also resulted in individual roots proliferating more in high N microenvironments, than if the plant were not N stressed. This fine root growth response exemplified compensatory growth since it compensated for N stress in soil macroenvironments by increasing exploitation of N-rich soil microenvironments.

The partitioning of growth to and within fine root systems of Douglas-fir was observed to be controlled by two physiological processes: (1) shoot growth as it affects carbon fixation and competition between roots and shoots for assimilates, and (2) compensatory growth responses of individual roots to high N microenvironments. These processes affect the quantity of root growth and its distribution within a heterogeneous soil.

RFNRP PERSONNEL

Dr. H. N. Chappell, Director
Mr. William Bennett, Database Manager
Mr. Robert Gonyea, Program Manager
Mr. Bert Hasselberg, Field Technician
Mr. Michael Johnson, Field Technician
Ms. Kate Stegemoeller, Growth and Yield Analyst

The RFNRP staff continued to evolve in 1986-88. Mike Rinehart, RFNRP and Stand Management Cooperative field work supervisor since 1982, left the College in September 1987. Mike made significant contributions to the cooperatives, and we wish him luck in his future endeavors. Bob Gonyea and Mike Johnson share fieldwork leadership and liaison duties for the cooperatives. Also in September 1987, Dan Opalach, RFNRP Graduate Research Assistant and Project Mensurationist since 1985, accepted a faculty position at Oregon State University. Dan is modeling small-tree growth for the CRAFTS cooperative, and plans to complete his dissertation in 1989.

Kathryn Stegemoeller joined the Project as Growth & Yield Analyst in January 1988. Kate completed her M.S. in forest biometry at the University of Minnesota; her thesis project involved the STEMS growth model. Bert Hasselberg joined the staff in April 1988 with responsibilities involving RFNRP and SMC fieldwork and other CFR projects. Bert has helped with Project fieldwork for several seasons.

Several College of Forest Resources faculty members actively participate in RFNRP projects including Drs. Bruce Bare, Dale Cole, Robert Edmonds, and Douglas Maguire. Professor Emeritus Stan Gessel continues to inspire us with his knowledge and energy. Dr. Robert Harrison joined the College faculty in July 1987 and has initiated a number of forest soils research projects. Rob was formerly at Oak Ridge National Laboratory, where he conducted research on nutrient cycling in forest ecosystems. Faculty interest and participation strengthens the RFNRP, and graduate students supervised by these faculty members provide for research on basic and applied topics beyond the scope of the core RFNRP effort.

Fieldwork in 1986-88 has been accomplished with the able assistance of Messrs. Al Durkee, Joel Clark, and Keith Yonaka. Appreciation is due Mrs. Veronica Gallardo, who handles RFNRP secretarial duties, and Mr. Jay Kuhn, for overseeing laboratory analyses.

COOPERATORS LIAISON COMMITTEE

Organization	Member
Barringer and Associates	Jack Barringer
Bureau of Land Management	Byron Thomas
Chevron Chemical Company	Newton Hawkinson
Cominco American Inc.	Warren Woodward
Hampton Tree Farms	Dennis Creel
International Paper Company	Gregory Johnson
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Plum Creek Timber Company	Bruce Beckett
USDA Forest Service	Donald Connett
Washington Department of Natural Resources	Harry Anderson
Weyerhaeuser Company	William Scott
Willamette Industries Inc.	Morris Bergman

TECHNICAL ADVISORY COMMITTEE

The RFNRP Technical Advisory Committee (TAC) provides review and counsel on Project reports and plans. RFNRP study plans, research proposals, manuscripts, and field and laboratory studies benefit from the active participation of TAC members. TAC review is also an important step in production of the RFNRP Report series. The willingness of TAC members to contribute their time and expertise is a key factor in the continued success of the Project. TAC participants in 1986-88 were:

Dr. Tim Ballard	University of British Columbia
Mr. Albert Becker	Georgia-Pacific Corporation
Dr. George Bengtson	Oregon State University
Dr. Peter Farnum	Weyerhaeuser Company
Dr. Paul Heilman	Washington State University
Mr. David McNabb	Oregon State University - FIR
Dr. Robert Meurisse	USDA Forest Service, Pacific Northwest Region
Dr. Richard Miller	USDA Forest Service, PNW Research Station
Dr. James Moore	University of Idaho
Mr. Dan Opalach	Oregon State University
Dr. Charles Peterson	Northrop Services
Dr. Robert Powers	USDA Forest Service, PSW Research Station
Mr. John Shumway	Washington Department of Natural Resources
Dr. Byron Thomas	Bureau of Land Management
Dr. Steve Webster	Washington State University
Dr. Gordon Weetman	University of British Columbia
Dr. Robert Zasoski	University of California
Dr. Larry Zuller	Georgia-Pacific Corporation

RFNRP PUBLICATIONS AND REPORTS

This list has been compiled to summarize publications, reports, and presentations on research results of the Regional Forest Nutrition Research Project. Included in this list are publications and reports dealing with forest fertilization by Project faculty, staff, and graduate students, and those which are results of research by collaborating workers utilizing RFNRP installations and data. Unpublished reports are on file at RFNRP offices in the College of Forest Resources.

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1971: **Regional Forest Nutrition Research Project Annual Report.** 1971. Institute of Forest Products. College of Forest Resources, University of Washington, Seattle. 25 p.

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