REGIONAL FOREST NUTRITION RESEARCH PROJECT

Biennial Report 1974–76

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UNIVERSITY OF WASHINGTON
COLLEGE OF FOREST RESOURCES

REGIONAL FOREST NUTRITION
RESEARCH PROJECT

BIENNIAL REPORT
1974 - 1976

COLLEGE OF FOREST RESOURCES
UNIVERSITY OF WASHINGTON

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1975 - 1976

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FOREWORD

The cooperative Regional Forest Nutrition Research Project will soon begin its ninth year of operation. Since summer 1969 over 1,450 field plots have been established in stands of Douglas-fir and western hemlock. The resulting quantity of data has become steadily more challenging to manage and more valuable for the insights which it provides to major questions affecting the productivity of Pacific Northwest forests.

Since 1969, demands on these forests for wood and other products, amenities, and land uses has increased remarkably. There appears to be no cessation to the upward climb of timber stumpage prices, and hence land managers are increasingly desirous of silvicultural information germaine to investment opportunities in maximizing yields. Even in a natural state, the forests of this region are among the most productive timber resources in the world. The magnitudes of gain that can be realized by fertilization and thinning are generally impressive as indicated by the 4-year growth data presented in this Biennial Report.

As the complex supply-demand relationships of our forest resources continue to evolve and become more intimately tied together, land managers will be under greater pressure to substantiate their policies and practices. Likewise, as management costs and product values continue to increase, decision-making criteria must necessarily become more refined. The staff of the Regional Forest Nutrition Research Project wish to thank those whose support has made possible its progress toward furthering these goals.

James S. Bethel, Dean
College of Forest Resources

INTRODUCTION

The Regional Forest Nutrition Research Project was initiated in 1969 with the primary objective of providing resource managers with more accurate data on the effects of fertilizing and thinning young-growth Douglas-fir and western hemlock forests.

Based on the needs for additional information which previous forest fertilization research in the Pacific Northwest had brought to light, the Northwest Forest Soils Council determined that an intensive field program with regional focus should incorporate the following goals:

1. to establish and maintain a series of fertilizing and thinning field trials on participants' lands in western Washington and western Oregon under various conditions of soils, climate, age, and site;

2. to collect and analyze response data from these plots and report results to subscribers;

3. to conduct supplemental research in related areas such as diagnosis of elemental deficiencies, analysis of the effects of fertilizer application on total ecosystems, effects on wood quality, economics of fertilization and thinning, and mensurational aspects;

4. to report findings regularly to subscribers and to advise them on fertilization problems and practices;

5. to cooperate with other programs and research designed to intensify forest management and increase wood production.

Because of the scope of this program, a cooperative funding approach was used to enlist a broad base of support from regional timber companies, fertilizer manufacturers, and governmental agencies involved with resource management. The College of Forest Resources of the University of Washington administers the project under the direction of Dr. Stanley P. Gessel.

The original research design called for simultaneous establishment of unthinned and thinned fertilizer plots. However, the funding level in 1969 did not permit the full program to proceed, and the cooperators decided to begin with the unthinned plots only. This became known as Phase I when, in 1971, sufficient funds had been generated to reincorporate the thinning-fertilizer trials. The latter portion of the program is referred to as Phase II. All plots were originally scheduled for final remeasurement after they had undergone four growing seasons.

The years 1975 and 1976 saw another large extension of the R.F.N.R.P. data base with the advent of Phase III. Measurement of the older plots is continuing to determine duration of response and effects of retreatment, and a number of new research plots have been established. Since 1969, approximately 1,450 permanent growth plots have been located under R.F.N.R.P. in western Washington and western Oregon. Over 90% of these plots are essentially undamaged by weather or man and still providing valuable data.

<u>Phase I (fertilization only)</u> Four-year measurments of diameter breast height (d.b.h.) and total height were completed in 1974. Six-year measurements were completed in 1976. Fertilizer response results based on the 4-year data are presented in this report. Six-year results are under analysis. Present plans call for refertilization of Phase I plots after eight growing seasons.

<u>Phase II (fertilization and thinning)</u> All 4-year remeasurements of the Phase II plots have now been taken, and preliminary results are presented in this report. Project mensurationists are currently working on the 4-year Phase II data.

Phase III This newest component of R.F.N.R.P. is concentrated on activity in these areas:

1. Fertilization and thinning of 10-20 year-old stands.
2. Additional experiments in areas of low natural forest productivity.
3. Re-treatment of existing Phase I plots, 8 years following initial fertilization.

Other Studies Under R.F.N.R.P.

Effect of fertilizer on tree form To date, stem analysis studies have been carried out in eight Phase I installations. The purpose of this work is to quantify growth along the entire tree bole in order to determine whether or not measurements of d.b.h. and height adequately describe changes affecting tree volume. R.F.N.R.P. is supporting a graduate student project in analysis of tree form data.

Correlation of soils and response data This study, which is described more fully elsewhere in this report, aims at using soil characteristics to refine fertilizer response estimates.

Investigation of foliar analysis as a predictor of fertilizer response Foliage collections are being taken from a number of responding and non-responding stands. Again, the goal is to develop a practical technique for predicting fertilizer response.

Source of nitrogen study in western hemlock Past fertilizations of hemlock stands have failed to provide clear-cut guidelines. Hemlock, as a species, is known to be able to respond to nitrogen. Commonly, however, hemlock does not respond in significant amounts under forest conditions. Perhaps the problem is overstocking, which is being investigated in the thinning-fertilizer experiments. Perhaps, too, a problem exists in the form of nitrogen applied. This aspect is addressed in a special series of experiments designed to test different forms of fertilizer nitrogen in stands of western hemlock.

Fertilizer and herbicides in young plantations Combinations of nitrogen fertilizer and selective herbicides are being applied to 3-5 year-old Douglas-fir plantations. Goals are to reduce vegetative competition and stimulate height growth so that trees move quickly ahead of competitive species and above the browse line.

Effect of fertilizer on wood quality An investigation of the effects of fertilization on wood characteristics that are related to value for various products has been underway for several years and is almost completed. Results will be published in the near future.

TABLE OF CONTENTS

1 - REGIONAL ANALYSIS OF FOUR-YEAR GROWTH RESPONSE OF THE TOTAL STAND FOR DOUGLAS-FIR[1]

Introduction

This section presents an outline of the analysis of 4-year growth data available from the Regional Forest Nutrition Research Project. Eighty-seven installations of six 1/10 acre plots each are distributed over natural Douglas-fir stands in western Washington and Oregon (Table 1). In each installation two plots were not treated, two received 200 lbs. nitrogen/acre, and two 400 lbs. nitrogen /acre, in the form of urea.

The primary objective was to provide an estimate of mean response to fertilizer according to age, site, and other relevant variables. Response is measured as increase in growth rate due to fertilizer. In simple equation form,

[Treated stand growth rate] = [Growth rate as in untreated stand] plus [Increase in growth rate due to fertilizer]

and therefore response can be thought of as:

Response = [Increase in growth rate due to fertilizer] = [Treated stand growth rate] minus [Growth rate as in untreated stand]

[1] Turnbull, K. J., and Peterson C. E. (1976), Analysis of Douglas-fir Growth Response to Nitrogenous Fertilizer (Part I: Regional Trends); Contr. 13, Inst. For. Prod., Col. For. Res., U. W.

The essential phases in analysis of the regional data were as follows:

1. Analyze the growth data from all control plots to obtain estimates of untreated stand growth rate (UGR)

   UGR = f(A,S,B,SN) ...Model No. 1

2. For each treated plot, use Model No. 1 to compute

[Treatment Response] = [Treated stand actual growth rate in plot] minus [Estimated growth rate as in untreated stand (Model No. 1)]

3. Analyze all data computed as in 2 above to obtain an estimating equation for treatment response (TR)

   TR = f(S,Log PN) ...Model No. 2

4. Combine UGR and TR to obtain an estimating equation for stand growth rate throughout the region:

   $\Delta V = f(A,S,B,SN) + f(S,\text{Log PN})$ ..Model No. 3

where ΔV = periodic annual gross increment of volume (cu.ft./acre/year); A = breast height age; S = 50 year-site index; B = initial basal area (sq.ft./acre); SN = number of stems/acre; PN = pounds of nitrogen/acre; Log denotes common (base 10) logarithms.

Results of Analysis

The major topic of interest is the effect of fertilizer on gross P.A.I. (periodic annual increment) of total volume. However, a short summary on response in basal area P.A.I. is also given below; that part of the analysis was conducted as an exploratory step towards estimating volume P.A.I.

Table 1

Number of 1/10-acre plots used in four-year gross response analysis of Douglas-fir. 413 plots

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I P.A.I	II P.A.I.	III P.A.I.	IV P.A.I.
10	0	3	3	1	-
	200	3	2	-	-
	400	2	2	1	-
20	0	3	14	12	2
	200	3	16	10	3
	400	3	12	14	-
30	0	9	21	12	6
	200	11	16	14	8
	400	12	15	18	8
40	0	3	17	15	6
	200	3	19	15	7
	400	1	26	13	4
50	0	2	4	2	-
	200	1	3	2	3
	400	2	2	4	-

1. Gross P.A.I. of Total Volume: The results of the volume increment study show a mean response of 56 cu.ft. per acre per year to 200 lbs. of nitrogen across the region. This mean response is equivalent to an 18% increase over the mean estimated growth rate of untreated stands. The mean response to 400 lbs. of nitrogen is approximately 64 cu.ft. per acre per year, equivalent to a 21% increase over estimated mean increment of untreated stands. Mean response may vary by ± 8 cu.ft. per acre per year from either level of fertilizer application (95% confidence level).

As is evident in Table 10, there is no significant interaction between nitrogen dosage and stand variables except for site index. Nitrogen dosage by itself also has a significant effect on P.A.I.

2. Gross P.A.I. of Total Basal Area: 200 lb. N-treated stands show a mean increase of about 20% over gross P.A.I. of untreated stands. Mean response to 400-lb. N is slightly (2%) more. The response in both N treatments is greatest in the lower sites and in the younger age classes (Table 7). This trend is due to significant interactions of nitrogen dosage with basal area and stems, both of which vary with age and site index.

Tables 2, 3, and 4 summarize the estimates of volume, basal area, and stems; smoothed estimates of volume and basal area can also be seen graphically in Figures 1 and 2 . Tables 5 and 6 contain data means and estimated values, respectively, of basal area P.A.I. The data means and estimated values of volume P.A.I. are summarized in Tables 8 and 9. The smoothed trends of estimated volume P.A.I. for both untreated stands and stands fertilized with 200 lb. N/ac are portrayed in Figure 3 .

Table 2

Estimated mean initial total volume for Douglas-fir
(cu.ft./ac., min. d.b.h. = 1.55 inches)

B.H. Age	Site Index 80	90	100	110	120	130	140	150
10	264.6	307.7	352.0	397.7	444.4	492.3	541.3	591.2
15	901.4	1082.0	1273.0	1476.7	1689.9	1913.1	2145.9	2388.1
20	1676.5	2044.7	2442.1	2867.7	3320.6	3800.3	4305.9	4836.9
25	2444.0	3009.4	3625.2	4290.1	5003.1	5763.1	6569.4	7421.1
30	3151.7	3905.8	4731.9	5628.9	6595.4	7630.4	8732.9	9902.1
35	3787.8	4715.4	5736.2	6848.8	8051.9	9344.4	10725.4	12193.9
40	4354.8	5439.9	6637.9	7947.3	9367.0	10895.0	12533.2	14277.8
45	4860.0	6087.2	7445.4	8933.3	10549.9	12294.2	14165.3	16162.3
50	5311.4	6666.8	8169.9	9819.5	11614.8	13554.8	15638.5	17865.5

Table 3

Estimated mean initial total basal area for Douglas-fir
(sq.ft./ac., min. d.b.h. = 1.55 inches)

B.H. Age	Site Index 80	90	100	110	120	130	140	150
10	40.8	42.4	43.8	45.1	46.4	47.6	48.7	49.8
15	84.5	89.8	94.8	99.6	104.2	108.6	112.8	116.9
20	118.2	127.1	135.6	143.8	151.6	159.3	166.7	173.9
25	142.0	153.8	165.1	175.0	186.7	197.0	207.1	217.0
30	158.7	172.5	186.1	199.2	212.0	224.4	236.6	248.6
35	170.4	186.0	201.1	215.8	230.2	244.3	258.1	271.6
40	178.6	195.4	211.8	227.8	243.4	258.7	273.8	288.6
45	184.4	202.1	219.4	236.4	253.0	269.3	285.3	301.0
50	188.5	206.9	224.9	242.6	259.9	276.9	293.7	310.2

Table 4

Estimated number of initial total stems
for Douglas-fir
(min. d.b.h. = 1.55 inches)

B.H. AGE	Site Index 80	90	100	110	120	130	140	150
10	2613.3	2047.3	1645.7	1350.3	1127.9	355.5	819.5	710.3
15	2371.1	1886.8	1538.0	1278.4	1079.8	924.5	800.7	700.4
20	1959.9	1571.8	1290.2	1079.2	916.8	789.1	686.8	603.5
25	1606.8	1294.6	1067.1	896.0	763.8	659.5	575.7	507.3
30	1330.8	1075.6	889.1	748.3	639.4	553.3	483.9	427.2
35	1117.6	905.3	749.8	632.3	541.1	469.0	410.7	363.0
40	951.6	772.1	640.4	540.8	463.4	402.0	352.5	311.9
45	820.4	666.5	553.5	467.8	401.3	348.5	305.8	270.7
50	715.1	581.6	483.4	409.0	351.1	305.1	367.9	237.3

Table 5

Data means for four-year gross basal area growth for Douglas-fir (sq.ft./ac./yr., minimum d.b.h. = 1.55 inches)

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I	II	III	IV
		P.A.I.	P.A.I.	P.A.I.	P.A.I.
10	0	13.1	10.5	10.8	-
	200	15.6	18.0	-	-
	400	14.1	16.5	16.0	-
20	0	9.4	8.3	8.0	10.2
	200	11.7	9.5	11.3	10.9
	400	7.8	10.3	11.0	-
30	0	6.0	6.4	5.6	7.4
	200	7.4	7.7	7.5	9.4
	400	7.5	8.2	7.7	9.6
40	0	5.6	5.1	5.0	5.3
	200	6.8	5.9	6.3	7.7
	400	4.5	6.5	5.9	7.1
50	0	6.0	5.2	3.9	4.5
	200	6.5	6.6	5.0	5.7
	400	5.8	7.0	5.4	-

Table 6

Estimated mean four-year gross total basal area growth for Douglas-fir (sq.ft./ac./yr., minimum d.b.h. = 1.55 inches)

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I	II	III	IV
		P.A.I.	P.A.I.	P.A.I.	P.A.I.
10	0	12.2	12.4	12.6	-
	200	15.1	15.7	-	-
	400	15.5	16.2	17.1	-
20	0	8.0	8.2	8.3	8.5
	200	9.4	9.9	10.5	11.5
	400	9.6	10.1	10.8	-
30	0	6.3	6.4	6.4	6.5
	200	7.3	7.5	7.9	8.6
	400	7.4	7.7	8.1	8.8
40	0	5.4	5.3	5.2	5.1
	200	6.2	6.3	6.4	6.7
	400	6.3	6.4	6.6	6.9
50	0	4.5	4.3	4.0	3.6
	200	5.2	5.0	4.9	4.9
	400	5.3	5.1	5.1	-

Table 7

Estimated mean response of four-year gross total basal area growth for Douglas-fir (sq.ft./ac./yr., minimum d.b.h. = 1.55 inches)

B.H. Age CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I	II	III	IV
		P.A.I.	P.A.I.	P.A.I.	P.A.I.
10	200	2.9	3.3	-	-
	400	3.3	3.8	4.5	-
20	200	1.4	1.7	2.2	3.0
	400	1.6	1.9	2.5	-
30	200	1.0	1.1	1.5	2.1
	400	1.1	1.3	1.7	2.3
40	200	0.8	1.0	1.2	1.6
	400	0.9	1.1	1.4	1.8
50	200	0.7	0.7	0.9	1.3
	400	0.8	0.8	1.1	-

Table 8

Data means of four-year gross total volume growth for Douglas-fir (cubic feet/acre/year, minimum d.b.h. = 1.55")

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I	II	III	IV
		P.A.I.	P.A.I.	P.A.I.	P.A.I.
20	0	410.4	223.3	98.3	-
	200	309.2	193.3	-	-
	400	432.6	3.5.7	165.5	-
20	0	423.2	367.0	306.8	255.4
	200	471.1	427.7	397.9	365.5
	400	406.5	472.2	372.7	-
30	0	376.3	377.3	273.9	287.5
	200	451.1	435.0	363.1	337.8
	400	435.2	455.3	354.0	329.1
40	0	405.2	363.9	294.6	229.8
	200	448.5	391.9	366.6	355.6
	400	399.3	400.8	357.4	320.4
50	0	449.1	376.3	238.7	230.2
	200	441.2	470.0	325.4	260.8
	400	426.9	513.9	366.1	-

Table 9

Estimated mean four-year gross total volume growth for Douglas-fir (cubic feet/acre/year, minimum d.b.h. = 1.55")

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I P.A.I.	SITE CLASS II P.A.I.	SITE CLASS III P.A.I.	SITE CLASS IV P.A.I.
10	0	248.4	213.1	178.0	-
	200	275.2	261.3	-	-
	400	278.7	267.6	256.6	-
20	0	421.7	351.7	284.2	219.4
	200	448.5	399.9	353.7	310.4
	400	452.0	406.2	362.8	-
30	0	452.7	374.1	298.9	227.8
	200	479.6	422.3	369.5	318.7
	400	483.1	428.6	377.6	330.5
40	0	445.7	366.5	291.2	220.4
	200	472.5	414.7	360.8	311.4
	400	476.0	421.0	369.0	323.2
50	0	428.2	351.1	278.1	209.6
	200	455.1	399.3	347.7	300.6
	400	458.6	405.6	356.7	-

Table 10

Estimated mean Response of Four-year gross total volume growth for Douglas-fir. (cubic feet/acre/year, minimum d.b.h. = 1.55")

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I P.A.I.	SITE CLASS II P.A.I.	SITE CLASS III P.A.I.	SITE CLASS IV P.A.I.
10	200	26.8	48.2	-	-
	400	30.3	54.5	78.6	-
20	200	26.8	48.2	69.5	91.0
	400	30.3	54.5	78.6	-
30	200	26.8	48.2	69.5	91.0
	400	30.3	54.5	78.6	102.8
40	200	26.8	48.2	69.5	91.0
	400	30.3	54.5	78.6	102.8
50	200	26.8	48.2	69.5	91.0
	400	30.3	54.5	78.6	-

Figure 1

Estimated trends of initial total volume for Douglas-fir (cu.ft./ac., min. d.b.h. = 1.55 inches)

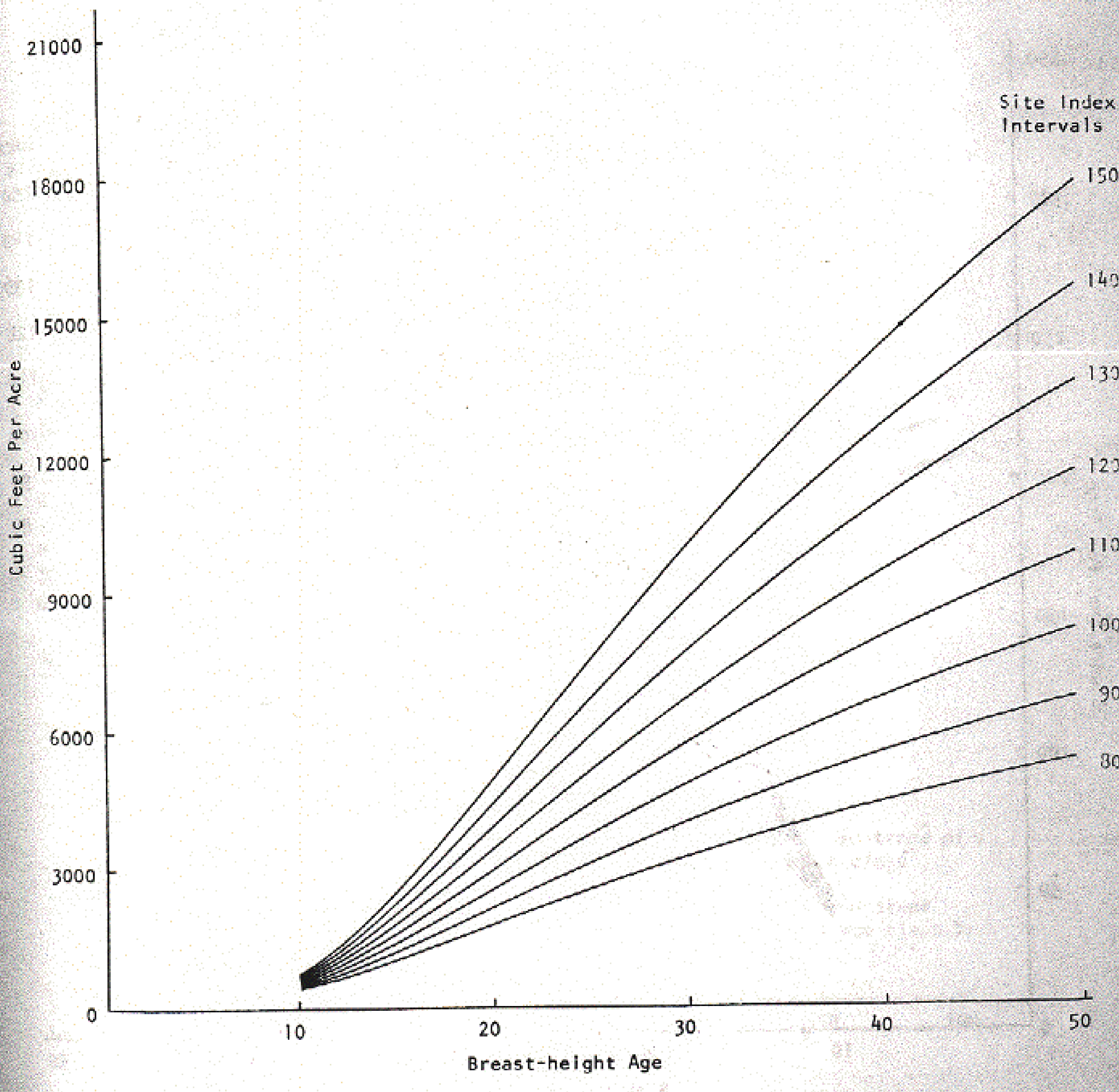


Figure 2

Estimated trends of initial total basal area for Douglas-fir (sq.ft./ac., min. d.b.h. = 1.55 inches)

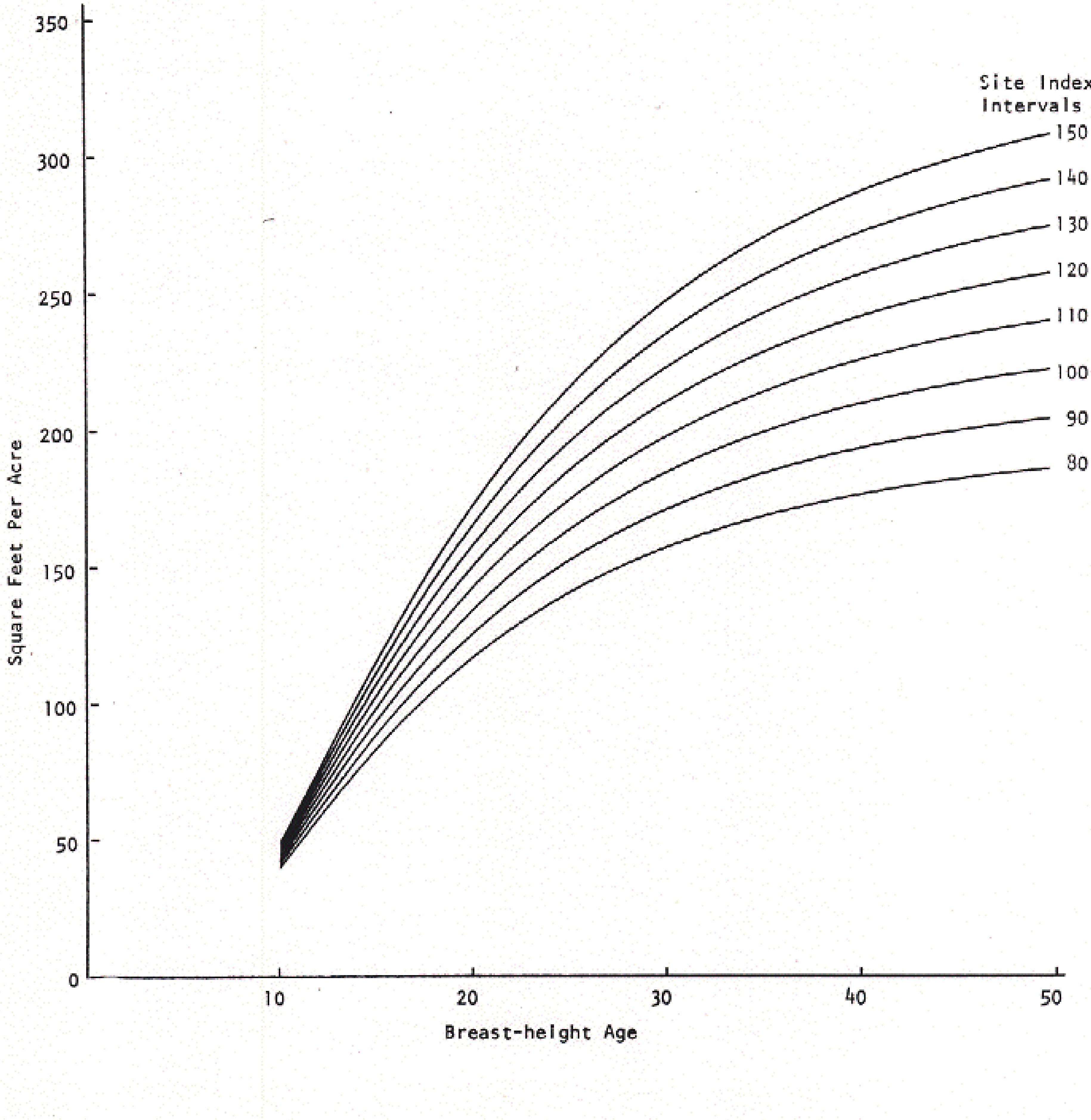
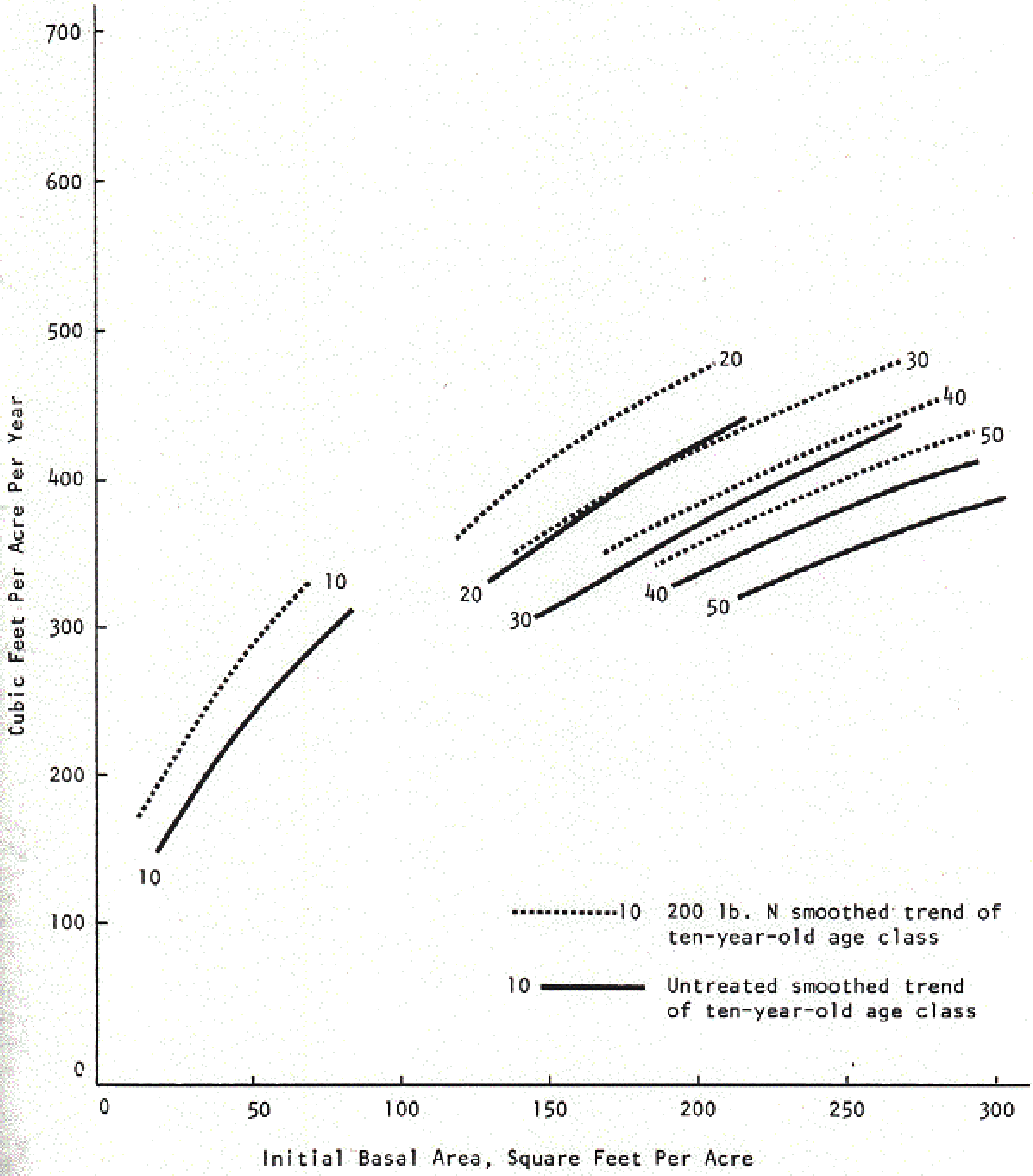
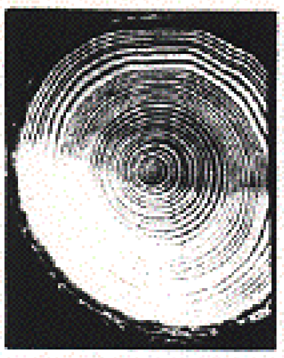


Figure 3

TREATMENT: 0 and 200 lbs. N per acre
Estimated trends of total gross volume P.A.I.

Site II





II - REGIONAL ANALYSIS OF FOUR-YEAR GROWTH RESPONSE OF THE MERCHANTABLE STAND FOR DOUGLAS-FIR

Introduction

The gross increment data (cu.ft./acre/year) was analysed for Phase I using stands in which cu.ft. merchantable volume was calculated for trees of d.b.h. greater than 6.5 inches and measured to a 4 inch top. The primary objective was to provide a regional estimate of mean response in merchantable units according to age, site, and other relevant variables. Response is measured as increase in growth rate due to fertilizer, or in equation form,

[Treated merchantable stand growth rate] = [Growth rate as in untreated merchantable stand] plus [Increase in growth rate due to fertilizer]

and thus response can be thought of as:

[Response] = [Treated stand growth rate] minus [Growth rate as in untreated stand]

Preliminary analysis revealed a substantial amount of variation of the merchantable growth rate unaccounted for by ordinary stand variables, and that a large part of this unexplained variation was due to ingrowth. For this reason, ingrowth was subtracted out of the P.A.I. such that the two elements of growth could be analysed separately. The essential phases from this point on in the analysis of the regional merchantable data were as follows:

Volume P.A.I. of the merchantable stand w/o ingrowth

1. Analyse the growth data from the control plots to obtain estimates of untreated stand merchantable growth rate (UMGR).

   $UMGR = f(S, B_M, A)$ .....Model No. 1

2. For each treated plot, use Model 1 to calculate

   [Treatment Response] = [Treated merchantable stand actual growth rate in plot] minus [Estimated growth rate as in untreated merchantable stand (Model 1)]

3. Analyse all data computed as in 2 above for significant relationships with stand variables and/or amounts of fertilizer, to obtain an estimating equation for treatment response (TR).

   $TR = f(S, LogPN)$....Model No. 2

4. Combine variables of UMGR and TR, and analyse the merchantable growth data from all (control and treated) plots to obtain an estimating equation for merchantable stand growth rate throughout the region:

   $\Delta V = f(A, S, B_M, LogPN)$....Model No. 3

   where ΔV = periodic annual volume increment, (cu.ft./ac.yr); A = breast height age; S = 50-year site index; B_M = initial merchantable basal area (sq.ft./acre); PN = pounds of nitrogen/acre; Log denotes common (base 10) logarithms.

Ingrowth

Although the mean merchantable ingrowth was about 12% of the merchantable gross increment (with ingrowth), among plots the ingrowth was highly variable, ranging from 0% to 40%. The ingrowth data means displayed a decreasing trend from low sites to high sites and from young stands to older stands. The ingrowth means for the plots treated with 0, 200, and 400 lb-N were 36.7 cu.ft./ac, 49.3 cu.ft./ac, and 46.5 cu.ft./ac, respectively.

From the preliminary inspection it appears that merchantable ingrowth is affected by fertilizer. Preliminary estimating equations for ingrowth suggest that ingrowth is related to parameters from the non-merchantable portions of the stands, but at this point no conclusions can be reached until the on-going analysis is completed.

Results of Analysis

Yield and Stocking

In addition to estimating merchantable growth rate in the untreated and treated stands, estimates of initial merchantable basal area (d.b.h. > 6.5 inches) and initial merchantable volume (to a 4 inch top) were also obtained (Tables 11 and 12, Figures 4 and 5). The smoothed estimates of merchantable basal area were used in the merchantable volume increment model to provide estimates of merchantable volume increment by classes of breast height age and site.

As discovered by plotting the data, merchantable volume has a strong linear relationship with site-height. Variation in merchantable basal area was sufficiently explained by breast-height age and site index, such that the addition of other stand variables did not make a significant contribution to the total variation explained.

Growth Rate w/o Ingrowth

The results of the merchantable volume increment study showed a mean response of 49 cu.ft. per acre per year to 200 pounds of nitrogen across the range of data. This response represents a 17% increase in the estimated untreated mean growth rate due to 200 pounds of nitrogen. The mean response to 400 pounds of nitrogen was 55 cu.ft. per acre per year for the region, representing an increase in the estimated untreated mean growth rate of about 19% due to 400 pounds of nitrogen. The standard error associated with these response estimates is 12-13% for both levels of fertilizer application.

Therefore, the actual mean merchantable response to either level of fertilizer application may vary by ± 6.5 cu.ft. (95% confidence level).

The relative means of response for each level of fertilizer application were significantly related to the logarithm (base 10) of pounds of nitrogen per acre. The response estimates showed no significant trends with age, site index, or initial merchantable basal area. However, the interaction between site index and dosage is included to present estimates of merchantable response in the same manner as the estimates of total gross response. In general, with increasing site index there is a decline in estimated response, in terms of both total and merchantable volume. It is worthwhile to note the difference in average response between total gross increment and merchantable gross increment. For the range of site classifications the difference appears almost negligible for sites I and II but progressively larger with the lower site classes. The estimated response was not significantly related to any of the stand variables with the exception of number of stems (merchantable).

The distribution of plots used in the analysis is given in Table 13. The data means and estimated means for volume P.A.I. are summarized in Tables 14 and 15; and the estimated response is summarized in Table 16. The smoothed trends of gross volume P.A.I. of merchantable stands are presented in Figure 6 for both untreated stands and stands fertilized with 200 lb.-N/ac.

Future study of response in terms of change in size distribution of (16-foot) logs and corresponding board-foot volume has been initiated. Examples of preliminary results obtained by use of the tarif volume taper equations are given in Figures 7 and 8.

Table 11

Estimated mean initial merchantable volume for Douglas-fir (cu.ft./ac., min. d.b.h. = 6.55 inches to a 4 inch top)

B.H. Age	80	90	100	110	120	130	140	150
				Site Index				
20	-	-	439.1	939.7	1487.9	2074.8	2693.6	3338.4
25	367.7	1005.0	1726.2	2515.5	3360.7	4252.4	5184.0	6150.6
30	1215.0	2090.4	3057.5	4099.9	5206.1	6368.2	7581.5	8843.1
35	2038.0	3115.5	4290.8	5548.9	6880.6	8280.3	9745.7	11276.2
40	2789.5	4036.5	5387.8	6831.0	8359.4	9970.2	11663.3	13439.6
45	3458.7	4849.1	6351.2	7955.5	9658.1	11458.7	13358.8	15360.5
50	4049.7	5563.1	7196.4	8943.2	10802.2	12774.8	14864.0	17072.9

Table 12

Estimated mean initial merchantable basal area for Douglas-fir (sq.ft./ac., min. d.b.h. = 6.55 inches)

B.H. Age	80	90	100	110	120	130	140	150
				Site Index				
20	-	-	11.9	39.9	65.0	87.3	107.3	125.0
25	7.1	43.9	76.4	105.0	130.1	152.3	171.9	189.4
30	55.6	92.3	124.2	151.8	176.0	197.3	216.3	233.4
35	91.7	127.2	157.7	184.1	207.2	227.7	246.3	263.4
40	118.0	152.0	181.0	206.2	228.4	248.5	266.9	284.1
45	137.1	169.5	197.2	221.4	243.1	262.9	281.3	298.7
50	150.9	181.9	208.5	232.1	253.3	273.0	291.4	309.1

Table 13

Number of 1/10-acre plots used in four-year merchantable response analysis of Douglas-fir. 394 plots

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I P.A.I.	SITE CLASS II P.A.I.	SITE CLASS III P.A.I.	SITE CLASS IV P.A.I.
20	0	3	14	12	2
	200	5	15	9	2
	400	3	13	12	-
30	0	9	21	12	6
	200	12	17	12	8
	400	13	15	17	8
40	0	4	18	14	5
	200	3	20	14	7
	400	1	27	12	4
50	0	2	4	2	-
	200	1	3	3	2
	400	2	2	4	-

Table 14

Data means for four-year gross merchantable volume growth (without ingrowth) for Douglas-fir (cu.ft./ac./yr., min. d.b.h. = 6.55 inches, to a 4 inch top)

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I	II	III	IV
		P.A.I.	P.A.I.	P.A.I.	P.A.I.
20	0	313.3	259.9	170.6	116.2
	200	390.6	309.5	210.9	113.5
	400	365.9	344.4	200.7	-
30	0	353.1	346.6	236.8	195.2
	200	424.6	388.3	323.5	244.5
	400	415.0	410.2	300.1	221.8
40	0	388.5	339.9	258.4	159.9
	200	426.5	371.2	328.5	239.2
	400	385.7	383.8	339.8	248.9
50	0	432.2	378.8	205.5	-
	200	436.7	491.9	304.6	208.5
	400	412.6	527.6	280.4	-

Table 15

Estimated mean four-year gross merchantable volume growth (without ingrowth) for Douglas-fir (cu. ft./ac./yr., min. d.b.h. = 6.55 inches, to a 4 inch top)

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I	II	III	IV
		P.A.I.	P.A.I.	P.A.I.	P.A.I.
20	0	389.3	284.4	179.4	74.5
	200	430.3	330.5	230.7	130.9
	400	435.6	336.5	237.4	-
30	0	396.5	309.5	222.4	135.3
	200	437.5	355.6	273.7	191.7
	400	442.9	361.6	280.4	199.1
40	0	412.8	334.6	256.5	178.3
	200	453.8	380.8	307.8	234.8
	400	459.1	386.8	314.5	242.1
50	0	432.6	359.8	287.1	-
	200	473.6	406.0	338.3	270.7
	400	478.9	412.0	345.0	-

Table 16

Estimated mean response of four-year gross merchantable volume growth (without ingrowth) for Douglas-fir (cu.ft./ac./yr., min. d.b.h. = 6.55 inches, to a 4 inch top

B.H. AGE CLASS (Yrs.)	TREATMENT (Pounds of N per acre)	SITE CLASS I	II	III	IV
		P.A.I.	P.A.I.	P.A.I.	P.A.I.
20	200 400	41.0 46.3	46.1 52.1	51.3 58.0	56.4 63.8
30	200 400	41.0 46.3	46.1 52.1	51.3 58.0	56.4 63.8
40	200 400	41.0 46.3	46.1 52.1	51.3 58.0	56.4 63.8
50	200 400	41.0 46.3	46.1 52.1	51.3 58.0	56.4 63.8

Figure 4

Estimated trends of initial merchantable volume for Douglas-fir (cu. ft./ac., min. d.b.h. = 6.55 inches, to a 4 inch top)

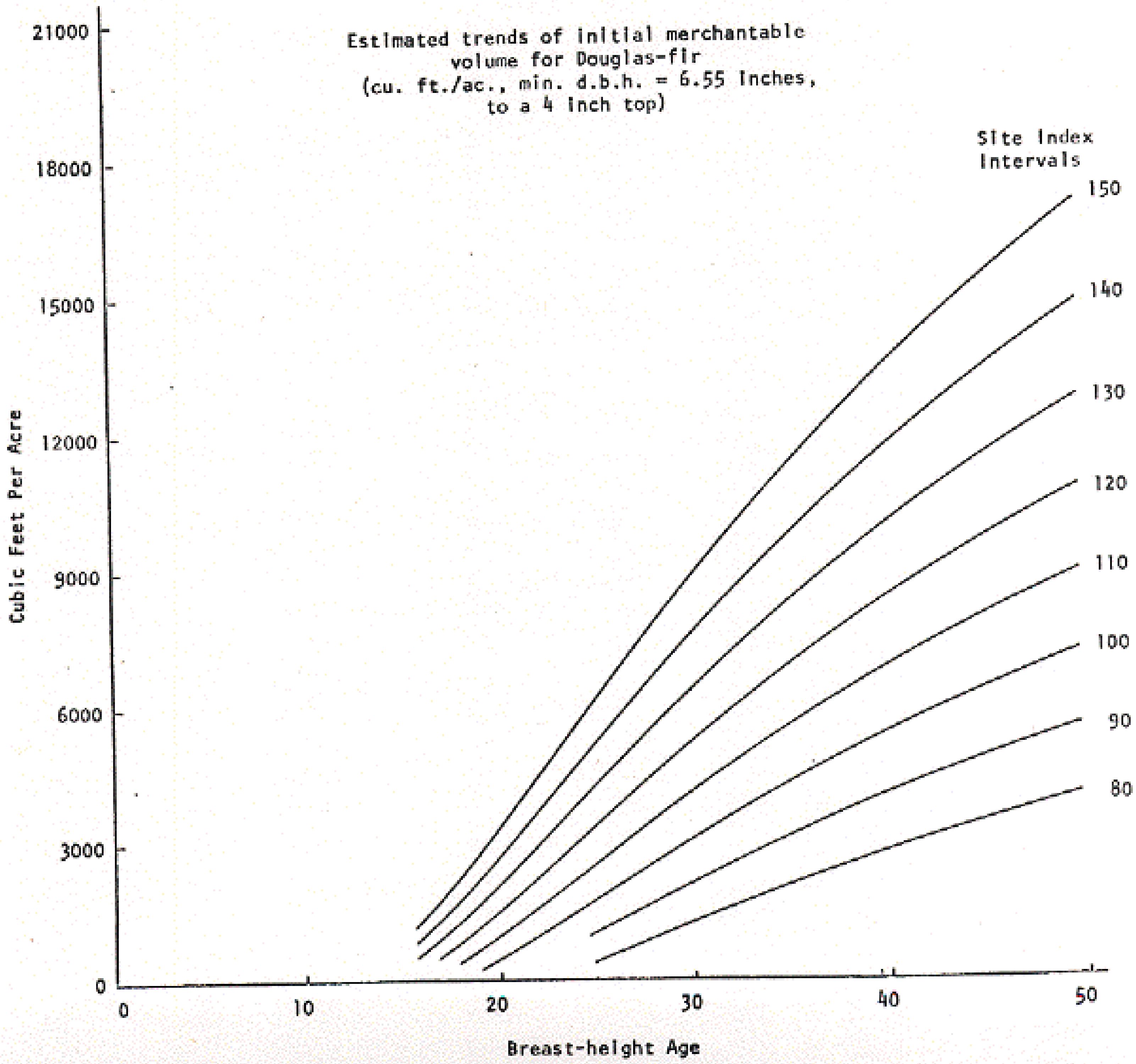


Figure 5

Estimated trends of initial merchantable basal area for Douglas-fir (sq. ft./ac., min. d.b.h. = 6.55 inches)

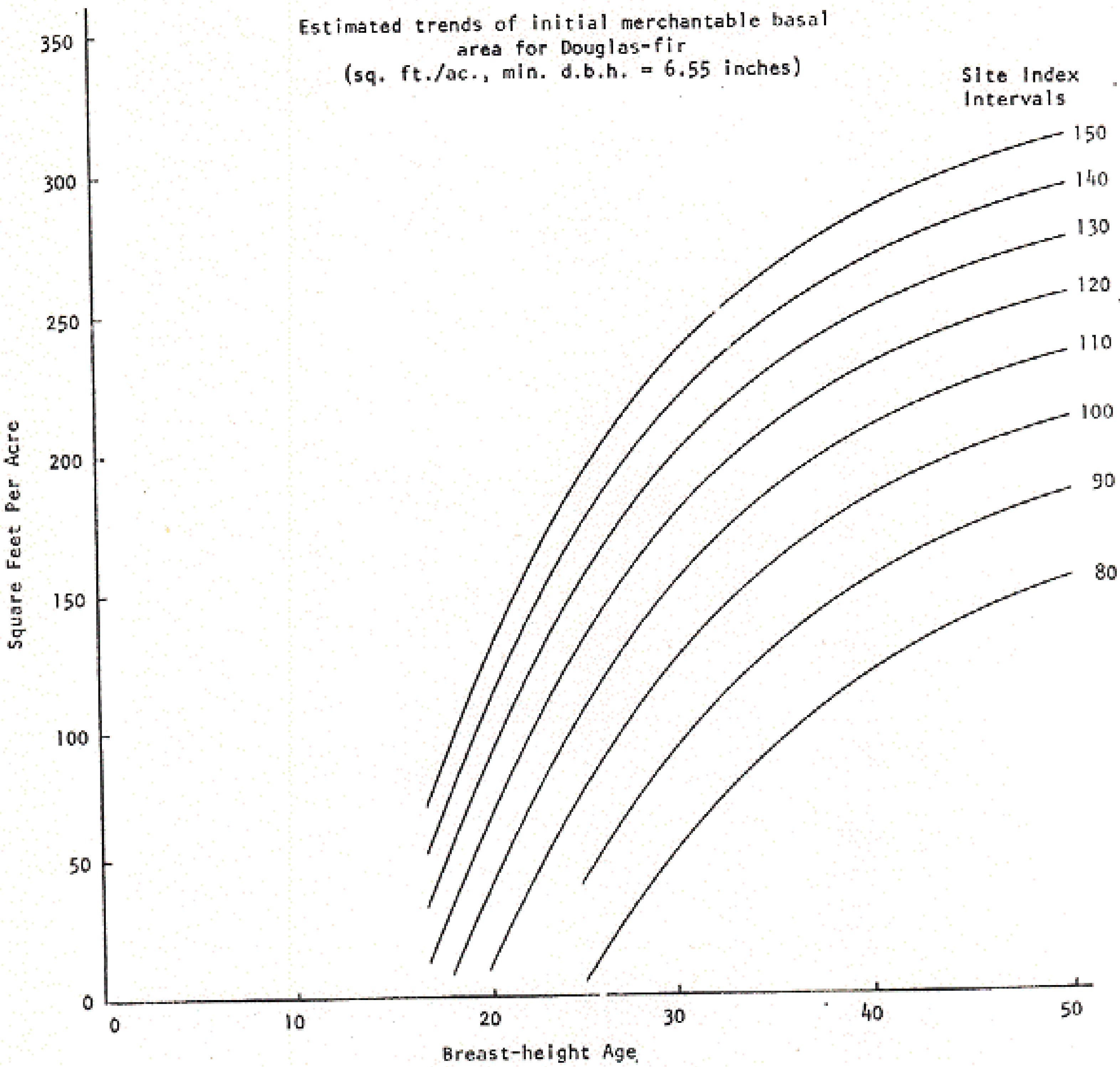


Figure 6

TREATMENT: 0 and 200 lbs. N. per acre
Estimated trends of merchantable gross volume
P.A.I. (d.b.h. > 6.5 inches, to a 4 inch top)

Site II

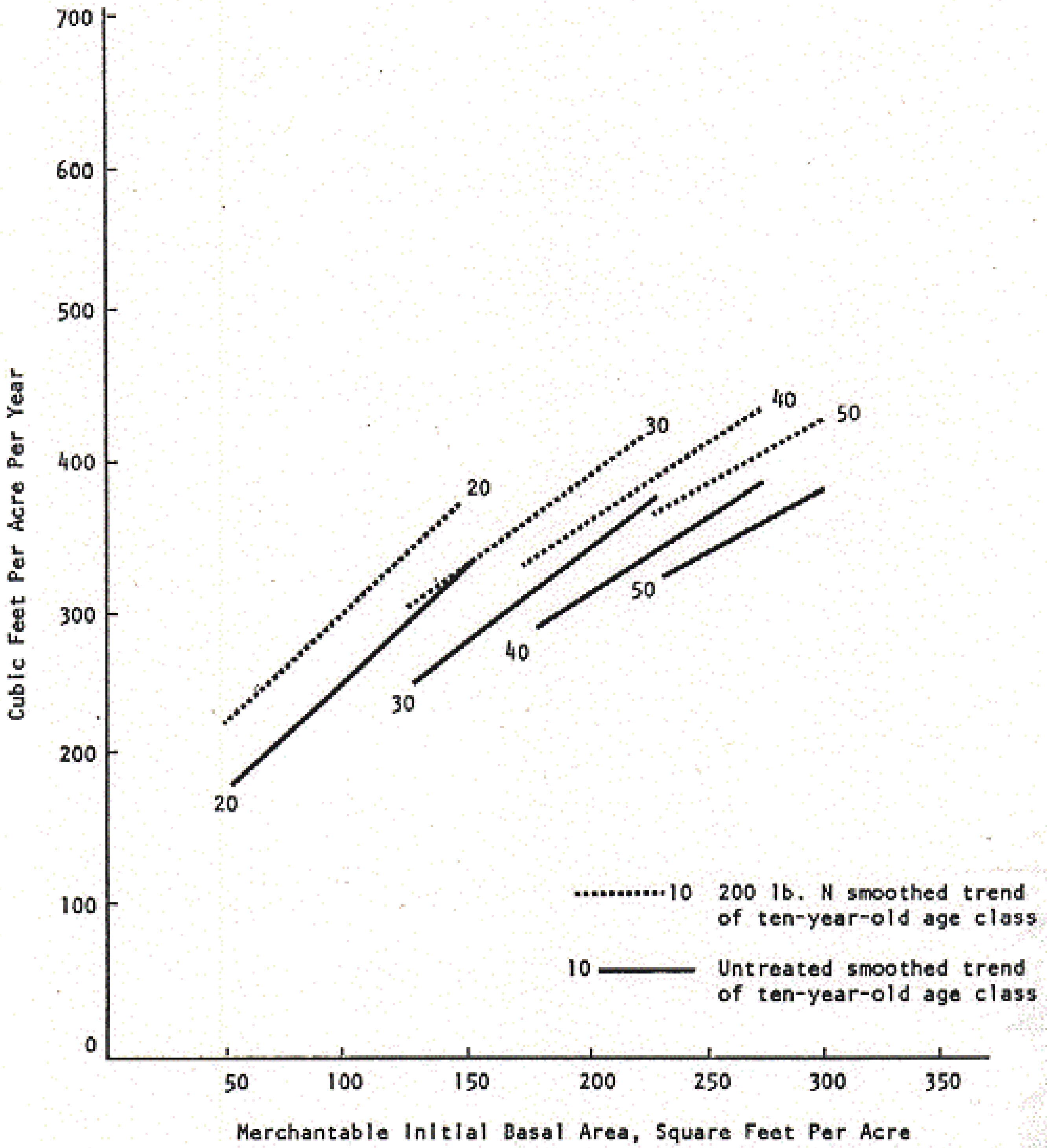


Figure 7

The change in size distribution of (16-foot) logs
(An example based on preliminary results)
Treatment levels: 0 lb-N and 200 lb-N per acre

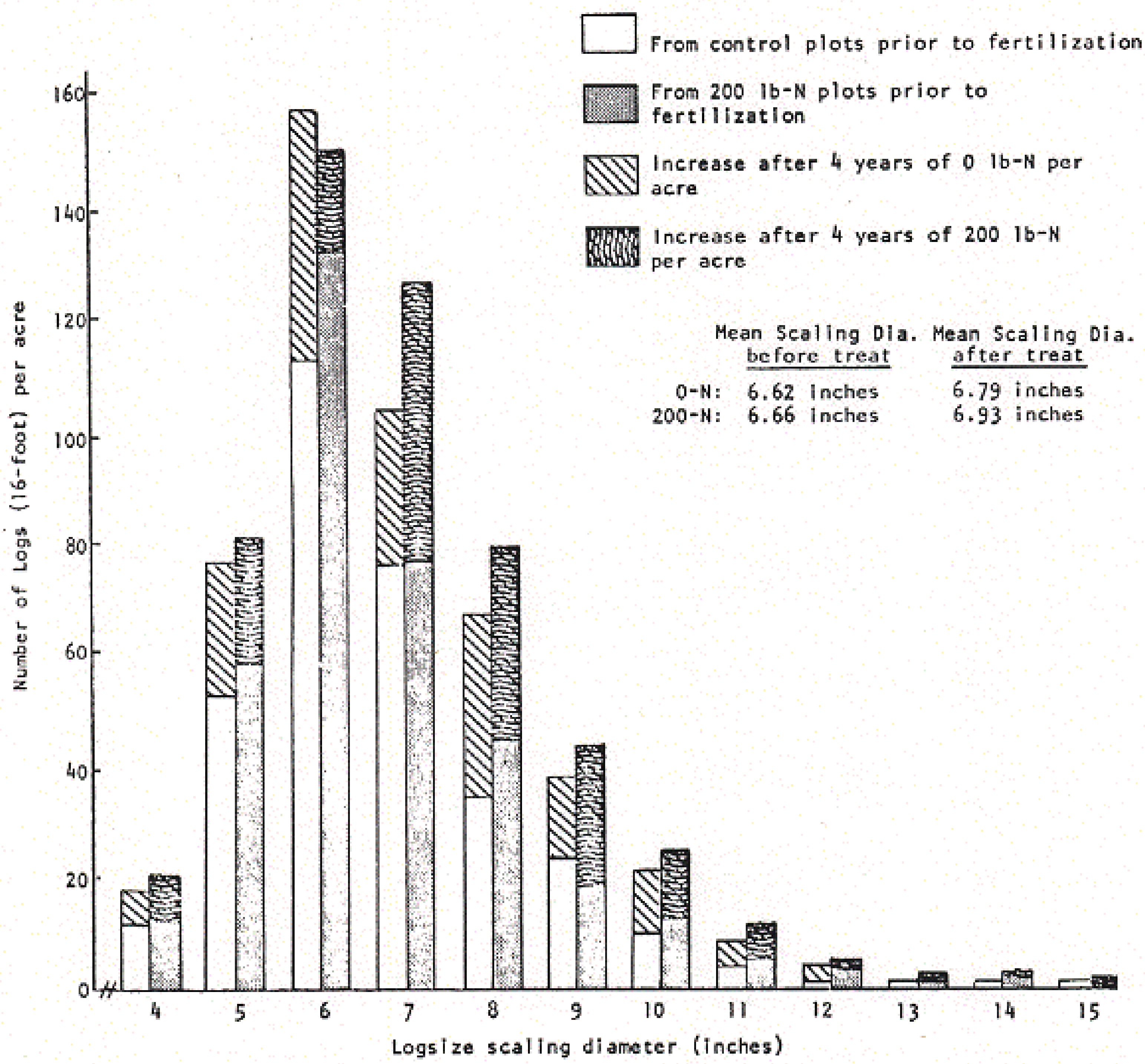
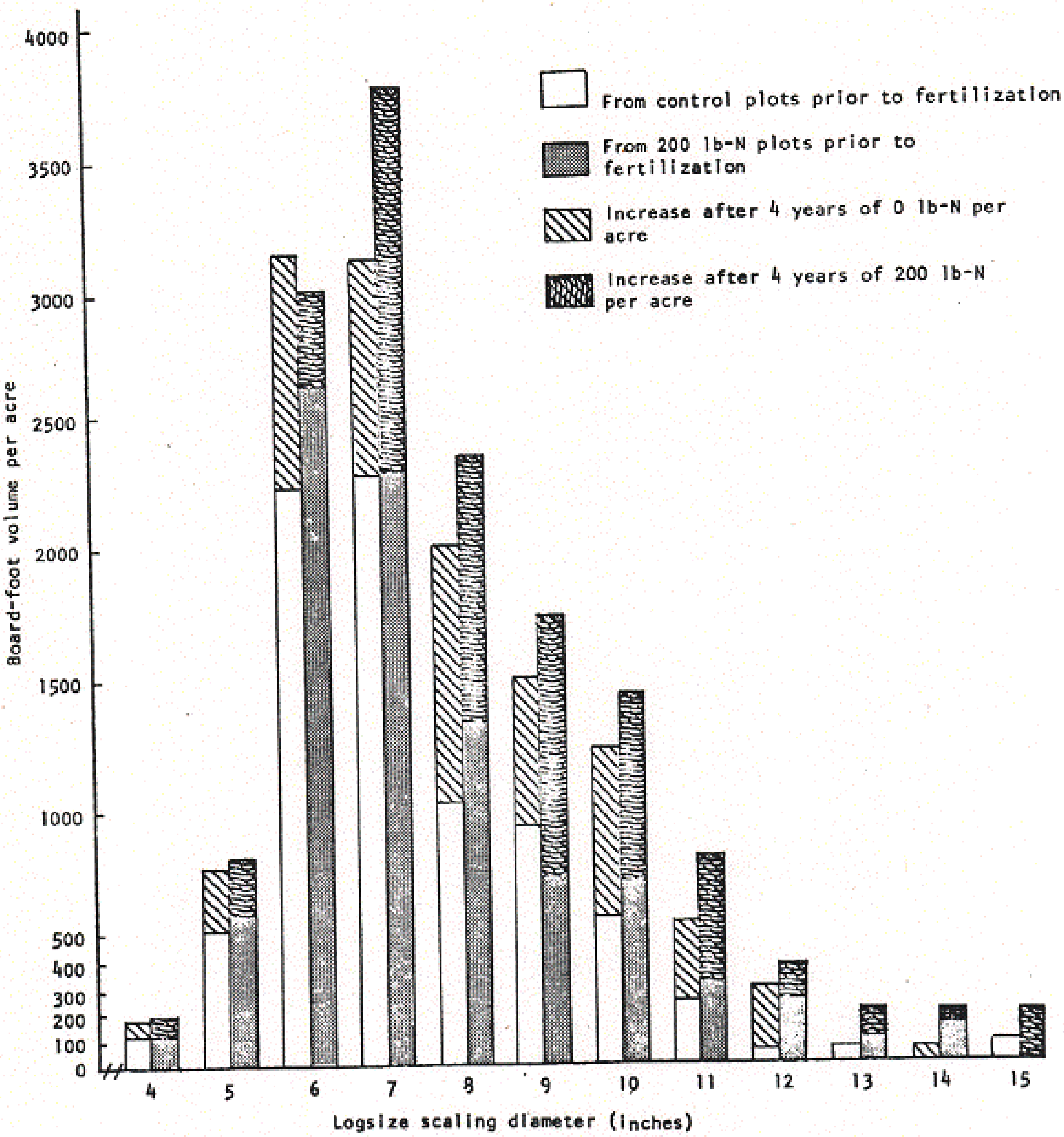
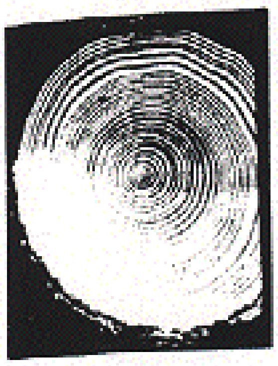


Figure 8

The change in distribution of board-foot volume (An example based on preliminary results)
Treatment levels: 0 lb-N and 200 lb-N per acre





III - PROVINCE ANALYSIS OF FOUR-YEAR GROWTH RESPONSE OF TOTAL STAND FOR DOUGLAS-FIR

Introduction

This section presents the analysis of 4-year growth data from the 87 six-plot installations of the Regional Forest Nutrition Research Project. The previous analyses were concerned with developing estimates of regional average trends of response to nitrogenous fertilizer. In this section, the analysis was aimed at discovering whether the response was different between the six provinces that form the region. If indeed the response was distinctly different, then separate tables of response estimates would be developed for each province.

The provinces (see map, Figure 9) were delineated as geographic units based on soil and climate. Since the differences in soil and climate between provinces are considerable, it would not be surprising to discover differences in response to fertilizer. The regional analysis provided estimates of response according to dosage and site index. This analysis aimed to find out whether, for given site index and nitrogen dosage, the amount of increase in volume growth rate is different between provinces. In simple terms the analysis consisted of the phases represented in Figures 10a and 10b, namely:

1. Test the province trends of untreated stand growth (Figure 10a) for statistically significant differences.

Figure 9
Map of Douglas-fir Provinces

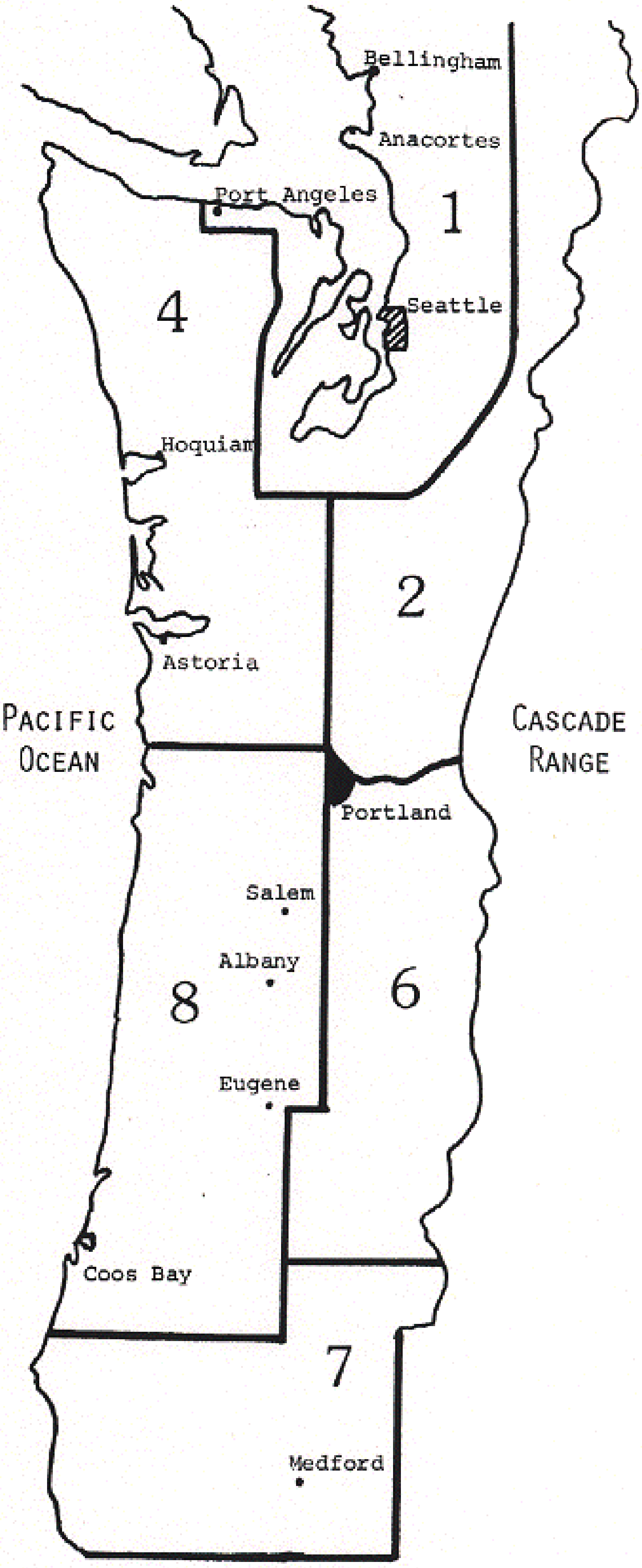
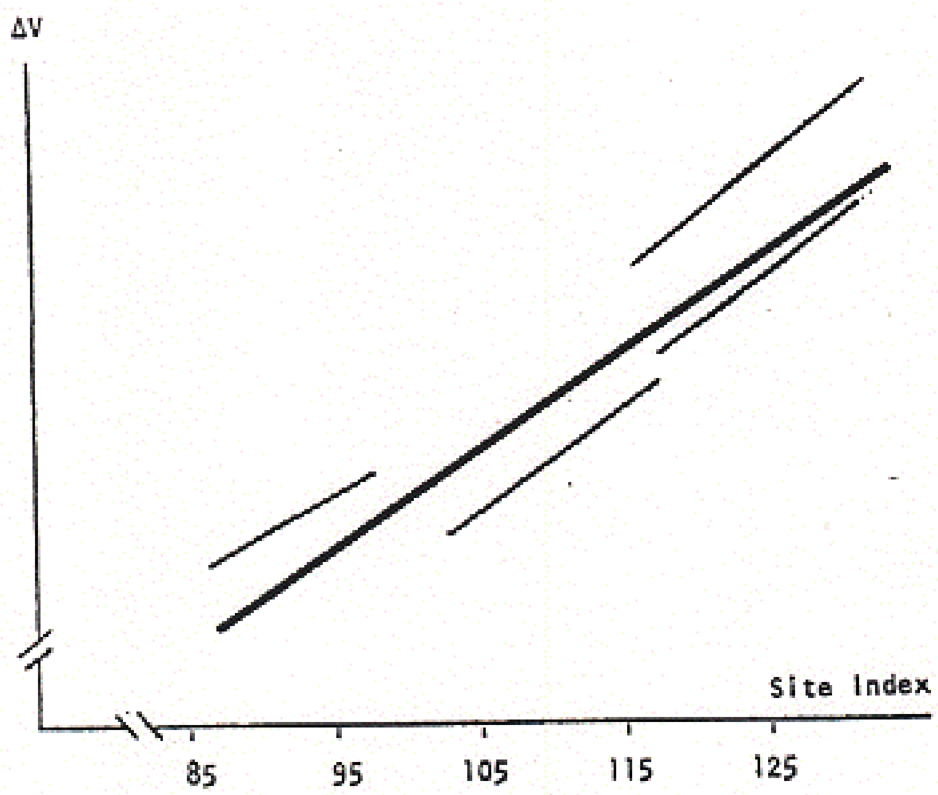


Figure 10

Diagram of Province trend lines and Region trend lines
for growth rate of treated and untreated stands,
and for treatment response.

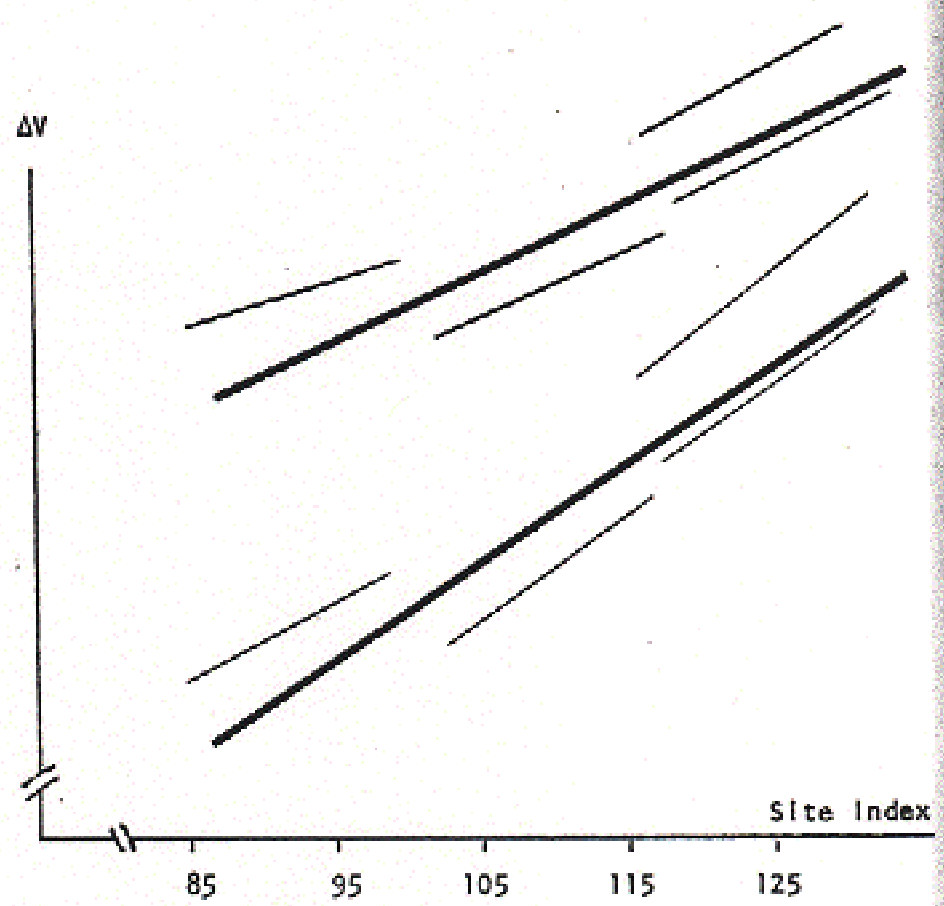
(For explanation of graphs, see RESULTS section)

Figure 10a   Trends of Untreated Stand Growth Rate



Untreated Stand Growth Rate = f(A,S,B,SN)

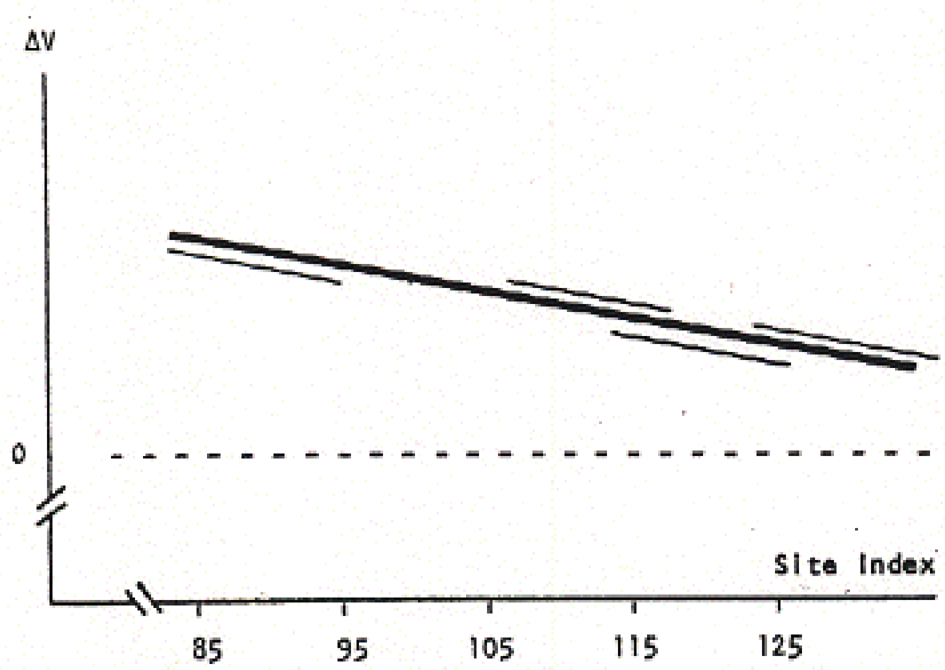
Figure 10c   Trends of Treated (top) and Untreated (bottom) Stand Growth Rate



Treated Stand Growth Rate = [Estimated untreated stand growth rate] plus [Estimated Response]

= f(A,S,B,SN) plus f(S, Log PN)

Figure 10b   Trends of Treatment Response



ΔV = periodic annual gross increment of volume, cu.ft./acre/year; A = breast height age; S = 50-year site index; B = initial basal area, sq.ft./acre; SN = number of stems/acre; PN = pounds of nitrogen/acre; Log denotes common (base 10) logarithms.

——— Province smoothed trend of volume P.A.I.

━━━ Region smoothed trend of volume P.A.I.

------------ Zero mean treatment response

Treatment Response = [Actual growth in untreated stands] minus [Estimated growth rate as in untreated stands]

= f(S, Log PN)

2. (a) if the untreated stand trends are not different between provinces, then compute response for all plots in all provinces as

[Response] = [Treated plot actual growth rate] minus [Regional estimate of P.A.I. as in untreated stands]

(b) If the untreated stand trends are different between provinces, then compute response for plots within each province as

[Response] = [Treated plot actual growth rate] minus [Province estimate of P.A.I. as in untreated stands]

3. Establish separate response trends (Figure 10b) for each province. Test these for statistically significant differences.

4. If response is different between provinces, construct separate response tables, one for each province. If not, then the regional average response tables of this study are sufficient.

Results of Analysis

The test of untreated stand trends of volume P.A.I. for the provinces, illustrated in Figure 10a, established that these are significantly different. The test of response trends for the provinces, illustrated in Figure 10b, established that these province response trends are not significantly different. What this means in terms of treated stand trends of volume P.A.I. as illustrated in Figure 10c, can be understood by recognizing that:

[Province treated stand growth rate] = [Province untreated stand growth rate] plus [Province Response]

The differences between province means of treated stand growth rate result from the significant differences between province means of untreated stand growth rate and not from differences in response. This is illustrated in Figure 11a; the province means of treated and untreated stand growth rate differ from their respective regional trend by approximately the same amount.

Figure 11b clearly shows that there is very little difference between the response estimates from the respective provinces and the response estimates from the regional trend for the respective provinces. Statistically, these differences are not significant. The large amount of variability associated with the response estimates is evidenced by the province example in Figure 12. Routine tests showed that the response model (Figure 10b) is appropriate for five out of the six provinces; response was not significantly related to age in any of the provinces except in province 7 (age-dosage interaction).

Regarding the province response estimates, statistical significance of some variables in the regression analysis should be interpreted with caution. The province sample size is, of course, much smaller than the regional sample size, and the response correlations are low ($.2 < r^2 < .6$). "Significance" of a variable in only one of six province data sets may simply be a result of sampling fluctuation; this should be studied in further tests and by additional sampling. There was no statistically significant difference in the estimates of total response obtained from the regional analysis and the subsequent analysis by province. Therefore no tables of response by individual provinces are presented in this report. Similarly, it was decided not to do analysis by province for the estimates of merchantable response.

Figure 11

Figure 11a Province means and Regional trend lines for growth in treated (200 lbs. Nitrogen) and untreated stands of Age 30 and the given site index

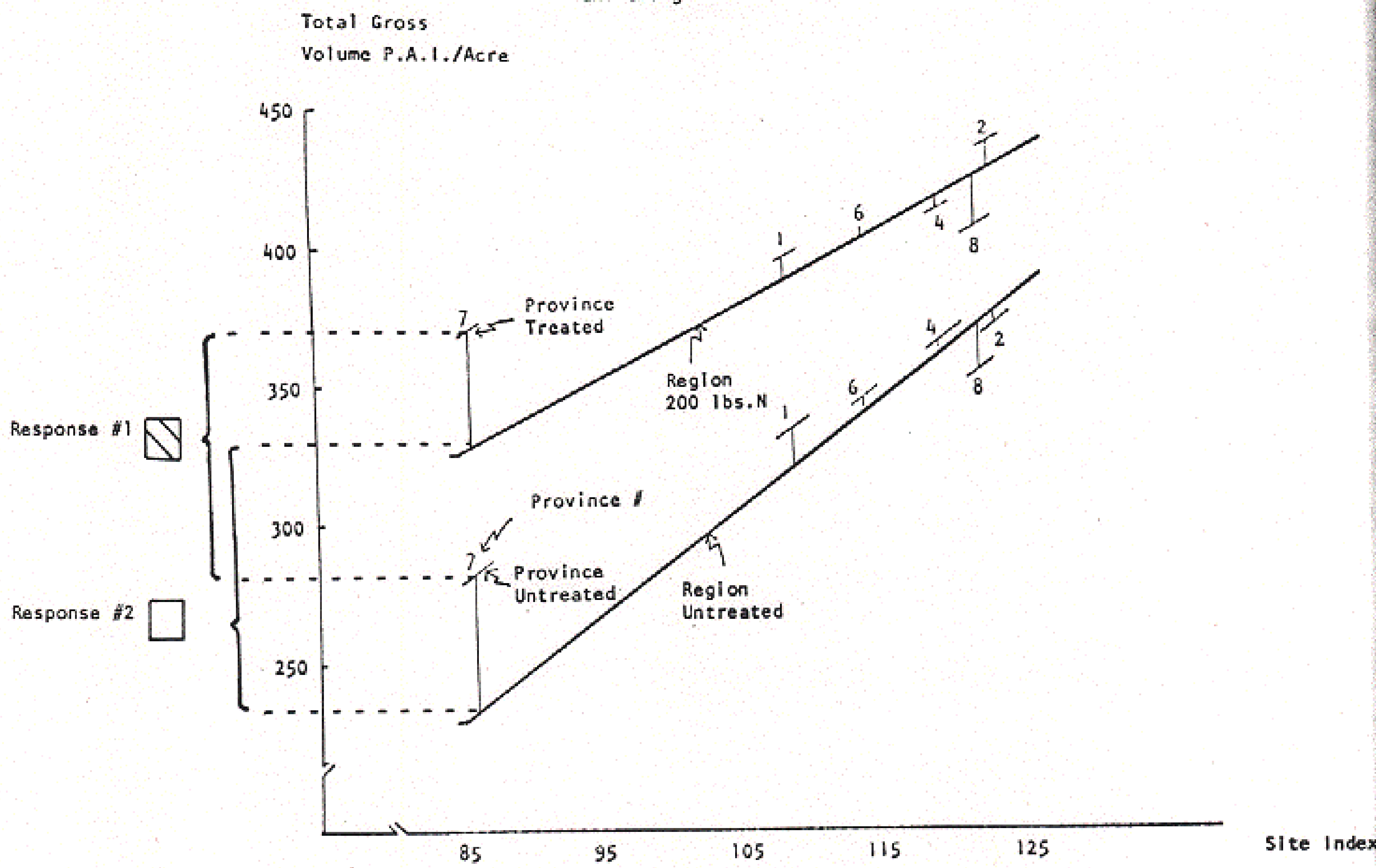
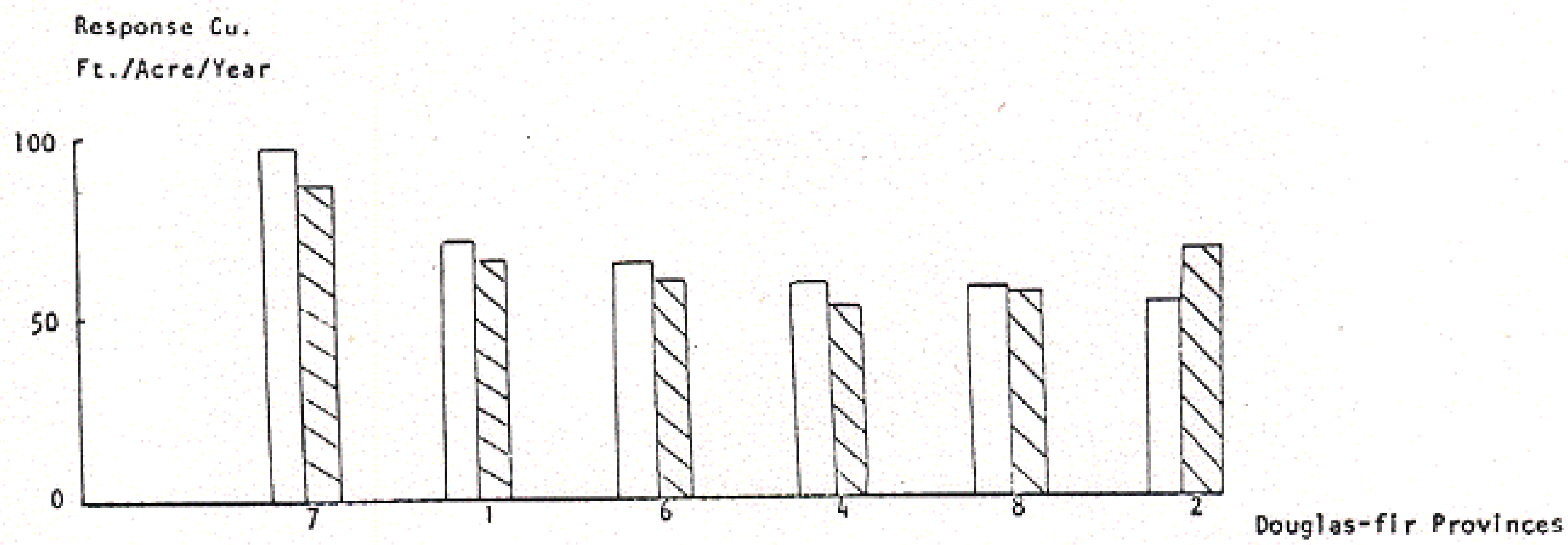


Figure 11b Comparison of Province mean response estimates computed from Province average untreated P.A.I. and from Regional average untreated P.A.I. (Computed from Figure 9a)

Response #1 = Province mean P.A.I. for 200 lbs.N minus its untreated mean P.A.I.

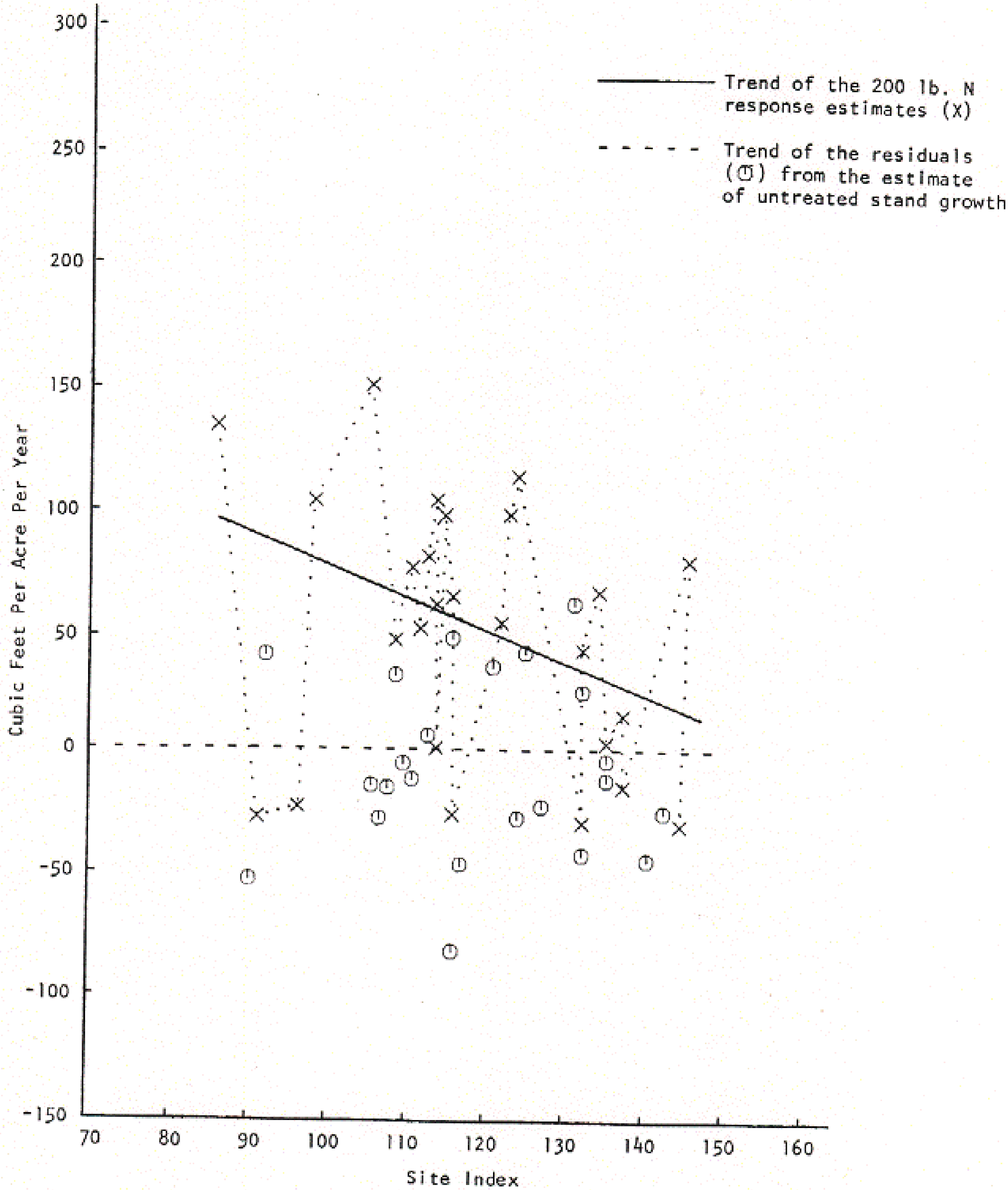
Response #2 = Regional average P.A.I. for 200 lbs.N minus Regional average P.A.I. for untreated stands, both at the province mean site index



Response #1 and Response #2 do not differ significantly for any given province, at the respective province mean site index.

Figure 12

Estimated trend of four-year gross response to 200 lb. N for a province; an example of the variability about the estimate



IV - ANALYSIS OF SINGLE INSTALLATIONS FOR DOUGLAS-FIR

Due to the importance of results from the Regional Forest Nutrition Research Project, cooperators have expressed a strong interest in having copies of the growth rate data for each of the plots in the 6-plot installations located on their company or agency land. Once a cooperator has the data in hand, the important question is, "How much can be learned from study of the data for one installation alone?"

The data supplied to cooperators has been, for each installation:

a. Site index (mean for installation), age (mean for installation), treatment, and "unadjusted" growth rate for each 1/10 acre sample plot.

b. "Adjusted" mean growth rate for each pair of plots corresponding to the three treatments (0 lbs. N, 200 lbs. N, 400 lbs. N). The "adjusted" growth rates are estimates of the mean growth rates that would have been observed if the initial volume per acre had been the same in every plot in the installation. These estimates were obtained by analysis of covariance.

In a technical note [2] it has been stated how the analysis of single installations should be done, and what limitations there are in such analyses.

The Regional study was not designed with the intention that single installations could be analysed individually. The examples in that note showed that, either for estimating response or for testing statistical significance of response, a minimum of four installations is needed. If the data has been "adjusted" by analysis of covariance, a minimum of three installations must be used. A more detailed technical examination of the design is to be given in a subsequent paper.

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[2] Turnbull, K. J., and Peterson, C. E. (1976), Analysis of Response Data From Single Installations: Contr. No. 15, Inst. For. Prod., Col. For. Res., U. W.

V - STEM ANALYSIS STUDY FOR DOUGLAS-FIR

The purpose of this study is to discover whether the geometry of stem form has been affected by fertilizing trees. The initial interest in this question originates from the use of volume estimating procedures in which it is assumed that for given d.b.h. and total height, trees in treated and untreated plots have on the average the same volume.

Data for the study are being obtained through stem analysis of sample trees felled in the buffer strips around the control, 200 lb. and 400 lb. plots. Initially eight installations representing the mean site index and age of the regional sample are being analysed. In each buffer strip, for each treatment six tree were felled: two large two average, and two small as determined by a simple rule. Increment core samples were also collected in the buffer strips and in the corresponding plots.

One pretreatment and several post treatment series of taper data have been collected for each sample tree. Analysis of volume and volume increment for treated and control plots is now in progress. Figure 13 indicates preliminary results in terms of individual tree basal area increments for sample trees in three installations in the 4 years before and after treatment.The 45° line is given for reference. Two general characteristics appear. The smaller increments, primarily on smaller trees, have changed little between periods and are virtually identical between treatments. The larger increments, primarily on the larger trees, exhibit a change between periods; the control plot tree increments have declined by approximately 15% while the treated plot tree increments have increased by approximately 20%.

While the stem analysis data will provide a basis for comparison between treatments as represented by the buffer strips, the increment core samples are being used to link the buffer strip sample to the plots, since the latter form the main basis for response estimates.

Figure 13

Preliminary example of basal area P.A.I. for Douglas-fir; behavior after 4 years of treatment (from stem analysis study)

Figure 13a Treatment: 0 lbs.-N per acre

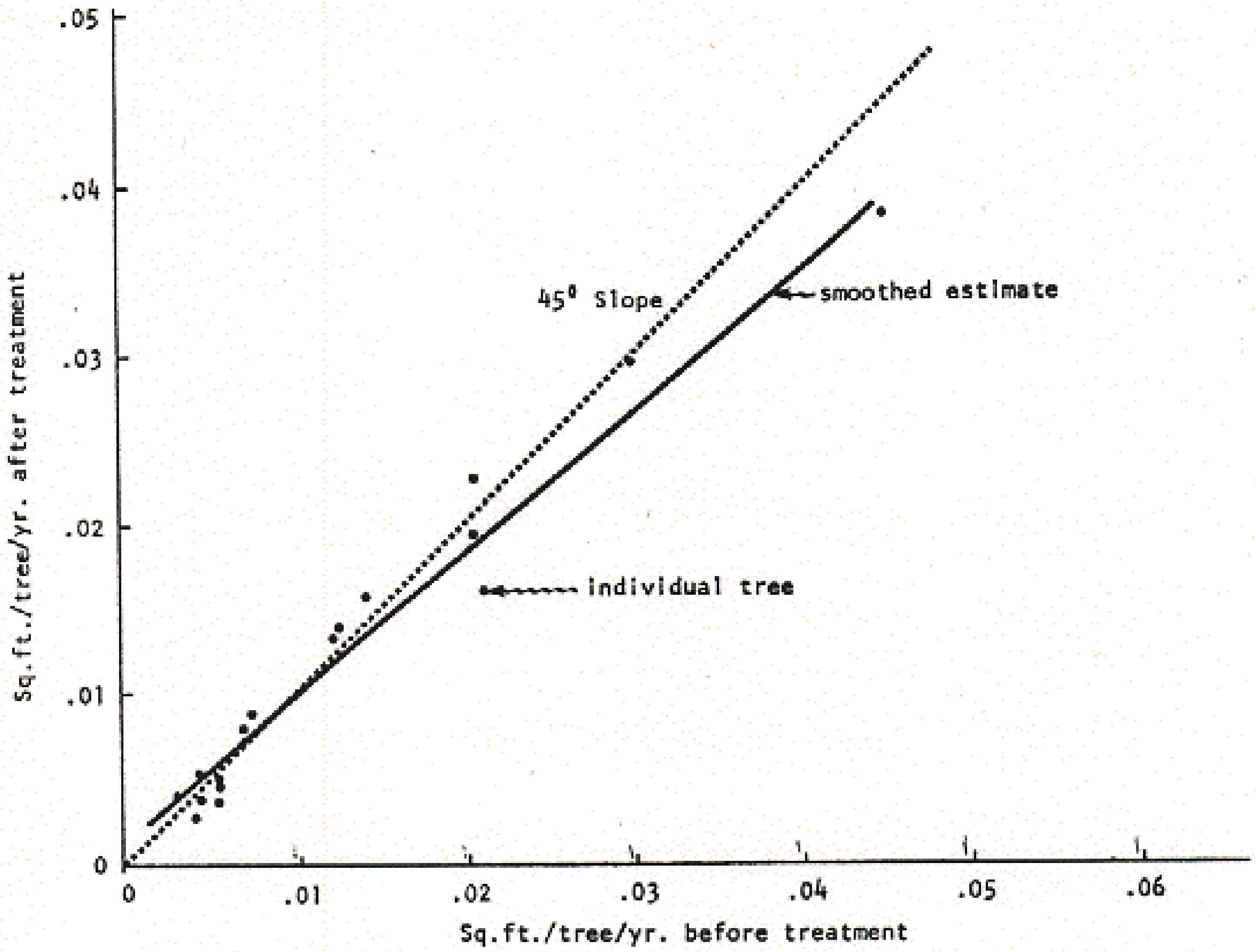
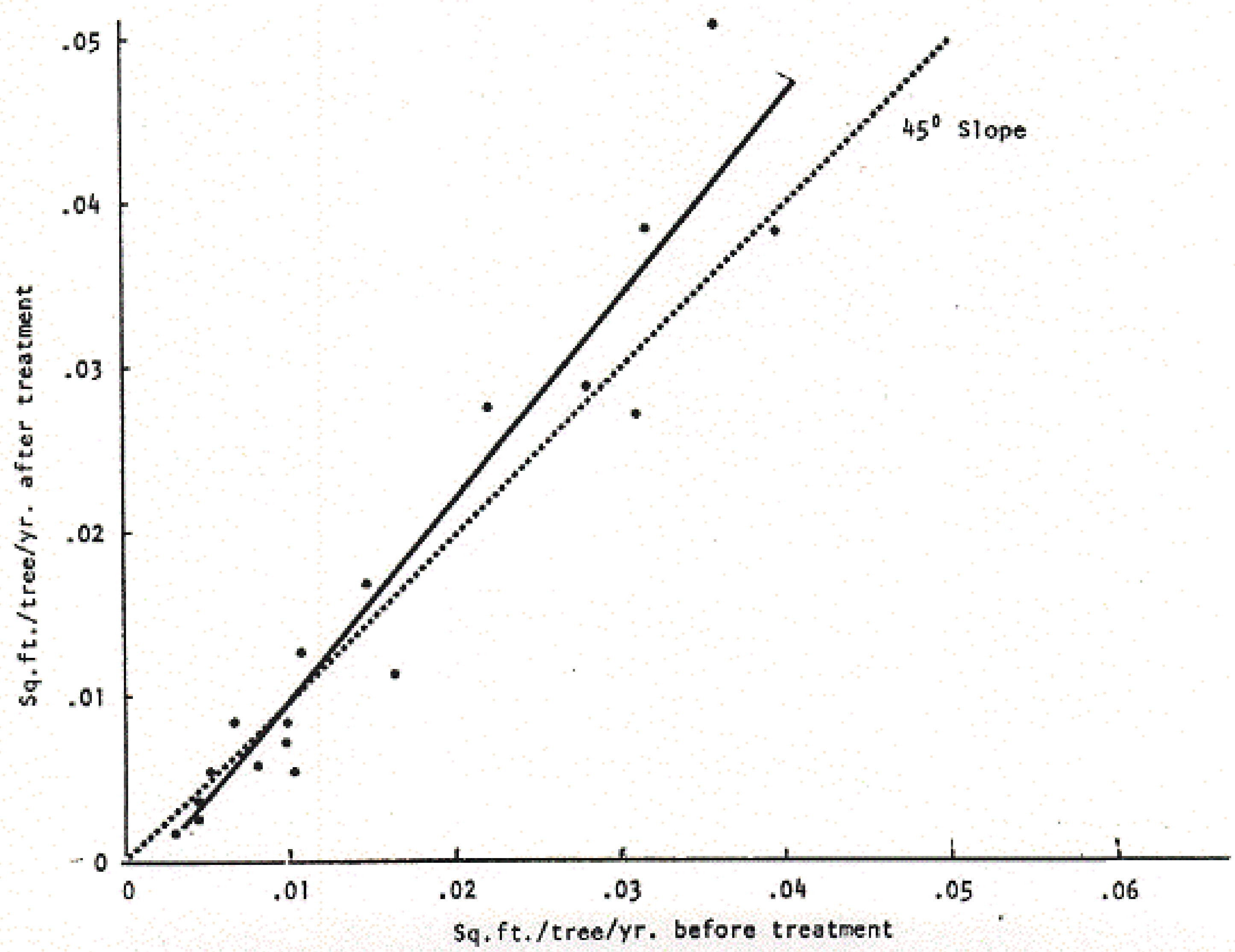


Figure 13b Treatment: 200 lbs.-N per acre



VI AN ECONOMIC ANALYSIS OF DOUGLAS-FIR RESPONSE TO NITROGEN FERTILIZER

A - Discussion of Results

Profitability of Fertilizer Investments

In this analysis a relatively simple planning problem was studied: What rates of return can be expected to be earned from one fertilization of well-stocked, unthinned stands of Douglas-fir, assuming that 200 pounds per acre of nitrogen are applied as urea, and that the extra wood attributed to fertilizer is harvested and sold ten years later. Table 17 contains results of this analysis for various age-site combinations.

Rates of return listed in Table 17 are called "real rates of return" because they are in terms of constant 1977 dollars. Effects of inflation have been removed. An investment earning a 4 percent real rate over a period of time during which the inflation rate averaged 6 percent would show a return of 10 percent if current year (inflated) prices were used in the analysis. Hence the use of noninflated dollar values eliminates distortions due to inflation and makes estimation of future returns and costs somewhat simpler.

In order to be consistent, interest rates in Table 17 should be compared with an alternative rate of return (or minimum rate which must be earned in order for the investment to be profitable) that is itself "real" or noninflated. Over many years, and in spite of the ups and downs of inflation, the real rate of return on conservative investments such as AAA bonds has remained relatively stable at 3 to 4 percent. Since forestry investments generally involve greater risks it is reasonable to require that they earn a higher rate, which will vary with individual organizations. Something in the order of a 6 percent "real" alternative rate seems reasonable for many situations. Using this as a cutoff in Table 17 it would not appear profitable to fertilize any 25 year-old stands, nor 35 year-old site I stands.

Stand Priorities for Fertilization

If the rates of return of Table 17 are used as an index of relative profitability, it is then possible to rank stands as to priority of treatment, as in Table 18. Assuming a variety of age-site possibilities for fertilization, first choice would fall on age 55, site III, second choice on age 55, sites II and IV, etc. These results should not be interpreted too specifically, however, as many other factors can influence profitability of fertilization, as will be discussed in part II. Table 18 can be interpreted simply: apply fertilizer so that response is high and that volume added is merchantable and of high value. In general terms this means avoid the highest sites and youngest ages.

Table 17 Unthinned Douglas-fir, Well-Stocked Stands

Predicted "Real" Rate of Interest Earned on Fertilizer Investment, 1977-1987, 200 Pounds Nitrogen Per Acre

Stand Age When Fertilized	50-Year Site Class			
	IV	III	II	I
25	0.7	1.9	0.9	(negative)
35	6.7	7.1	6.2	2.8
45	9.7	11.2	10.3	6.1
55	11.7	12.8	11.7	7.8

Table 18 Unthinned Douglas-fir, Well-Stocked Stands

Priorities for Fertilization With 200 Pounds Nitrogen Per Acre, 1977-1987 Investment Period

Stand Age When Fertilized	50-Year Site Class			
	IV	III	II	I
25	15	13	14	16
35	9	8	10	12
45	6	4	5	11
55	2*	1	2*	7

* = tie

Effect of Stumpage Price and Investment Period on Profitability of Fertilization

Expected profitability of fertilizer investments, as with all investments, depends in large measure on value assumptions and length of the investment period. Table 19 compares, for a site III stand that is 45 years old when treated, the profitability under four assumptions as to future stumpage price and seven investment periods (length of time between fertilizer application and sale of fertilizer-induced wood). In all cases the shorter the investment period the higher the estimated real rate of return, which merely reflectes the interest opportunity cost of time. Stumpage price assumptions #3 and #4 appear conservative in light of recent past experience; however, 10-year investments earn real rates of return of 7.5 percent and 6.4 percent, respectively. Again, one should not attempt to interpret Table 19 too narrowly. In general, investment periods longer than 20 years are shaky in terms of profitability.

Amount of Nitrogen to Apply

The most profitable rate of nitrogen to apply to Douglas-fir forests can be estimated using data on costs of applying varying amounts of nitrogen and comparing these costs with returns expected from various levels of nitrogen. Results of this "marginal analysis" for a site III, 45 year-old stand, and using a 6 percent "real" discount rate, are depicted in Figure 14. Based on four years of data, the optimal rate of nitrogen application appears to be in the neighborhood of 175 pounds per acre. Any changes in assumptions of the analysis that increase fertilizer returns relative to costs (such as higher stumpage price, lower fertilizer cost, shorter investment period or lower guiding rate of return) will tend to increase the optimal level of nitrogen. It is also possible that the 400 lbs. of nitrogen per acre treatment will result in a considerably longer duration of response, and this too would increase the optimal level. Time will tell.

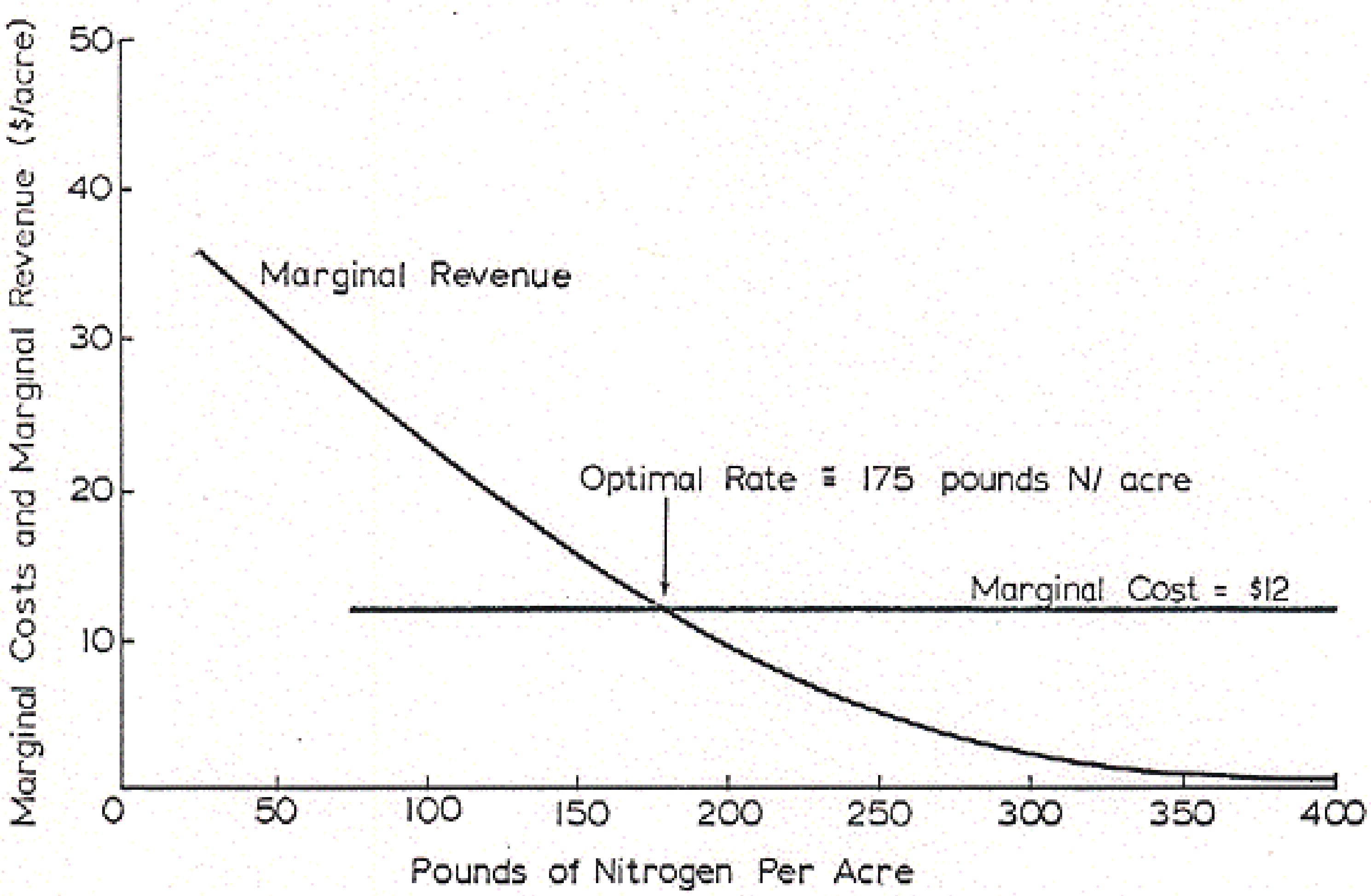
Table 19 Effect of price assumption and investment period on real rate of return, Douglas-fir, Site III, age 45 when fertilized.

Stand Age When Fertilizer Volume Response is Harvested		Stumpage Price Assumption #1		Stumpage Price Assumption #2		Stumpage Price Assumption #3		Stumpage Price Assumption #4	
Age	Date	Stumpage Price ($/M bd.ft.)	Real Rate of Return	Stumpage Price ($/M bd.ft)	Real Rate of Return	Stumpage Price ($/M bd.ft.)	Real Rate of Return	Stumpage Price ($/M bd.ft.)	Real Rate of Return
45	1977	74	--	74	--	74	--	74	--
55	1987	139	11.2	121	9.6	99	7.5	90	6.4
60	1992	161	8.4	133	7.0	105	5.3	100	5.0
65	1997	187	7.0	147	5.7	110	4.2	110	4.2
70	2002	217	6.2	162	5.0	115	3.5	121	3.8
75	2007	251	5.7	179	4.5	121	3.1	134	3.5
80	2012	291	5.3	198	4.1	128	2.8	148	3.3
85	2017	337	5.0	218	3.8	134	2.6	163	3.1

Notes:
(1) Volume gain from fertilizer = 1,100 board feet
(2) Stumpage prices are in terms of 1977 dollars
(3) Rates of return are in terms of 1977 dollars
(4) Price assumption #1, 6.5% real annual increase 1977-1987, 3% thereafter
(5) Price assumption #2, 5% real annual increase 1977-1987, 2% thereafter
(6) Price assumption #3, 3% real annual increase 1977-1987, 1% thereafter
(7) Price assumption #4, 2% real annual increase 1977-2017

Figure 14

Marginal Costs and Marginal Revenue
as a Function of Nitrogen Applied
Unthinned Douglas-fir, 50-year Site III, Age 45
6% "Real" Guiding Rate of Return
10 Year Investment Period



B - Selecting Stands to Fertilize

Biological Aspects--Select stands most likely to respond

1. Predominantly Douglas-fir
2. Well-stocked
3. Good spacing--thinned if available
4. No major disease, animal or weather damage

Appraisal Aspects--Select stands with high stumpage value

1. Accessible--short log haul--good road
2. Not too steep, regular terrain
3. Low logging cost
4. No major timber defects
5. In general, select stands so that wood added by fertilization is both merchantable and of high value

Investment Aspects--Select stands most profitable to fertilize

1. See age-site priority, Table 18.
2. Minimize investment period--try to recover volume added by fertilizer within 20 years
3. Consider fertilizing 6 to 10 years prior to final harvest or thinning

Operational Aspects--Select stands it is practical to treat with a helicopter

1. Reasonably large job to minimize move-in cost per acre
2. Homogenous stocking--not too many holes or hardwoods in stand
3. Contiguous and regular configuration--avoid small checkerboard ownership if possible
4. Reasonably straight unit boundaries
5. Not too badly cut up with streams and lakes--these require buffer strips
6. Heliports available and accessible by good road

C - Data Base and Assumptions for Economic Analysis

The profitability of forest fertilization is based on (1) measured merchantable yield due to fertilization ("volume gain"), (2) value of this increased yield ("value gain"), (3) number of years until value gain is realized ("investment period"), (4) current cost of fertilization, and (5) interest rate earnable on alternative investments ("guiding rate of return").

Fertilizer has two value-adding effects on a forest: (1) increased growth resulting in higher yield, and (2) increased tree size resulting in higher value. Both of these aspects have been included in this study of the economics of forest fertilization.

Increased Yield Due to Fertilizer

Table 20 is an estimate of board foot volume gain from one fertilization by age and site class, assuming that nitrogen is applied at the rate of 200 pounds per acre. This table is based on 4-year cubic foot response data from RFNRP plots. Conversion to board feet is made using board foot/cubic foot ratios based on average diameter and tarif for each age-site class (Chambers and Wilson, 1972, Table 10)[1]. Assumptions concerning duration of response, application irregularities, and mortality loss are built into Table 20.

Increased Value Due To Fertilizer

Stumpage price estimates for 1977 by site class and age class are presented in Table 21. Differences between sites and ages are based on the average tree size associated with each, and primarily reflect harvest cost differences (Figure 15), although wood from larger trees is also somewhat more valuable because of higher lumber recovery per cubic foot of wood input (Figure 16). For trees

[1] Chambers, Charles J. and Franklin M. Wilson, 1972. "Empirical yield tables for the Douglas-fir zone," State of Washington, Dept. of Natural Resources, D.N.R. Report No. 20R, Table 10.

Table 20

Unthinned Douglas-fir, Well-Stocked Stands

Total Volume Gain From One Fertilization With 200 Pounds Nitrogen Per Acre

Stand Age When Treated	50-Year Site Class IV	III	II	I
	(Bd. ft./acre, Scribner, 6" top)			
25	740	650	500	340
35	1,010	870	690	460
45	1,220	1,100	860	520
55	1,360	1,190	940	580

Table 21

Unthinned Douglas-fir, Well-Stocked Stands

1977 Average Stumpage Prices by Site and Age

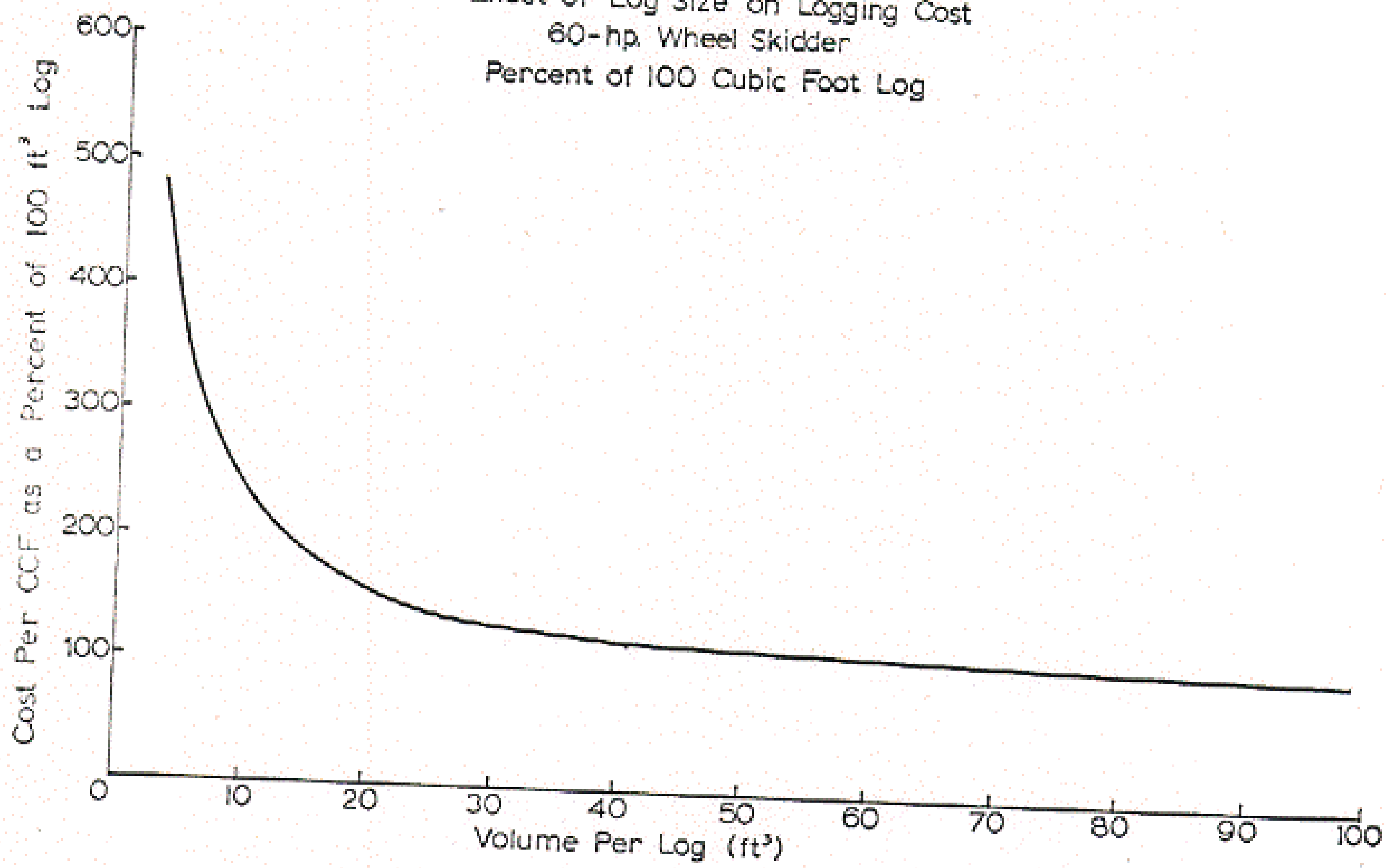
STAND AGE	50-YEAR SITE CLASS IV	III	II	I
	($/M BD. FT.)			
25	29	35	40	48
35	44	56	67	79
45	58	74	90	101
55	70	89	104	117
65	80	99	112	126

Figure 15

Effect of Log Size on Logging Cost

60-hp. Wheel Skidder

Percent of 100 Cubic Foot Log

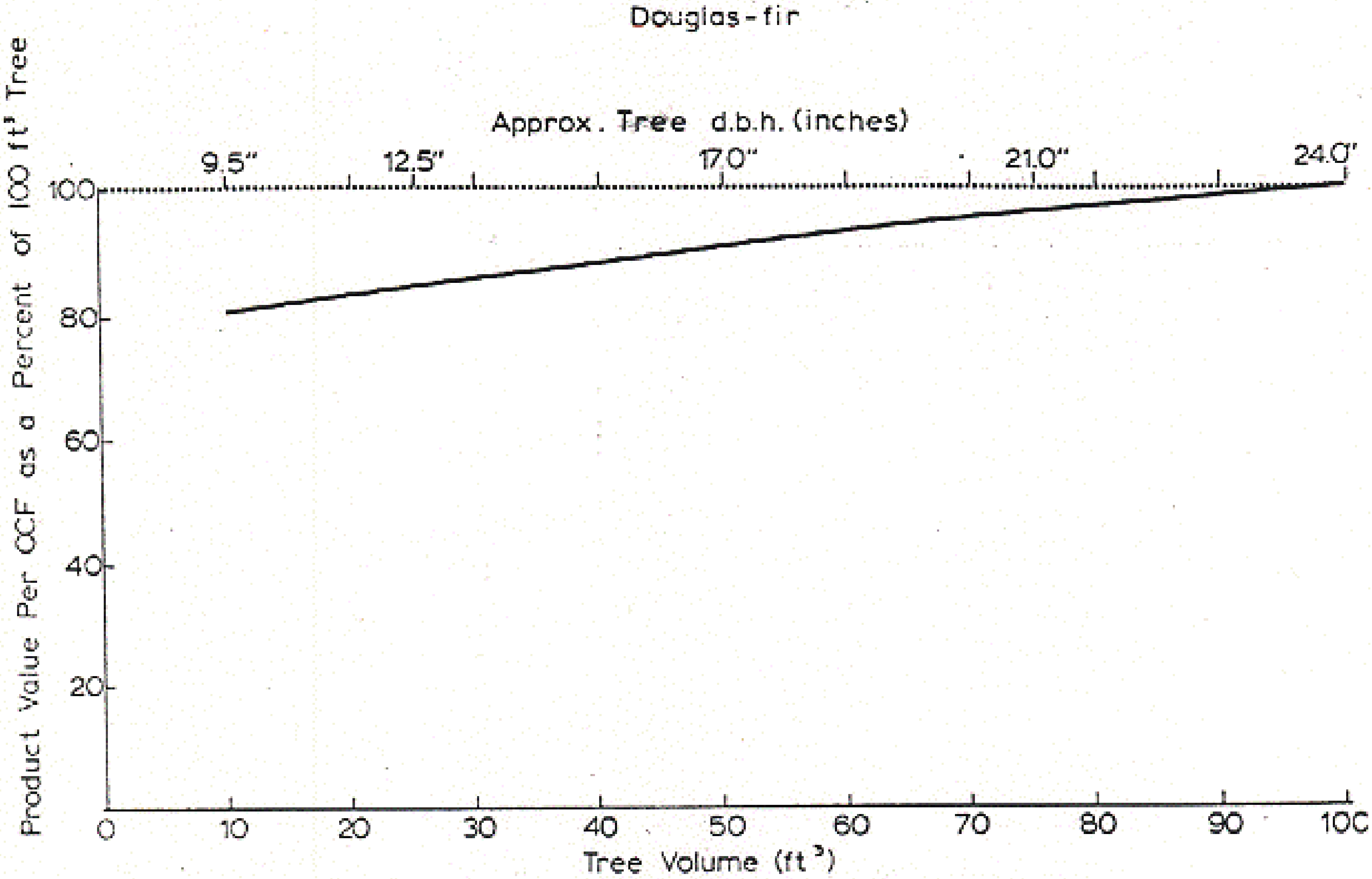


Source: T.C. Adams, "Production Rates in Commercial Thinning of Young-growth Douglas-fir," PNW - 41, Table 4.

Figure 16

Effect of Tree Size on Product Value

Douglas-fir



Based on data reported by Dobie, Kasper and Wright, 1975, "Lumber and chip values from B.C. Coast Tree and Log Classes," B.C. Forest Products Lab.

smaller in diameter than approximately 12 inches, even small differences in size have a profound effect on harvest cost and consequently on stumpage value. It has long been recognized that the primary benefit of thinning is to increase dimension of residual trees. Fertilizer too has this ability to increase tree size, and hence add value over and above volume increase. Below 12 inches in diameter the size-increasing effects of fertilizer are probably as important as its volume-adding effect.

Stumpage price estimates for 1987, when fertilizer volume gain is assumed to be sold (Table 22), are based on a real price increase of 5 percent per year, which reflects trends of stumpage and small log prices over the past 15 years in western Washington and western Oregon. An increase in the relative value of small trees was also included in the preparation of Table 22 as technology of harvesting small logs improves. Stumpage prices of Table 22 are in terms of 1977 dollars.

Value gain from fertilization is estimated in Table 23, which was derived by applying stumpage prices of Table 22 to volume gains of Table 20. Again, values of Table 23 are in terms of constant 1977 dollars. Cost of applying 200 pounds of nitrogen per acre (435 pounds of urea) was assumed to be $53 per acre (Table 24).

Table 22

Unthinned Douglas-fir, Well-Stocked Stands

Estimated Stumpage Prices in 1987 by Site and Age, in Terms of 1977 Dollars

Stand Age in 1987	50-Year Site Class			
	IV	III	II	I
25	59	69	77	90
35	77	98	116	123
45	100	121	141	152
55	110	139	164	184
65	118	149	170	193

Table 23

Unthinned Douglas-fir, Well-Stocked Stands

Value Gain From Fertilization With 200 Pounds Nitrogen
Per Acre, Ten-Year Period 1977-1987, In Terms of 1977 Dollars

Stand Age	50-Year Site Class			
	IV	III	II	I
25	57	64	58	42
35	101	105	97	70
45	134	153	141	96
55	160	177	160	112

Table 24

TYPICAL COST BREAKDOWN - FOREST FERTILIZATION (1977 COSTS, 200 POUNDS NITROGEN PER ACRE)

FIXED COSTS - (DO NOT VARY WITH FERTILIZER RATE)

	Cost/acre
Contract negotiation for fertilizer supply and application	$ 0.80
Heliport construction	0.40
Road repair, maintenance, and snow removal.....	0.50
Helicopter move-in	0.60
Crew and equipment move-in and set-up	0.30
Calibration of spreading bucket	0.25
Move between heliports	0.25
Area delineation, pilot orientation	0.10
Compliance, water sampling, landowner supervision	1.00
General administraiton by applicator	0.30
Total.....	$ 4.50

VARIABLE COST (DO VARY WITH FERTILIZER RATE)

Fertilizer (urea @ $145/ton).....	31.50
Transportation to railroad	2.40
Unload, transportation to heliport, unload	2.80
Storage, demurrage	0.20
Load helicopter	0.65
Helicopter application	10.40
Crew transportation to and from job	0.50
Crew housing	0.25
Watchman	0.10
On-ground supervision	0.30
Total.....	$48.65

Total per acre cost of job: $53.15

Amount of Nitrogen to Apply

Cost studies of forest fertilization have resulted in the cost breakdown presented in Table 24. Two aspects are important: (1) only a small proportion of total costs are fixed with regard to rate of nitrogen applied, and (2) variable costs are almost linear with respect to rate of nitrogen applied (e.g. if you double the rate of nitrogen per acre you also double the amount of urea needed, and hence this component of cost). Figure 17 demonstrates this graphically and provides an estimate of fertilization cost per acre as a function of nitrogen applied.

Volume gain from fertilization also depends on the amount of nitrogen applied. Figure 18 illustrates this relationship, although it must be remembered that in RFNRP only data for treatments of 200 and 400 pounds of nitrogen per acre are available. Hence the form of this curve is in doubt in the range of low rates of nitrogen.

The general approach to comparing costs and returns from various rates of nitrogen is to use marginal analysis. This procedure examines the change in costs and returns. As long as the increase in nitrogen dosage results in more returns than costs it is profitable to make the increase. The "optimal" solution is where marginal returns just equals marginal costs. At this point the investment in fertilization will bring the maximum profit. Such an analysis is presented in Table 25, using a 6 percent "real" guiding rate of return for discounting fertilizer value gain from 1987 to 1977. Data on marginal costs and marginal revenues are graphed in Figure 14.

Figure 17
Fertilization Costs Per Acre as a Function of Rate of Nitrogen Per Acre

1977 Costs, Urea cost: $145/ton

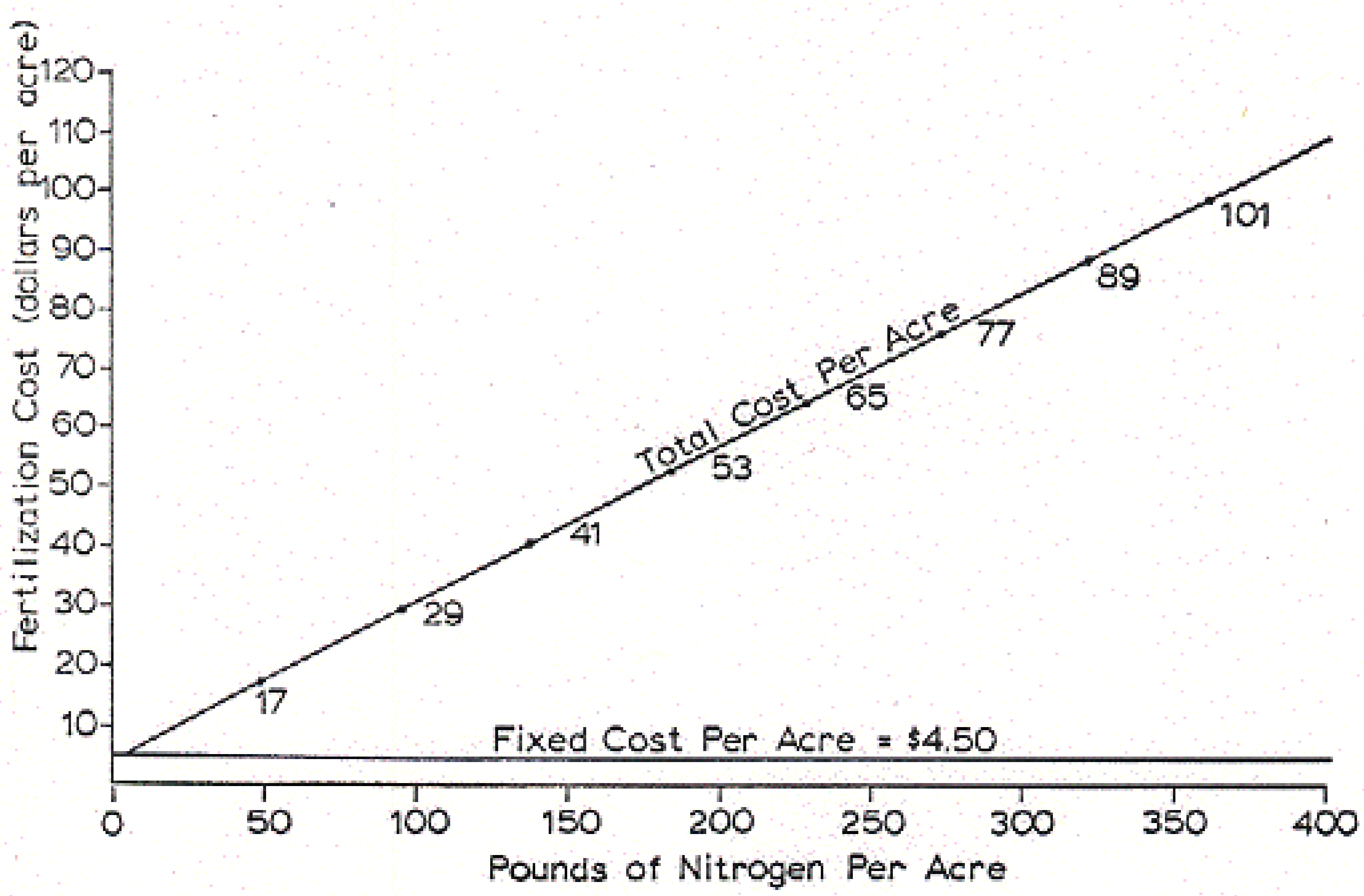


Figure 18
Board foot volume gain as a function of nitrogen applied
Unthinned Douglas-fir, 50-year Site III
Based on four-year response data, Age 45

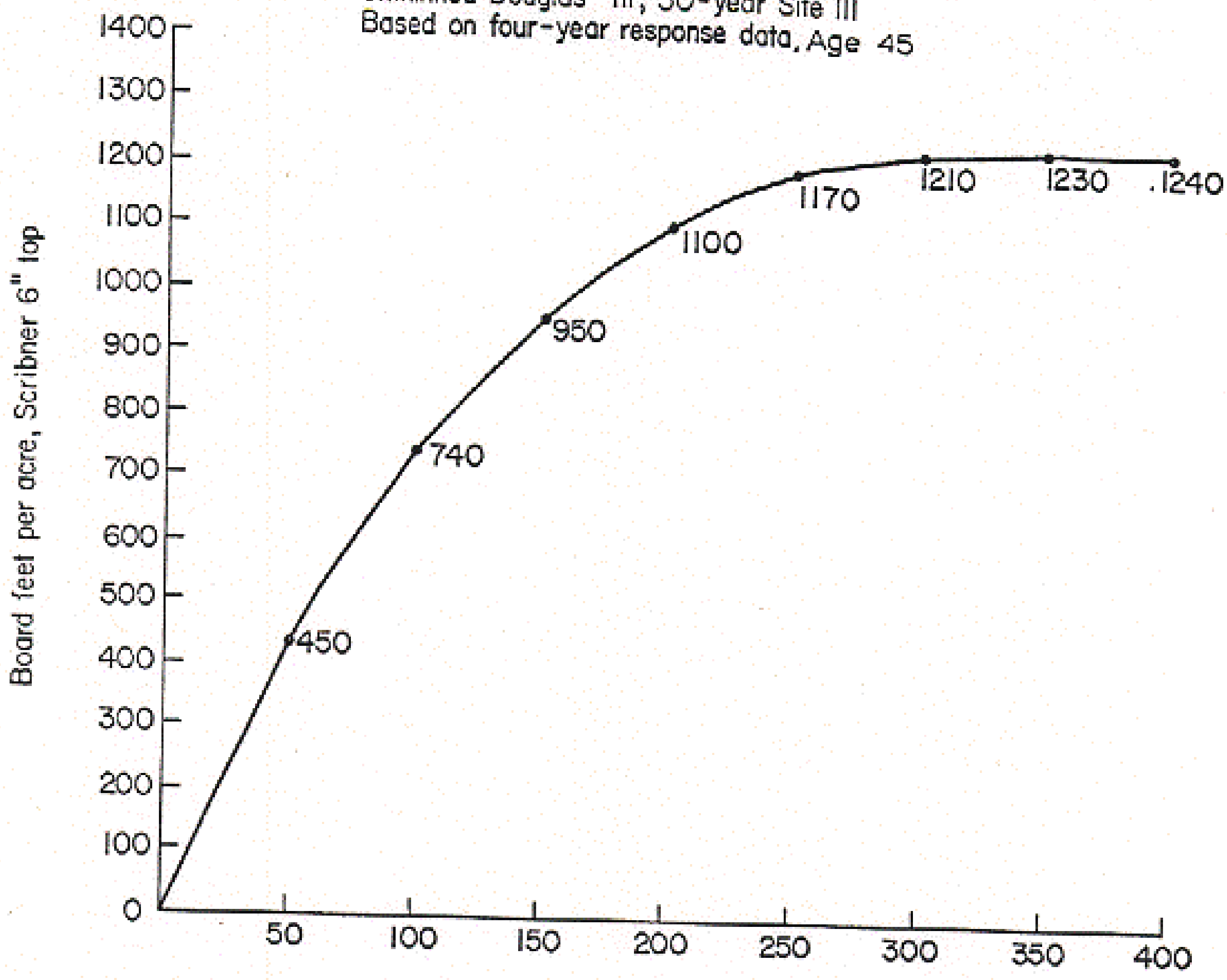


Table 25. Marginal Analysis Used to Determine Optimal Rate of Nitrogen to Apply, Unthinned Douglas-fir, Total Age 45, 50-yr Site III, 6% Real Guiding Rate of Return, 1977-1987 Investment Period.

Nitrogen Applied	Estimated Vol. Gain from Fertilization	Estimated Value of Fertilizer Gain in 1987*	Discounted Value of Fertilizer Gain @ 6%	Marginal Revenue	Total Fertilization Cost in 1977	Marginal Cost
(lbs/acre)	(bd.ft./acre)	($/acre)	($/acre)	($/acre)	($/acre)	($/acre)
0	0	0	0		0	
50	450	63	35	35	17	
100	740	103	58	23	29	12
150	950	132	74	16	41	12
200	1100	153	85	11	53	12
250	1170	163	91	6	65	12
300	1210	168	94	3	77	12
350	1230	171	95	1	89	12
400	1240	172	96	1	101	12

*Price assumption: 1977 stumpage price = $74/M bd. ft.
1987 stumpage price estimate = 139/M bd. ft. (in terms of 1977 dollars)
72% of stumpage price increase is due to a 5% rise in "real" rate of price increase.
28% of stumpage price increase is due to larger tree size.

VII - ANALYSIS OF FOUR-YEAR RESPONSE DATA OF PHASE I WESTERN HEMLOCK

Introduction

In the formulation of the experimental design of the Regional Forest Nutrition Research Project in 1968, it was decided that approximately 36 of the proposed 126 installations should be established in western hemlock stands. At that time hemlock was gaining recognition as a valuable and somewhat remarkable timber species. However, the limited amount of hemlock fertilization which had been conducted prior to 1968 did not exhibit the same consistency of results as appeared to happen with the more extensively-sampled Douglas-fir, and it was anticipated that a uniform experimental design would help to clarify the response pattern of hemlock.

The attribute of variability in hemlock has been substantiated by the analysis of the R.F.N.R.P. installations. Relative to Douglas-fir, the variances associated with most individual installations and groupings of installations are large and growth estimates of basal area and volume do not fall into obvious statistically-significant trends. The relative extent to which this is due to actual variability of response to fertilizer, to small sample size, to inadequate sensitivity of measurement techniques and analytical methods, and to other factors affecting growth is indeterminate at this time.

However, some trends have emerged. Hemlock's growth rate can, in certain instances, be stimulated by the addition of urea-nitrogen fertilizer. A favorable response is more probable in young stands, breast height ages 10 and 20, than with older stands in the 30 and 40-year age categories. Positive response is also more probable in the Western Washington Cascades (Province III) than in the Olympic peninsula (Province V), and the Oregon Coast (Province IX), where results virtually cancel to show no overall significant responses. If the data is to be taken at face value, which, as will be discussed later, is not necessarily the case, there may appear to be instances where an actual depression of growth on treated plots relative to control plots is occurring.

Hence, western hemlock is confirmed as something of an enigma. It can occupy the role of a pioneering species outpacing even Douglas-fir in the rate at which it grows during its juvenile period, or it can remain in a tolerant understory position for decades. In a major portion of the "Douglas-fir Region" it can grow on the range of sites upon which Douglas-fir grows and a number where Douglas-fir apparently loses out competitively. Its adaptability to a wide range of conditions seems to reflect itself in a wide inherent variability of morphological and physiological characteristics.

The following analysis of the hemlock installations presents the absolute mathematical differences in basal area and cubic volume increments over a 4-year period, with appropriate expressions of the variation associated with these increments. In-depth analysis or adjustment of data by covariance and regression are not presented in that a major objective of this report is to highlight the variation and hypothesize on some possible causes in order to point out appropriate avenues for future work on western hemlock.

Analysis of Basal Area Response

As mentioned above, three major western hemlock zones were delineated in the original phase I experimental design. These were selected because they differed substantively in terms of geological and climatic characteristics. The three zones are province III -- the Cascade foothills of western Washington, province V -- the Olympic Peninsula and northwest Oregon, and province IX -- the Oregon Coast. These correspond respectively with the Douglas-fir provinces II, IV, and VIII.

Suitable stands were difficult to locate; the ultimate distribution of western hemlock installations is given in Table 26. There are 27 installations described in this report. Of the 29 which were established, one was accidently refertilized by the landowner and a second was decimated by a windstorm. An additional installation lost two plots in a snowstorm. Since each installation originally consisted of two control plots, two plots fertilized with urea at 200 lbs. of nitrogen per acre, and two plots fertilized with urea at 400 lbs. of nitrogen per acre, there are 160 surviving plots included in this 4-year response analysis.

An examination of Table 26 makes apparent some major shortcomings of the hemlock data in terms of ultimate ability to establish relationships by regression. Sixteen cells representing different combinations of site, age, and province are sampled by only one installation. Only four cells are sampled by more than one installation, and these are all in the two older age categories in site class II, as, in fact, are almost half of the total installations. A number of cells have no installations in them at all; however, sites I and IV were not part of the original experimental design.

Data are summarized in Table 27 on 4-year gross basal area growth response for all installations. Gross basal area simply adds the difference between the initial plot basal area (all live stems of all species in excess of 1.55" d.b.h.) and the 4-year-remeasurement live-tree basal area to the initial basal area of any mortality which occurred. Hence, gross basal area equals net basal area (without ingrowth) plus mortality.

In each instance, the average basal area periodic annual increment (P.A.I.) of two similarly treated plots is compared to the average P.A.I. of the two control plots. The probability of occurrence of the difference between the two means to have been caused by some effect other than chance is indicated in a test of significance.

An example of the use of Table 27 is the top line, installation number 18 in Province III. The data for the control versus 200 pound nitrogen treatment are:

	Control-0 lb. N	200 lb. N
Basal Area	Plot 103 =	Plot 105 =
P.A.I.	7.40 sq.ft.	7.80 sq.ft.
Basal Area	Plot 108 =	Plot 106 =
P.A.I.	7.50 sq.ft.	8.90 sq.ft.

$\Sigma X_c = 14.90$ sq.ft. $\qquad \Sigma X_2 = 16.70$ sq.ft.

$\overline{X}_c = 7.45$ sq.ft. $\qquad \overline{X}_2 = 8.35$ sq.ft.

Difference = Treated minus Control = $\overline{X}_2 - \overline{X}_c$ = +0.90 sq.ft. In order to determine the variance associated with each mean, the following formula is used.

$$s^2 = \frac{\Sigma X^2 - \frac{(\Sigma X)^2}{n}}{n - 1}$$

Since n = number of samples per treatment, n is equal to 2:

$$s_c^{\,2} = 0.005 \qquad s_2^{\,2} = 0.605$$

Table 26 Four-year response data for phase I western hemlock, number of installations by site, age, and province.

B. H. Age Class (yrs)	Site I			Site II			Site III			Site IV			Age Class Total			Sum
	Province															
	III	V	IX	III	V	IX	III	V	IX	III	V	IX	III	V	IX	
10		1	1		1		1						1	2	1	4
20				1	1	1				1			2	1	1	4
30		1	1	3	1	2	1	1					4	3	3	10
40				2	4	1	1	1					3	5	1	9
Province Total	0	2	2	6	7	4	3	2	0	1	0	0	10	11	6	
Site Class Total	4			17			5			1						27

Table 27 Four-year gross basal area growth response by plot comparison method, phase I western hemlock installations, all trees initially over 1.55" D.B.H.

Province	Installation	Initial Breast Height Age (yrs)*	Initial 100-yr Site Index (feet)	200 lb Plots' Mean Basal Area P.A.I. Response Over Control Plots Mean Total Gross P.A.I. (sq.ft./acre/yr)	Percent Response	Probability Level of Calculated "t" Value of 200 lb. Basal Area Response	400 lb Plots' Mean Basal Area P.A.I. Response Over Control Plots Mean Total Gross P.A.I. (sq.ft./acre/yr)	Percent Response	Probability Level of Calculated "t" Value of 400 lb. Basal Area Response
III	18	28	176 (II)	+0.90/ 7.45	+12%	.70+	+0.75/ 7.45	+10%	.70+
	23	34	167 (II)	-0.60/ 5.45	-11%	.98+	-0.35/ 5.45	- 6%	.70+
	24	20	95 (IV)	+4.70/12.15	+39%	.98+	+5.55/12.15	+46%	.99+
	44	41	154 (III)	+0.75/ 5.70	+13%	.60+	+0.60/ 5.70	+11%	.50-
	58	26	155 (III)	+0.35/ 8.80	+ 4%	.50-	+0.05/ 8.80	+ 1%	.50-
	108	42	170 (II)	+0.35/ 6.00	+ 6%	.50-	No Difference	-	-
	109	31	161 (II)	+0.60/ 6.70	+ 9%	.50-	+0.35/ 6.70	+ 5%	.50-
	111	38	178 (II)	+1.45/ 5.25	+28%	.80+	+1.20/ 5.25	+23%	.70+
	112	15	143 (III)	+2.75/13.10	+21%	.70+	+3.85/13.10	+29%	.70+
	117	17	171 (II)	+1.55/12.85	+12%	.60+	+1.25/12.85	+10%	.99+
V	2	45	152 (III)	-0.25/ 4.95	- 5%	.50+	+0.30/ 4.95	+ 6%	.50+
	3	28	159 (II)	+0.20/ 8.10	+ 2%	.50-	-0.70/ 8.10	- 9%	.50-
	4	36	182 (II)	+0.95/ 5.50	+17%	.50+	+0.70/ 5.50	+13%	.60+
	9	36	164 (II)	-0.45/ 7.05	- 6%	.80+	+0.15/ 7.05	+ 2%	.50-
	15	30	187 (I)	-1.00/ 7.55	-13%	.70+	-0.10/ 7.55	- 1%	.70+
	38	37	158 (II)	+0.30/ 4.70	+ 6%	.50+	+0.10/ 4.70	+ 2%	.50-
	39	18	172 (II)	+0.15/13.60	+ 1%	.50-	-1.75/13.60	-13%	.50+
	42	38	168 (II)	-0.45/ 5.65	- 8%	.60+	+0.80/ 5.65	+14%	.70+
	80	29	143 (III)	-0.60/ 9.25	- 6%	.50+	-0.15/ 9.25	- 2%	.50-
	84	14	194 (I)	+0.80/13.00	+ 6%	.50-	+0.20/13.00	+ 2%	.50-
	100	12	175 (II)	+1.85/10.40	+18%	.50-	-0.80/10.40	- 8%	.50-
IX	48	30	186 (I)	-1.10/ 7.80	-14%	.80+	-1.05/ 7.80	-13%	.50-
	49	31	181 (II)	+0.15/ 7.25	+ 2%	.50-	-0.40/ 7.25	- 6%	.50-
	70	26	159 (II)	-2.15/10.55	-20%	.80+	-0.80/10.55	- 8%	.50-
	72	36	161 (II)	-0.65/ 5.80	-11%	.60+	No Difference	-	-
	73	20	172 (II)	-2.15/14.20	-15%	.70+	-2.70/14.20	-19%	.90+
	86	12	186 (I)	+1.50/15.80	+ 9%	.80+	No 400 lb. plots	-	-

*Installations up to #49 established in 1969, numbers 58 and greater in 1970.

In order to test for significance, these variances are pooled:

$$s^2 = \frac{s_c^{\ 2} + s_2^{\ 2}}{2n-2}$$

where "n" is the number of plots represented in each variance. Hence, for the example,

$$s^2 = \frac{0.005 + 0.605}{2} = 0.305$$

The standard error of the difference between treatment means is then calculated:

$$s_{\overline{X}_2} - \overline{X}_c = \sqrt{\frac{2s^2}{n}} = \pm\ 0.55 \text{ sq. ft.}$$

To apply the "t" test of significance, a corresponding "t" value must be calculated:

$$t = \frac{(\overline{X}_2 - \overline{X}_c)}{s_{\overline{X}_2} - \overline{X}_c} = \frac{0.90}{0.55} = 1.64$$

Since "t" is herein used to test the null hypothesis that two means are the same versus an alternative hypothesis that they differ, regardless of how, a two-tailed "t" test is used. A "t" distribution table then shows that for two degrees of freedom a "t" value of 1.64 lies between a probability level of 70 and 80; i.e., a "t" this large will occur by chance less than 30% of the time. How far can such results be interpreted? For one thing a "t" value as obtained in the example is not "significant" at the 95% level. The "least significant difference" between 200 lb. and control plot means which would be required to obtain that level of significance for installation 18 would be 2.37 sq.ft., not the 0.90 sq.ft. actually obtained. A confidence interval based on 70 percent probability might not be enough for many purposes, but perhaps it does present sufficient odds to fertilize a forest stand.

This raises the next point. Installation 18 in the example is a site II, age class 30 stand located in Province III. Can a landowner with 70% confidence expect a 12% response to 200 lbs. of nitrogen on any similarly described situation? The answer, of course, is no. By itself installation 18 provides no estimate of the variation that can be anticipated within site II, age 30 stands in Province III. The "population" which it can be related to is simply the specific stand sampled by the study plots. Province III, site II, age 30 does happen to be one of four "populations" represented by more than one sample (Table 26). Three installations occur here, numbers 23 and 109 in addition to number 18. If all 6 control plots and 6-200 pound treated plots are included in a mathematical comparison, the mean response is 0.30/6.53 sq.ft./ac./yr. (+5%) with a standard error of difference of ± 0.85 sq.ft./ac./yr. Hence, the inclusion of the two other installations caused a major increase in the apparent variability within this data cell.

Other groupings of data produced the results indicated in Table 28. The grand mean for all 160 plots was 8.81 ± 3:64 sq. ft./ac./yr.

Discussion of Basal Area Analysis

From this general summary, it would appear that Province III, the western Washington Cascades, is more likely to produce a response to fertilizer than are the two coastal provinces. The response obtained by a 400 pound application in Province III is one percentile larger (16%) than that obtained by a 200 pound application (15%). That is approximately consistent with the additional magnitude of response gained by 400 versus 200 pounds in the regional Douglas-fir results (21% vs. 18%). Douglas-fir also demonstrated with relative consistency inverse relation of basal area response to site quality and age.

In the case of western hemlock, there appears to be a greater likelihood of response in the younger ages. Unfortunately, samples are small and there are exceptions. Likewise, there appears to be a trend toward increasing response with decreasing site quality. But, again, the sample size is restricted. Several site III stands did not appear on the basis of the mean unadjusted differences between plots to respond in a significant way.

It should be noted that there are potential interactions of data which no doubt are clouded by straight arithmetical averaging in the manner done in Table 28. For instance, the numerical magnitude of basal area periodic annual increment in younger hemlock stands is greater than in older stands, as would be expected. On the average, age group 10 stands (all treatments) produced a P.A.I. of 13.75 sq.ft./acre/year, age 20 produced exactly the same, 13.75 sq.ft./acre/

Table 28 Four-year gross basal area growth response by grouping of plot data for provinces, age groups, site classes, and cells in which more than one installation occur. Standard Error is the Standard Error of Difference on the pooled variance in each category.

Category (number of installations in parentheses)		200 lb. Response (sq. ft./acre/year)	400 lb. Response (sq. ft./acre/year)
All Installations	(27)	+0.37 ± 0.10 (+4%)	No Difference
Province III	(10)	+1.28 ± 0.28 (+15%)	+1.33 ± 0.29 (+16%)
Province V	(11)	+0.14 ± 0.22 (+2%)	-0.11 ± 0.19 (-1%)
Province IX	(6)	-0.73 ± 0.51 (-7%)	-0.99 ± 0.42 (-11%)
Age 10	(4)	+1.72 ± 0.49 (+13%)	+1.08 ± 0.76 (+9%)
Age 20	(4)	+1.06 ± 0.32 (+8%)	+0.59 ± 0.39 (+4%)
Age 30	(10)	-0.33 ± 0.10 (-4%)	-0.24 ± 0.11 (-3%)
Age 40	(9)	+0.22 ± 0.07 (+4%)	+0.43 ± 0.07 (+8%)
Site I	(4)	+0.05 ± 0.84 (0%)	-0.32 ± 0.90 (-3%)
Site II	(17)	+0.12 ± 0.13 (+1%)	-0.13 ± 0.12 (-2%)
Site III	(5)	+0.60 ± 0.55 (+7%)	+0.93 ± 0.58 (+11%)
PIII, A30, SII	(3)	+0.30 ± 0.85 (+5%)	+0.25 ± 0.55 (+4%)
PIX, A30, SII	(2)	-1.00 ± 0.67 (-11%)	-0.60 ± 0.82 (-7%)
PIII, A40, SII	(2)	+0.90 ± 0.30 (+16%)	+0.60 ± 0.24 (+11%)
PV, A40, SII	(4)	+0.90 ± 0.18 (+2%)	+0.44 ± 0.19 (+8%)

year, age 30 fell to 7.70 sq.ft./acre/year, and age 40 produced only 5.84 sq.ft./acre/year. Particularly with only 8 of 27 installations occurring in the 10 and 20-year age classes, the likelihood of chance factors producing larger numerical differences between treatments in younger installations is magnified.

One would similarly expect the magnitude of periodic annual increment for a given age to lessen with lower site quality. Hence, unless the proportion of installations per age and site category are indentical within and between provinces, there are built-in artifacts to consider before jumping to conclusions based on summaries such as those presented in Table 28.

To ferret out such sources of variation as they affect the mathematical behavior of the data base would require modelling. Preliminary modelling has been attempted with the hemlock individual plot data, with correlation results that were somewhat unimpressive. The problem is, essentially, that within the hemlock data there is often as much evidence to warrant adjusting the conclusions in one direction as in the opposite direction.

For instance, it would be logical to assume that perhaps some installations failed to respond because there was simply insufficient room available to permit expansion of foliar biomass; the site is already growing to capacity. Certainly a visual inspection of the canopies of many hemlock installations would argue for such a conclusion. A test was undertaken using the installations' average initial basal area as a percent of normal basal area to see if percent stocking influenced response to fertilizer treatment.[1] Sixteen of 27 installations were determined to be "overstocked" by 3 to 34%. Of these, eight were "positive" responders to 200 lbs. N, and eight were "negative" responders to 200 lbs. N. However, of the nine stands that were "understocked," eight responded favorably (60-95% NBA) and only one responded unfavorably (97% NBA). The two remaining installations were 100% of normal basal area.

[1] Source of normal yield Tables was U.S.D.A. Bulletin 1273, "Yield of Even-aged Stands of Western Hemlock," G. H. Barnes, 1962, Table 7, p.13.

Another shortcoming of the manner of data presentation in Table 27 is that it does not explain what the sources of variation were within individual installations. Certainly the plots varied by many factors in addition to their reaction to fertilizer treatment, including initial stocking, diameter distribution, species composition, (of the 27 installations, only eight were 90+ stocked with western hemlock), soil characteristics, disease incidence, mortality, and so on. As examples of how these may be interpreted to affect conclusions, if Installations X, Plot "A" had 20% greater initial basal area than did Installation X, Plot "B", will not "A" produce more growth simply because it has more basal area to produce growth on? Or, is plot "A" overstocked to the point that its tree crowns have no room to grow into, and hence plot "B" will outgrow it? Of the 80 plot replications in the hemlock data, 54 responded in the first manner and 26 in the second manner.

Since plots within an installation are so subject to inherent natural variation, and since this variation seems to particularly mask treatment growth differences, a mensurational technique which gets away somewhat from non-uniform stocking and species conditions may be desirable.

A technique of pairing trees has been developed which, in essence, enables greater sample sizes than is possible by using plots as the sample basis.[2]

In the case of Douglas-fir, it has been shown that response to fertilizer is most likely to be accrued by the larger trees, the dominants and codominants. In an attempt to determine if this might also happen with western hemlock, pairing was done in all hemlock installations with dominant and codominant trees. Trees in the two 200 lb. plots of an installation were matched on the basis of similar initial diameter with trees in the installation's two control plots. It is assumed that in a given stand trees of the same diameter should grow at the same rate over a short period, and any response to fertilizer can then be measured as the difference in diameter growth between treated and control trees. In order to employ as large a sample as possible, control trees were first matched with 200-lb. treated trees to the exact initial diameter when possible, the remainder to the tenth inch when possible, and finally to the fifth inch. Control trees which could not be matched within those limits were not included in the analysis.

Results are presented in Table 29. Fifteen of 27 installations showed differences

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2 Gagnon, J.D. "A Simple and Quick Method to Assess Yearly Diameter Growth Response to Fertilization in Natural Forest Stands." Canadian Forestry Service Bi-monthly Research Note Vol. 31:4, 1975.

Table 29 Four-year breast height diameter growth response by paired tree method, phase I western hemlock, control vs. 200 pounds nitrogen, minimum DBH = 1.55".

Province	Installation	Number of Tree Pairs	D.B.H. Response (Percent Increase or Decrease of 200 lb. Over Control)	Probability Level of Calculated Two-Tailed t Value of D.B.H. Response
III	18	91	+ 5%	.60 +
	23	46	+ 19%	.98 +
	24	138	+ 55%	.99 +
	44	22	- 11%	.90 +
	58	42	- 15%	.90 +
	108	36	+ 35%	.99 +
	109	54	- 1%	.50 -
	111	28	+ 1%	.50 -
	112	45	+ 37%	.99 +
	117	61	+ 17%	.99 +
V	2	61	- 19%	.98 +
	3	91	- 2%	.50 -
	4	54	+ 39%	.99 +
	9	45	+ 1%	.50 -
	15	45	+ 19%	.98 +
	38	31	+ 15%	.50 +
	39	154	+ 14%	.99 +
	42	32	+ 24%	.95 +
	80	34	- 19%	.90 +
	84	118	- 1%	.50 -
	100	132	+ 28%	.99 +
IX	48	54	- 12%	.70 +
	49	44	- 1%	.50 -
	70	61	- 16%	.98 +
	72	49	+ 9%	.50 +
	73	126	+ 2%	.50 -
	86	193	+ 2%	.50 -

significant at the 90% level or higher. Ten of these responded positively, including five in province III and five in province V. Five installations responded negatively, including two in province III, two in province V, and one in province IX. Where the plot arithmetic difference had shown a positive increase with treatment, seven installations increased percentage of gain by the paired-tree method. In two installations, former plus conclusions based on plots were reversed to minus conclusions. Where the plot arithmetic differences had shown a decreased growth with treatment, two installations became more negative, three reversed to positive, and in one installation the percentage magnitude of the negative response was reduced.

It should be noted that tree-pairing in this analysis was done simply from data cards, with no ability to match trees between treatment on any bases except species, crown class, and initial diameter. Such important variables as total height, crown characteristics, physiographic situation, and competitive relationships to neighboring trees were not able to be incorporated. The data are presented only in that they are felt to be the most sensitive measures currently available from the plot data.

Other things being equal (which they never are in western hemlock) it would be presupposed that without the effect of smaller trees and other species to complicate the analysis, a paired-tree approach would intensify the percentage magnitude of a trend based on plot averages. This happened in nine of 15 instances described above. However, the assumption that western hemlock should respond similarly to Douglas-fir (on the larger stems) may itself be misleading. As a shade-tolerant species, understory hemlock is often observed to grow quite rapidly. It is conceivable that response, if it occurs, might be distributed among components of a hemlock stand in an entirely different manner than is normally the case with Douglas-fir.

Analysis of Cubic Volume Response

Data are presented in Table 30 on four-year gross cubic volume growth response for all installations. Figures are for total stem volume, as expressed by the periodic annual increment (P.A.I.), for all trees of all species initially in excess of 1.55" d.b.h.

Although wood volume is of greater ultimate interest to cooperators in the R.F.N.R.P. than basal area is, the latter has been given greater attention in this report. That is because, as a preliminary means of assessing response to fertilizer treatment, measurement of tree diameters is considered to be less subject to error than superimposition of a relatively small sample of tree heights. Tree heights are particularly difficult to measure with consistent accuracy in hemlock stands because of the trees' drooping leaders and the density of the canopy. Further, the variable growth pattern of hemlock is more likely to change the suitability of the height samples initially selected to represent the plot than may be the case with Douglas-fir. By concious attention to these problems they will in time sort out; however, an attempt to detect response based on 4-year height growth differences is not feasible with the measurements taken to date.

A further problem with using volume increment at this stage of the hemlock analysis is that to understand more fully the magnitude of figures obtained at an individual installation it is necessary to assess such factors as number of stems, diameter class distribution, and species composition. These variables have proportionately greater and more complicated impacts on volume increment than they do with basal area increment.

The volume data presented in Table 30 essentially show the same general patterns-- or non-patterns -- as did basal area. This would be expected; previous mensurational work in R.F.N.R.P. with Douglas-fir has shown that the measurement of basal area increment accounts for a large percentage of volume increment. The overall grand means are shown below.

<u>Province III</u> - (Washington Cascades)

Control $\overline{X}_c$ = 400 cu.ft./ac./yr.
200 lb N $\overline{X}_2$ = 433 cu.ft./ac./yr. (+8%)
400 lb N $\overline{X}_4$ = 420 cu.ft./ac./yr. (+5%)

<u>Province V</u> - (Olympic Peninsula, NW Oregon)

Control $\overline{X}_c$ = 429 cu.ft./ac./yr.
200 lb N $\overline{X}_2$ = 424 cu.ft./ac./yr. (-1%)
400 lb N $\overline{X}_4$ = 432 cu.ft./ac./yr. (+1%)

<u>Province IX</u> - (Oregon Coast)

Control $\overline{X}_c$ = 450 cu.ft./ac./yr.
200 lb N $\overline{X}_2$ = 429 cu.ft./ac/yr. (-5%)
400 lb N $\overline{X}_4$ = 435 cu.ft./ac./yr. (-8% relative to 5 installations which have 400 lb. plots)

Table 30 Four-year gross cubic volume growth response by plot comparison method, phase I western hemlock installations, all trees initially over 1.55" D.B.H.

Province	Installation	Initial Breast Height Age (yrs)*	Initial 100-yr Site Index (feet)	200 lb Plots' Mean Cubic Volume P.A.I. Response Over Control Plots Mean Total Gross P.A.I. (cu.ft./acre/yr)	Percent Response	Probability Level of Calculated "t" Value of 200 lb. Cubic Volume Response	400 lb Plots' Mean Cubic Volume P.A.I. Response Over Control Plots Mean Total Gross P.A.I. (cu.ft./acre/yr)	Percent Response	Probability Level of Calculated "t" Value of 400 lb. Cubic Volume Response
III	18	28	176 (II)	+ 16/545	+ 3%	.50-	- 37/545	- 7%	.50-
	23	34	167 (II)	- 29/432	- 7%	.50-	-142/432	-33%	.80+
	24	20	95 (IV)	+100/248	+40%	.95+	+100/248	+40%	.60+
	44	41	154 (III)	- 52/438	-12%	.50-	+ 32/438	+ 7%	.50-
	58	26	155 (III)	+ 20/484	+ 4%	.50-	- 64/484	-13%	.60+
	108	42	170 (II)	+ 12/468	+ 3%	.50-	+ 40/468	+ 9%	.60+
	109	31	161 (II)	+ 18/402	+ 4%	.50-	- 13/402	- 3%	.50-
	111	38	178 (II)	+158/388	+41%	.80+	+198/388	+51%	.95+
	112	15	143 (III)	+ 64/256	+25%	.60+	+ 22/256	+ 9%	.50-
	117	17	171 (II)	+ 22/338	+ 7%	.50-	+ 66/338	+20%	.70+
V	2	45	152 (III)	+ 46/380	+12%	.60+	+ 74/380	+19%	.80+
	3	28	159 (II)	+ 8/480	+ 2%	.60+	- 8/480	- 2%	.50-
	4	36	182 (II)	+ 10/516	+ 2%	.50-	+ 13/516	+ 3%	.50-
	9	36	164 (II)	+ 22/456	+ 5%	.50+	+ 2/456	0%	.50-
	15	30	186 (I)	- 89/511	-17%	.80+	+ 13/511	+ 2%	.50-
	38	37	158 (II)	- 95/414	-23%	.80+	+ 34/414	+ 8%	.50-
	39	18	172 (II)	- 34/474	- 7%	.50-	- 61/474	-13%	.50+
	42	38	168 (II)	- 38/396	-10%	.50-	+ 16/396	+ 4%	.50-
	80	29	143 (III)	+ 40/436	+ 9%	.50-	+ 44/436	+10%	.50-
	84	14	194 (I)	+ 28/428	+ 6%	.50+	- 26/428	- 6%	.60+
	100	12	175 (II)	+ 42/228	+18%	.60+	- 73/228	-32%	.80+
IX	48	30	186 (I)	- 4/506	- 1%	.50-	- 82/506	-16%	.50+
	49	31	181 (II)	+ 8/464	+ 2%	.50-	- 65/464	-14%	.70+
	70	26	159 (II)	-136/498	-27%	.80+	- 3/498	- 1%	.50-
	72	36	161 (II)	+ 67/351	+19%	.50-	+ 71/351	+20%	.60+
	73	20	172 (II)	-112/556	-20%	.70+	-120/556	-22%	.70+
	86	12	186 (I)	+ 46/328	+14%	.80+	No 400 lb. Plots	-	-

*Installations up to #49 established in 1969, numbers 58 and greater in 1970.

The magnitude of the cubic volume increment figures is not as sharply related to age as is the case with basal area increment, and the trend is reversed. The mean P.A.I. for all installations in age category 10 is 318 cu.ft./ac./yr., age category 20 is 401 cu.ft./ac./yr., age category 30 is 459 cu.ft./ac./yr., and age category 40 is 446 cu.ft./ac./yr. It would be expected that cubic volume increment would also increase with increasing site quality, of course, but the unequal distribution of installations across the age-site range frustrates simple arithmetic demonstration of this.

V. Conclusions

As a consequence of indications that the younger age categories of hemlock may respond favorably to fertilizer, eight new installations have been established under the phase III program which began in 1975. These will in time permit greater accuracy in establishing regression relationships.

However, the empirical trial approach has indicated that it is necessary to look more deeply at the root causes of variation within and between installations, the oldest of which have now existed for 8 years.

More intensive field measurement techniques, such as determination of pre-treatment growth rates and stem analysis, may be necessary to sort out some of the variability. Relating mensurational results to environmental and soil conditions is required. Evidence that fertilization of hemlock with urea may in some cases cause a depression of growth -- is it real? Or is it a chance fluke of the data base? Is it conceivable that plots which show a "negative response" actually did respond to fertilizer treatment, and that their foliage area increased so dramatically that they were ravaged by wind or snow, so that their response was their ultimate undoing? Do many coastal hemlock stands already possess so much available nitrogen that additions are merely luxury? In areas where hemlock is a pioneering species, do its rate of growth and its potential to respond to growth stimuli simply peak out at an earlier age than Douglas-fir? Does the seeming omnipresence of the root-rot pathogen Fomes annosus negate potential for response? Is a form of nitrogen other than urea more suited to hemlock's physiology and rooting habit? These are all avenues which the R.F.N.R.P. will be exploring in the future.

VIII - THINNING AND FERTILIZATION - PRELIMINARY PHASE II RESULTS

The Phase II thinning treatment for both Douglas-fir and western hemlock retained 60 percent of initial basal area in well-spaced primarily dominant and codominant trees. All thinned plots (six per installation) were reduced to a common level of basal area. Nitrogen, as urea, was applied to two plots at the rate of 200 pounds per acre and to two plots at 400 pounds per acre. Fertilization was conducted in late winter, following fall thinning.

Douglas-fir Results

Site and age distribution for the 240 plots included in the Douglas-fir thinning-fertilizer study are given in Table 31. Most plots are contained in breast height age classes 20 and 30, and site classes II and III. Two-year growth data after treatment are now available on all plots, and are presented in Table 32. Percent response to fertilizer over the thinned but unfertilized controls is shown in Table 33. Results strongly support previous findings (RFNRP, 1974) that thinning enhances response to fertilizer. Average increase in growth for all study areas was 31% for 200 lbs. nitrogen per acre and 32% for 400 lbs. nitrogen per acre.

Table 34 contains an estimate of 4-year growth following thinning and fertilization. Basis for this table is the relationship between 2 and 4-year results for 54 plots for which 4-year data are available. These relationships are then used to adjust all 2-year data. Table 35 is derived from Table 34 and presents estimates of total 4-year volume response to fertilizer in thinned stands. Reading Table 35, for example, four years after thinning, stands of breast height age class 30 and 50-year site class III showed 440 cubic feet per acre more volume if they had been treated with 200 lbs. of nitrogen per acre at the time of thinning than stands which had been similarly thinned but not fertilized. Tables 34 and 35 should be regarded as preliminary unsmoothed results, and will be revised when all 4-year growth data are available.

Table 31

Thinned Douglas-fir. Number of Sample Plots by Site and Age

B.H. Age Class (Yrs.)	Treatment (Pounds of N Per Acre)	50-Year Site Class I	II	III	IV	Total
10	0	2	4	6	0	12
	200	2	4	6	0	12
	400	2	4	6	0	-12
20	0	0	12	4	4	20
	200	0	12	4	4	20
	400	0	12	4	4	20
30	0	8	6	10	2	26
	200	8	6	10	2	26
	400	8	6	10	2	26
40	0	0	8	6	0	14
	200	0	8	6	0	14
	400	0	8	6	0	14
50	0	0	0	6	2	8
	200	0	0	6	2	8
	400	0	0	6	2	8
Total	0	10	30	32	8	80
	200	10	30	32	8	80
	400	10	30	32	8	80

Total No. Sample Plots = 240

Table 32

Thinned Douglas-fir. Two-Year Gross Annual Growth After Thinning and Fertilization, Cubic Feet Per Acre, Total Stem

B.H. Age Class (Yrs.)	Treatment (Pounds of N Per Acre)	Two-Year Periodic Annual Increment* 50-Year Site Class I	II	III	IV
		(ft^3/acre)**	(ft^3/acre)	(ft^3/acre)	(ft^3/acre)
10	0	49	170	149	-
	200	86	251	230	-
	400	101	231	227	-
20	0	-	228	155	113
	200	-	280	244	166
	400	-	288	256	167
30	0	219	199	198	224
	200	255	238	275	328
	400	256	221	288	361
40	0	-	186	188	-
	200	-	238	232	-
	400	-	242	232	-
50	0	-	-	141	120
	200	-	-	176	166
	400	-	-	174	162

*Based on plot averages for 240 plots

Table 33

Thinned Douglas-fir. Percent Response to Thinned but Unfertilized Control, Two Years After Treatment

B.H. Age Class (Yrs.)	Treatment (Pounds of N per Acre)	50-Year Site Class				Total for Age Class
		I	II	III	IV	
		(%)	(%)	(%)	(%)	
10	0	-	-	-		-
	200	76	48	54		53
	400	106	36	52		49
20	0		-	-	-	-
	200		23	57	48	31
	400		26	65	48	35
30	0	-	-	-	-	-
	200	16	20	39	46	27
	400	17	11	45	61	28
40	0		-	-		-
	200		28	23		26
	400		30	23		27
50	0			-	-	-
	200			25	38	28
	400			23	35	26
Total for Site Class	0	-	-	-	-	
	200	19	25	38	51	
	400	22	23	41	50	

Average response to 200 lbs. N = 31%
Average response to 400 lbs. N = 32%

Table 34

Thinned Douglas-fir. Estimate of Four-year Growth After Thinning and Fertilization, Cubic Feet Per Acre, Total Stem

B.H. Age Class (Yrs.)	Treatment (Pounds of N per Acre)	Four-year Gross Periodic Annual Increment* 50-Year Site Class			
		I	II	III	IV
		(ft^3/acre)	(ft^3/acre)	(ft^3/acre)	(ft^3/acre)
10	0	-	250	182	-
	200	-	346	294	-
	400	-	312	302	-
20	0	-	335	189	138
	200	-	386	312	212
	400	-	389	340	222
30	0	322	292	242	273
	200	352	328	352	420
	400	346	305	383	480
40	0	-	273	229	-
	200	-	328	297	-
	400	-	327	309	-
50	0	-	-	172	146
	200	-	-	225	212
	400	-	-	231	215

*Based on two-year plot averages for 234 plots and relationship between two-year and four-year growth for 54 plots.

Table 35

Thinned Douglas-fir Preliminary Estimate of Four Year Response to Fertilizer, Cubic Feet Per Acre, Total Stem

B.H. Age Class (Yrs.)	Treatment (Pounds of N per Acre)	Total Four-Year Gross Volume Response			
		50-Year Site Class			
		I	II	III	IV
		(ft^3/acre)	(ft^3/acre)	(ft^3/acre)	(ft^3/acre)
10	0	-	-	-	-
	200	-	384	448	-
	400	-	248	480	-
20	0	-	-	-	-
	200	-	204	492	296
	400	-	216	604	336
30	0	-	-	-	-
	200	120	144	440	588
	400	96	52	564	828
40	0	-	-	-	-
	200	-	220	272	-
	400	-	216	320	-
50	0	-	-	-	-
	200	-	-	212	264
	400	-	-	236	276

Eventually, fertilizer results from unthinned and thinned stands will be merged so that land managers can compare thinning and fertilizing practices both separately and in combination. Figure 19 represents an initial attempt at this using 4-year data for stands of breast height age class 30 and 50 year site class III. Unthinned data are based on Phase I results for well-stocked stands while thinned data are from Table 34. In general it can be said that fertilization at the time of thinning virtually eliminates growth loss due to stocking reduction, with stand growth captured on well-spaced desirable stems. Data on merchantable volume growth are not yet available; however, it is obvious that fertilization and thinning will result in substantial merchantable volume gains since stand growth is distributed among relatively few trees. Average tree size will also be affected by thinning and fertilization, as is demonstrated in Table 36. Larger tree size translates directly into higher stumpage value because of the effect of tree size on harvest cost and product recovery.

In general, it appears that the combination of thinning and fertilization of young Douglas-fir stands is a forest management practice that has a profound impact on tree volume and value. Much work remains to be done under RFNRP in the mensurational and economic analysis of thinning plot data, and this area will receive high priority in the future. Augmenting the Phase II data base are the 18 Phase III experimental areas with thinning and fertilization treatments of 10 to 20 year-old stands. Two-year data from these plots will be available in 1978.

Figure 19
Gross Annual Growth of Fertilized and Thinned Stands, Four Years After Treatment, Douglas-fir, Site III, B. H. Age 30 When Treated

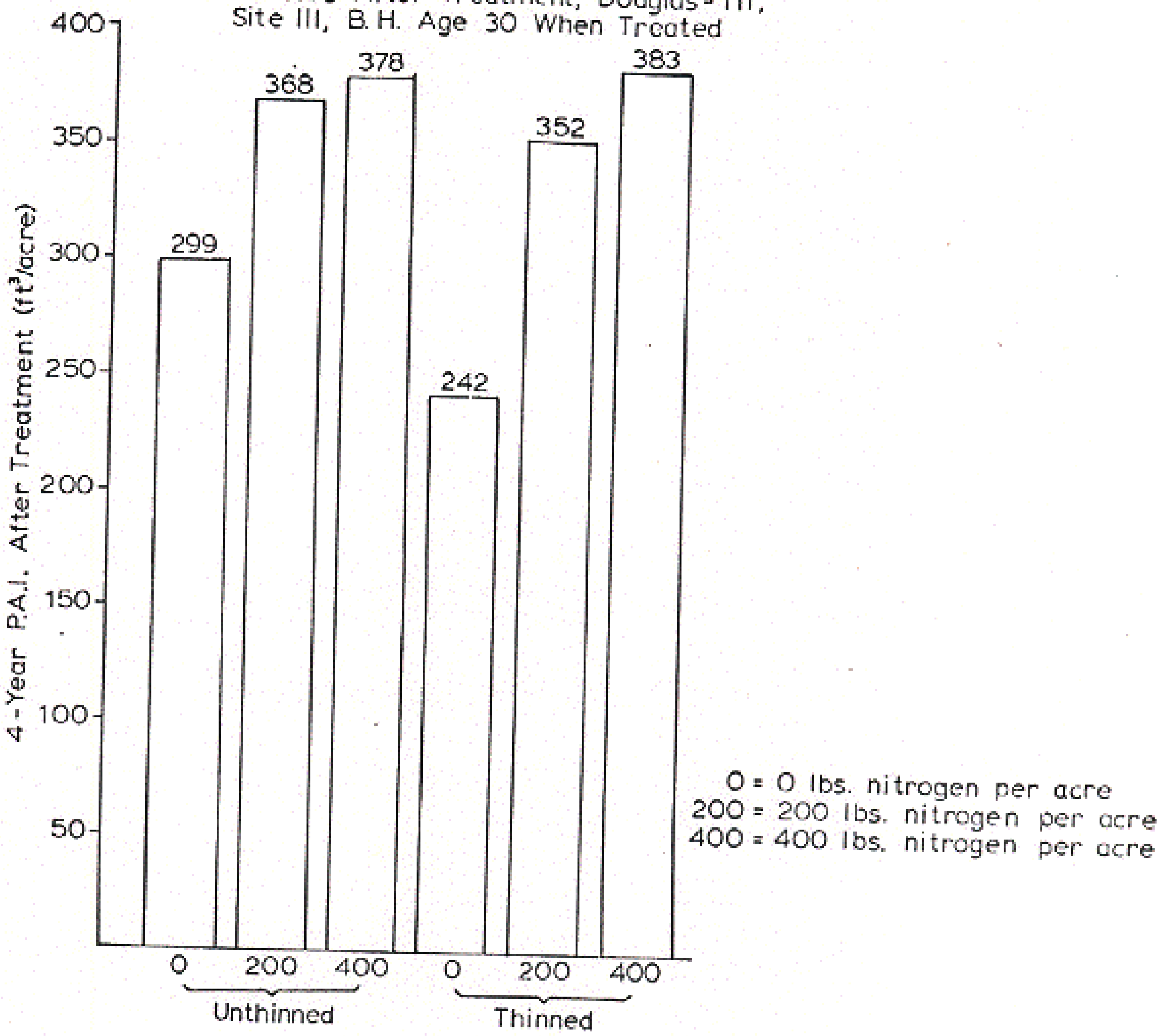


Table 36

Comparison of Thinned and Fertilized Stands, Four-Year Period After Treatment, Douglas-fir Site III, B. H. Age 30 When Treated

Treatment	Residual Volume After Treatment	Net 4-Year Growth	Volume 4 Years After Treatment	No. Trees Per Acre	Ave. Vol. Per Tree	Net Growth as a Percent of Unthinned Control
	(ft^3/acre)	(f^3/ac)	(ft^3/acre)		(f^3/ac)	(%)
Unthinned ON	5180	1076	6256	691	9.1	100
Unthinned 200 N	5180	1325	6505	691	9.4	123
Unthinned 400 N	5180	1361	6541	691	9.5	126
Thinned 0 N	3697	949	4646	360	12.9	88
Thinned 200 N	3697	1380	5077	360	14.1	128
Thinned 400 N	3697	1501	5198	360	14.4	139

Eight thinning-fertilizer installation were established in western hemlock stands under Phase II. Two-year data for these areas based on plot comparisons are presented in Table 37, with installations sorted by age class in the top portion of the table, and by geographic location in the bottom portion. The only distinction that can be made from these results is that thinned stands of breast height age 10 to 20 seem to respond reasonably well to nitrogen fertilizer, regardless of geographic location (Cascades vs. Coast), while somewhat older stands apparently do not. Whether these results can be generalized is not known at this time. Additional data on 10 to 20 year-old stands and their response to thinning and fertilization will be available when Phase III growth measurements are made (winter, 1977-78).

Four-year data are available for seven of the eight western hemlock installations, and, sorted by age class, these are given in Table 38. Response in the younger stands appears to continue.

Given these results, along with the Phase I hemlock results, probably the best advice that can be given owners of western hemlock stands is to consider fertilization only in areas and stand conditions where response has been demonstrated. Even where plot comparisons indicate response, additional analysis should be undertaken to determine whether response is real or the product of plot variability. Currently, research is being directed toward the development of reliable methods of detecting response at a specific experimental location.

Table 37

Thinned Western Hemlock. Percent Response to Thinned but Unfertilized Control, Two Years After Treatment

Sorting of Plots by Age

B. H. Age 10-20

Installation Number*	Percent Response** 200 lbs. N/acre	Percent Response** 400 lbs. N/acre	100-Year Site Index
121	+13	+18	186
130	+24	+44	164
133	+25	+32	151
153	+10	+17	180
Averages	+18	+28	170

B. H. Age 21-30

Installation Number*	Percent Response** 200 lbs. N/acre	Percent Response** 400 lbs. N/acre	100-Year Site Index
122	+6	-6	163
123	-2	+3	184
127	+9	+5	166
132	+6	-8	168
Averages	+5	-6	170

Sorting of Plots by Geographic Location

Washington Cascades

Installation Number*	Percent Response** 200 lbs. N/acre	Percent Response** 400 lbs. N/acre
122	+ 6	- 6
127	+ 9	+ 5
130	+24	+44
133	+25	+32
Averages	+16	+19

Washington-Oregon Coast

Installation Number*	Percent Response** 200 lbs. N/acre	Percent Response** 400 lbs. N/acre
121	+13	+18
123	- 2	+ 3
132	+ 6	- 8
153	+10	+17
Averages	+ 7	+ 7

*Each installation contains six 1/10 - acre plots

**Percent response based on gross cubic foot volume growth

Table 38

Thinned Western Hemlock. Four-year Growth After Thinning and Fertilization. Cubic Feet Per Acre, Total Stem

B. H. Age 10-20

Installation Number	Four-Year P.A.I. (ft^3/acre)		
	0 lbs. N/acre	200 lbs. N/acre	400 lbs. N/acre
121	316	360	348
130	284	343	348
133	274	357	379
153*	-	-	-
Average	291	353	358
Percent Response	-	+ 21	+ 23

B. H. Age 21-30

Installation Number	Four-Year P.A.I. (ft^3/acre)		
	0 lbs. N/acre	200 lbs. N/acre	400 lbs. N/acre
122	375	346	335
123	290	320	338
127	322	332	334
132	417	404	360
Average	351	350	342
Percent Response	-	0	- .3

*Only two-year data for Installation #153 are available at this time.

IX - SOILS-FOLIAR ANALYSIS PROGRAM

Soils Investigation

When the fertilizer project began in 1969, the Technical Advisory Committee and the project administration decided to embark on a soils study program of field installations as funds and manpower became available. This study was planned to gather information on soil parameters to be analyzed in conjunction with the mensurational data. It was hypothesized that this would enable more accurate growth response predictions and might assist in explaining anomalous response data.

There were not sufficient funds nor manpower to perform an exhaustive study and a subcommittee of the Technical Advisory Committee was formed to draw up a low cost but effective program. It was agreed that information on the soils of the installations would be of value for interpretation purposes. Due to a number of factors, including additional financial support, efficient field operations, management of the project with no administtative costs to the project, and above all, the cooperation and assistance of forest soil specialists on the Technical Advisory Committee, the goals set out in the program have been reached. Sufficient soils, physiographic and climatic information has been collected from all 160 Phase I and Phase II installations to achieve the major goals of the soils investigation.

Data processing and statistical analysis are underway and will continue over the next 12-month period with a view to supplementing the statistical analysis of mensurational data. Each of 50 variables for soil, physiographic and climatic characteristics has been put on computer cards for all 160 installations. Data screening has begun, and the results of the various statistical analyses will be available for subsequent reports.

Foliar Analysis

Research in this approach to predicting response has been delayed while up-to-date growth response was generated. As these data are now becoming available several developments are occurring:

Through cooperation of Australian researchers foliage samples are being collected and sent to the Forest Research Laboratory in New South Wales. Previous results with Pinus radiata in Australia have shown that a particular ratio between organic sulphur and nitrogen is necessary in the foliage. Excess sulphur is accumulated as sulphate in the foliage to balance nitrogen. If sufficient sulphur is not available, this element can become limiting and nitrogen is not likely to produce a response.

Analysis of samples sent to Australia from installations showing different apparent levels of response seems to substantiate the conclusions from radiata pine. In other words, some installations which show little response may be suffering from sulphur deficiency, which needs to be corrected befor nitrogen response can be achieved.

This lead is being followed by collecting foliage from more installations. A review is being conducted of some low-responding installations where sulphur has been applied on complete fertilizer treatments.

X - ELEMENTAL NITROGEN DYNAMICS IN LOW-SITE STANDS OF THE DOUGLAS-FIR REGION: A SUMMARY OF STUDIES CONDUCTED AT THE COLLEGE OF FOREST RESOURCES, UNIVERSITY OF WASHINGTON

Introduction

Early in the College's forest fertilizer investigations it became clear that information other than measured growth response of treated plots was required in order to understand the roles of essential elements in forests and the impacts of nutrient additions on the ecosystem. Predictions from agricultural experience at that time indicated that applied nitrogen might rapidly leach from forest systems and any effect would hence be short-lived. If this were proven to be true, drainage waters from fertilized forest areas could have a serious impact on associated aquatic systems.

These considerations, among others, caused the College to engage in a line of research termed mineral cycling. The objective was to obtain quantitative information on the sources, stores, and rates of movement of the major essential elements in both natural and fertilized forest stands. This review explains the nature of such studies more fully. These basic studies have been largely financed by the National Science Foundation either through individual research grants or as part of the Coniferous Forest Biome ecosystem study. Other studies mentioned in this report have been supported by the U. S. Army Corps of Engineers and the Regional Forest Nutrition Research Project.

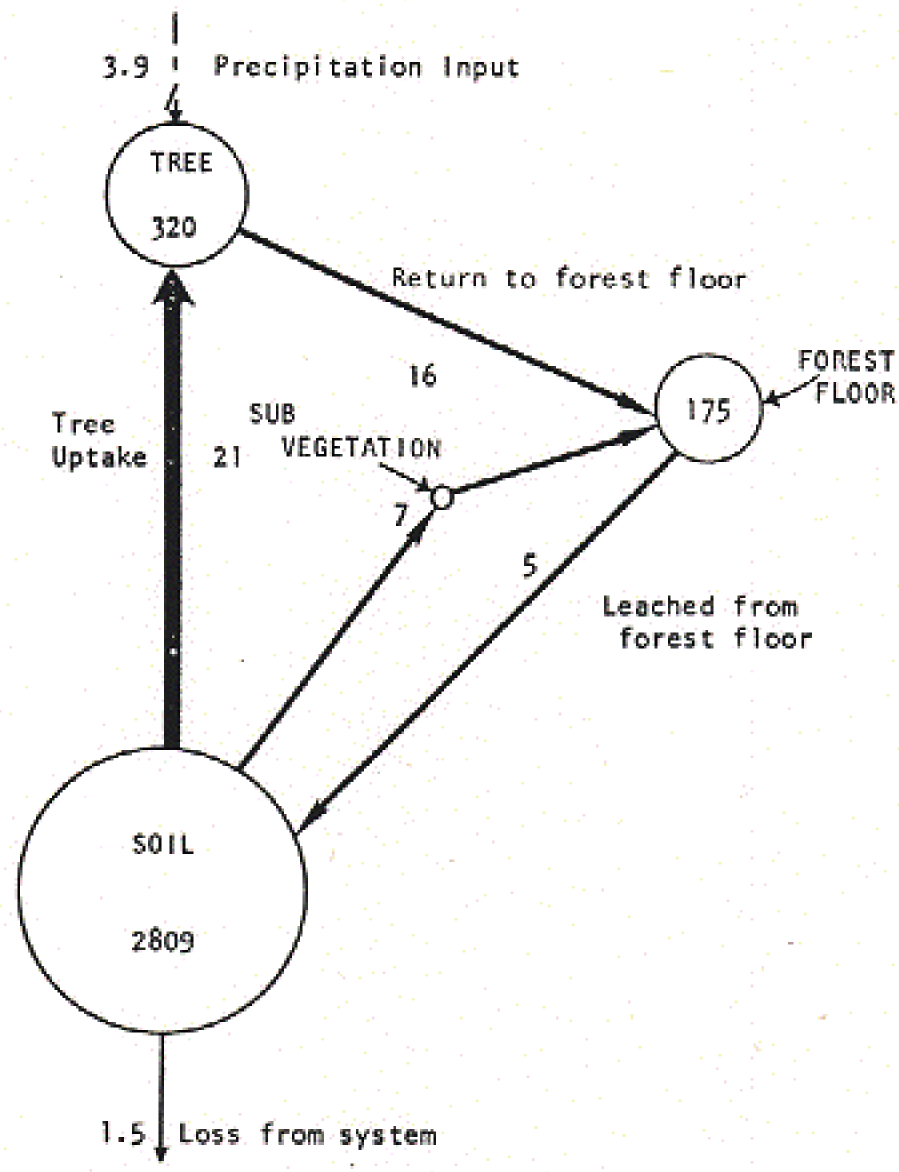
Figures in this report are presented in metric units. Kilograms per hectare are often considered roughly equivalent to pounds per acre for ease of translation. Actually, 1 Kg/ha = 0.8922 lb/ac.

Initial Work in Nutrient Cycling

Heilman and Gessel (1963) began nutrient cycling studies in the region in order to account for the fate of applied nitrogen in a variety of Douglas-fir stands. Following their success at that, Cole et al. (1968) conducted the first comprehensive baseline study of nutrient cycling for macronutrients including nitrogen in a second-growth Douglas-fir ecosystem. An example of the basic model used in this study is shown in Figure 20 . The nitrogen cycle in a 36-year-old Douglas-fir ecosystem is shown as an example and for reference later in this discussion. This model has served as a basis for expansion and refinement of nutrient cycling studies conducted subsequently in the region.

Figure 20

Nitrogen cycle in a 36-year-old site IV Douglas-fir ecosystem
(from Cole et al., 1968)
Numbers are kilograms per hectare



Nutrient Cycling During Stand Development

As part of the International Biological Program studies in the Coniferous Forest Biome, Turner (1975) studied patterns of nutrient cycling during Douglas-fir stand development. Stands that were studied aged from 9-95 years. It was found that during initial phases of stand development, the stand draws upon soil nutrients and begins to accumulate them in tree tissue (Figure 21).

Prior to canopy closure, understory biomass is highest and the understory has a significant role in mineral cycling of the entire system. Figure 22 is an example of the understory nutrient accumulation pattern from site IV stands where canopy closure occurred at about age 25. With canopy closure, foliar biomass reaches a steady-state condition (Figure 23). The age at which canopy closure occurs is dependent upon stand density and site.

Nitrogen and potassium are relatively mobile within the biological system; i. e., potassium is readily leached from foliage and nitrogen can be retranslocated. Accumulation of nitrogen and potassium in foliage (Figure 21) reaches a steady-state condition at the same time foliar biomass does. Calcium, being relatively immobile in the biological system, continues to accumulate, particularly in older foliage.

Forest floor weight (i. e., organic litter) increases throughout the first 70 years of stand development in site IV stands (Figure 24), showing no tendency to reach steady-state simultaneously with foliar biomass. Nitrogen and calcium content of the forest floor also increase during this time span. Potassium, however, is readily leached from the forest floor because it remains in ionic form in tissues. Thus, potassium accumulation in the forest floor is markedly lower than it is for nitrogen or calcium (Figure 25).

Figure 21

Accoumulation of nitrogen, postassium, and calcium in the foliage of various aged stands of Douglas-fir (site IV, Everett series soil) (Cole et al. 1975)

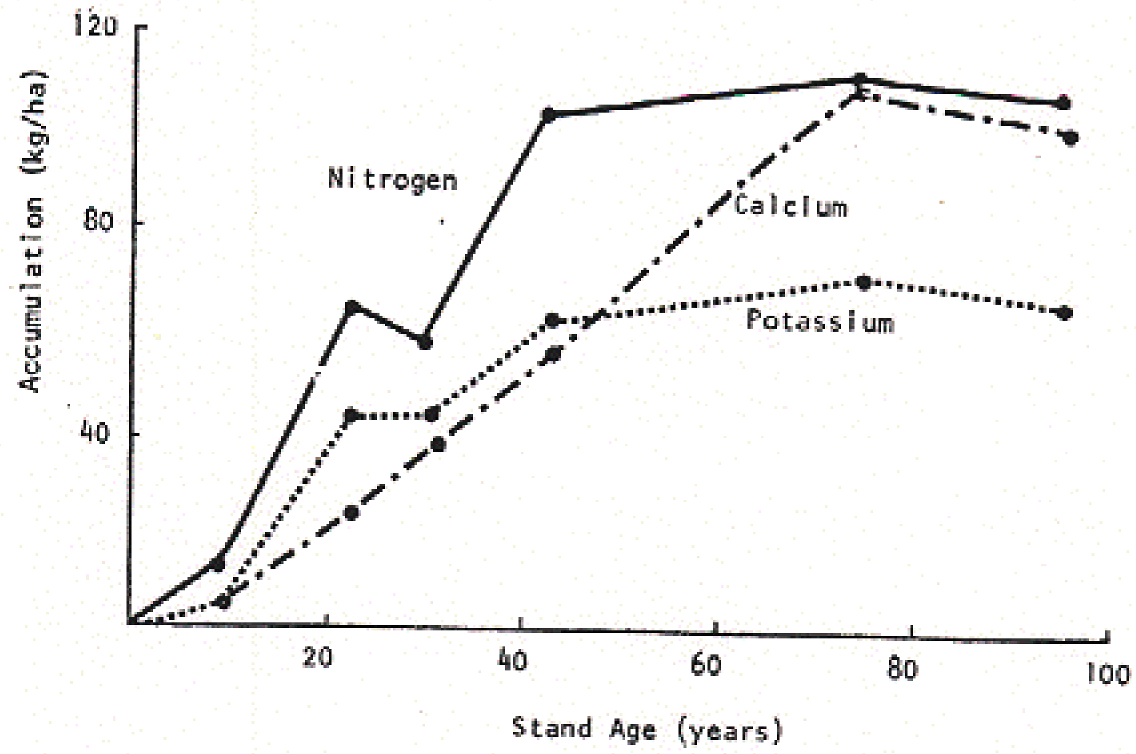


Figure 22

Accumulation of nitrogen, potassium, and calcium in the understory vegetation of various aged stands of Douglas-fir (site IV, Everett series soil) (Cole et al., 1975)

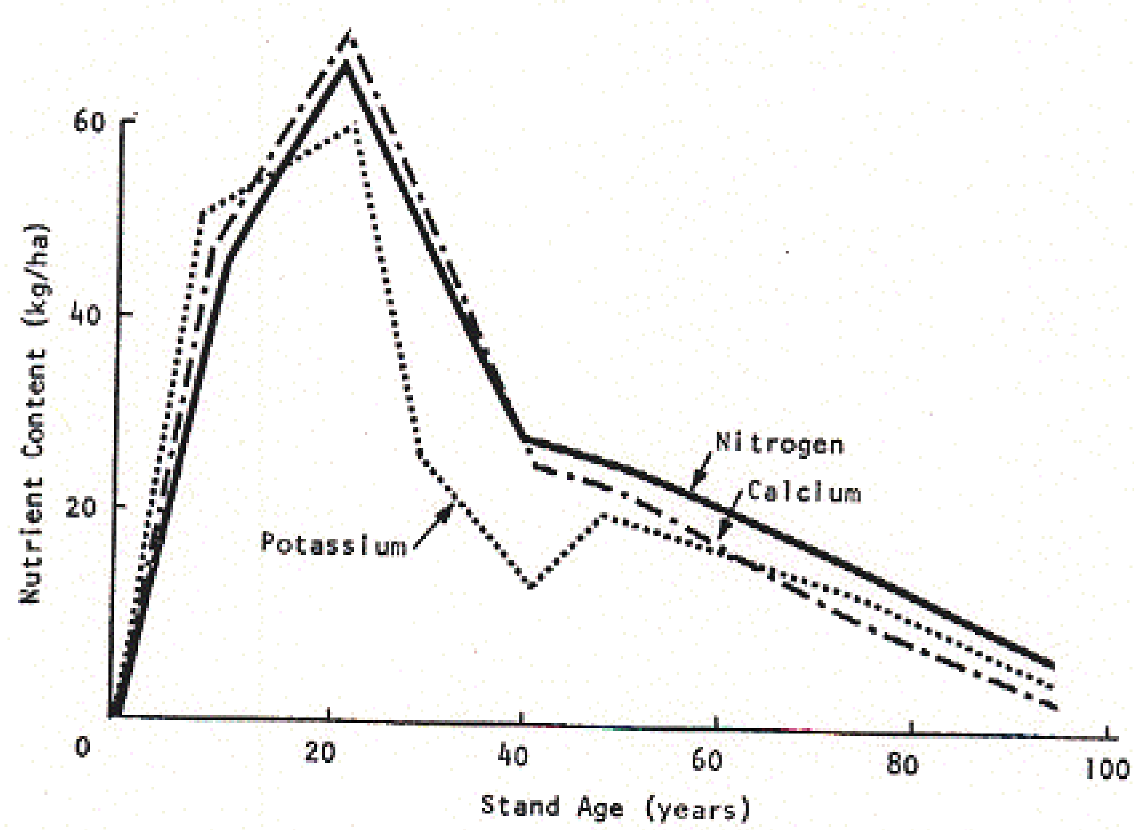


Figure 23

Theoretical relationship between foliar biomass, stand age, and stand density (stems per hectare) for Douglas-fir stands of low productivity (site quality IV) (Cole et al., 1975)

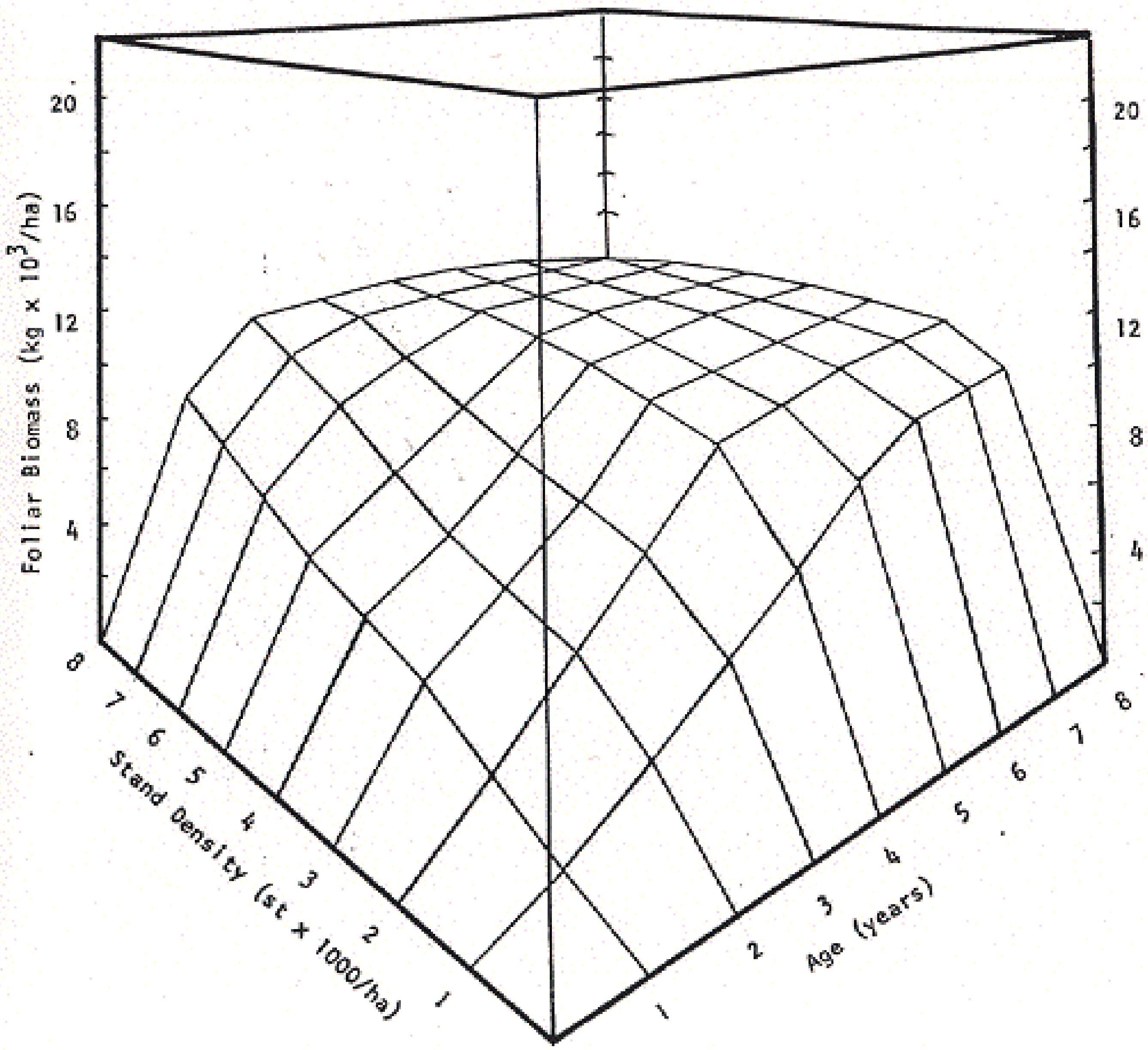


Figure 24

Accumulation of forest floor mass under various aged stands of Douglas-fir, standard errors indicated, (site IV, Everett series soil) (Cole et al., 1975)

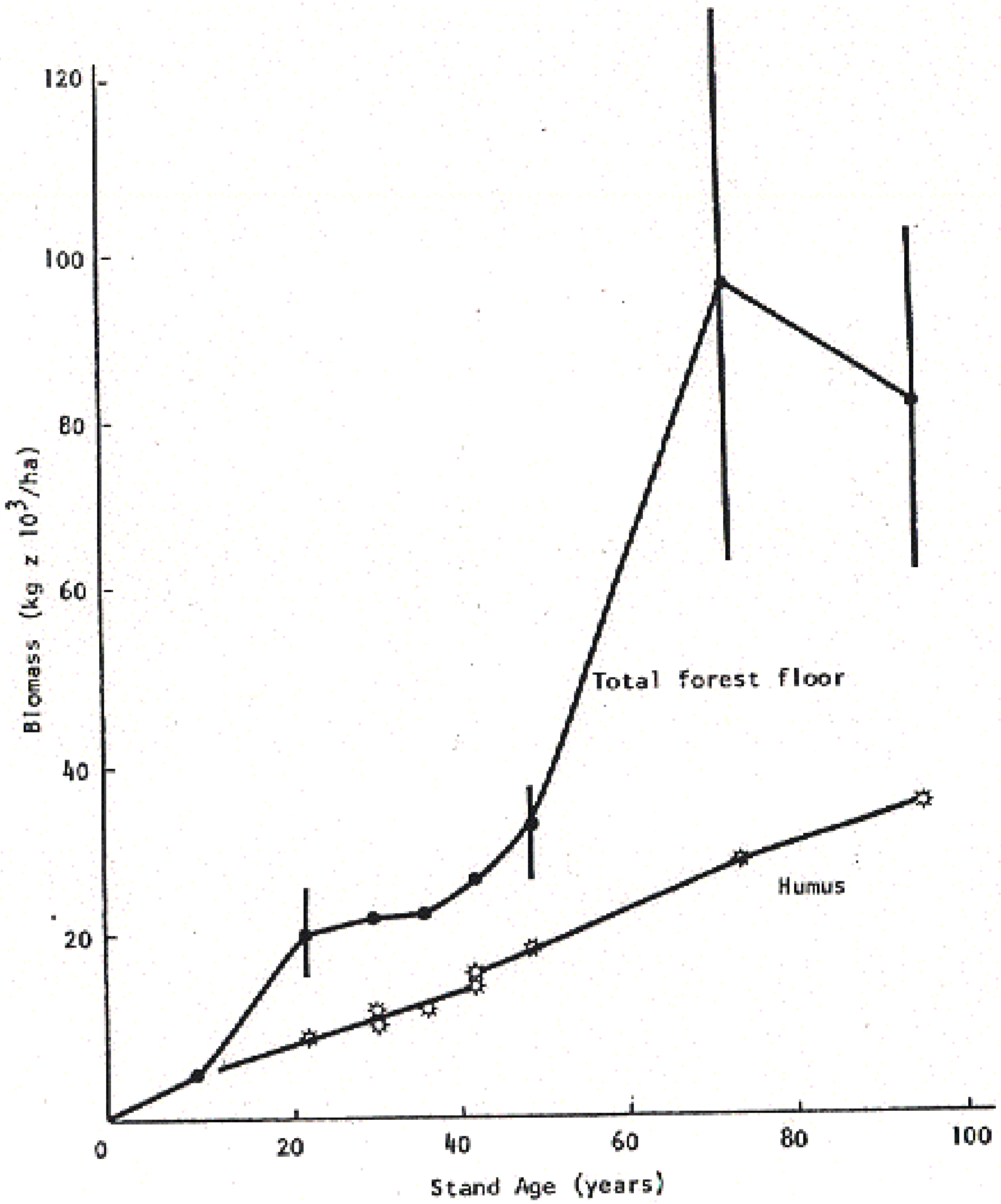
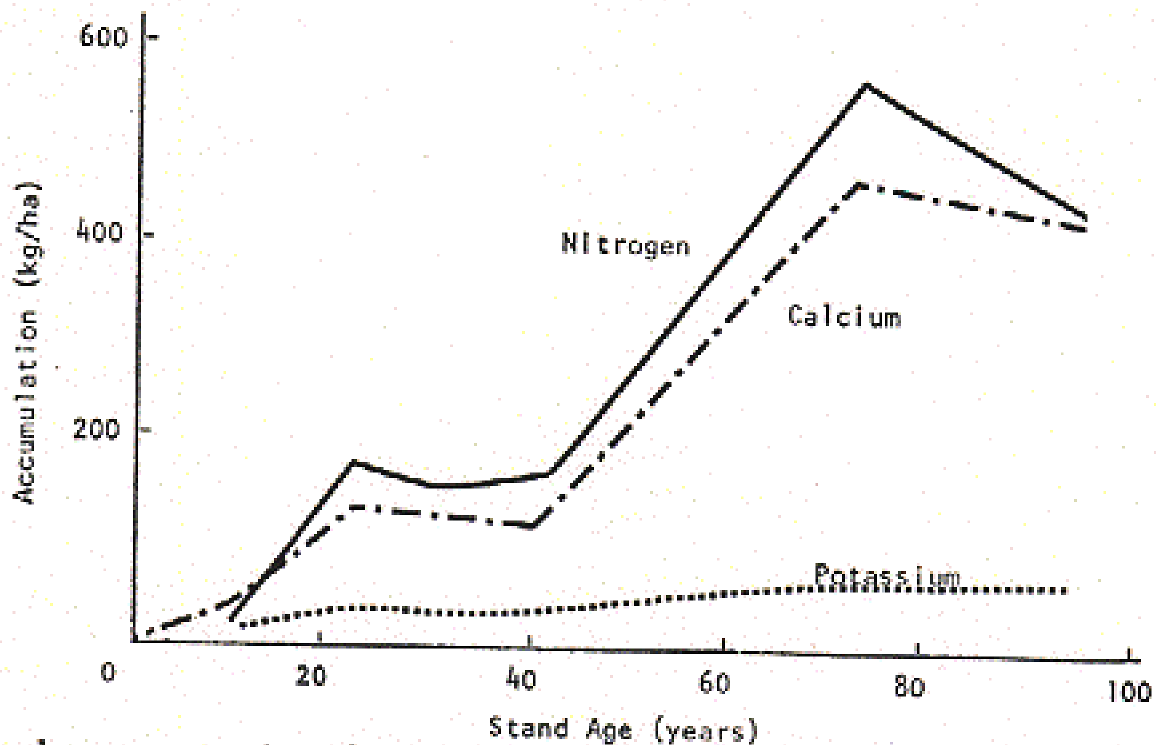


Figure 25

Accumulation of nitrogen, calcium, and potassium in the forest floor of various aged stands of Douglas-fir (site IV, Everett series soil) (Cole et al., 1975)



After canopy closure, uptake of nitrogen declines and the trees become increasingly dependent upon internal recycling from older tissues to meet their nitrogen demands. The nitrogen demands are ameliorated somewhat by longer needle retention times in older trees. This allows constant foliar density with less needle replacement (Cole et al., 1975).

Uptake of potassium and calcium increases up to 25-30 years after which it is relatively constant; neither nutrient is translocated within the tree. The reasons for the lack of translocation are evident. Potassium is readily leached from foliage before translocation occurs, whereas calcium is tightly bound as a cell wall contituent or a precipitate such as calcium oxalate so that calcium accumulates in older foliage. Thus, as the stand matures and needle retention time increases, calcium consumption by older foliage increases (Cole et al., 1975).

Nutrient budget calculations for the forest floor indicate that the stand derives an increasing proportion of its nitrogen and calcium uptake requirements from the forest floor rather than the soil as the stand matures (Table 39). Since potassium readily leaches through the forest floor, the uptake of potassium from the soil does not appreciably change during this period. Thus, rather than withdrawing nutrients from the living system, the forest floor appears to provide a storage pool of nutrients available for uptake.

Using Turner's data as a basis, Riggan (1976) constructed a model that simulates nitrogen and biomass accumulation in Douglas-fir stands. The structure of the model is depicted in Figures 26 and 27. The model can simulate the growth and dynamics of a developing Douglas-fir stand even though the effects of light, water, and other environmental variables are neglected. This does not imply that nitrogen is the only factor affecting tree growth, since other environmental effects are built into many of the observed nitrogen-growth relationships. This model does indicate, however, that nitrogen can be used as a driving variable for forest growth, and therefore results of nitrogen fertilization should be predictable.

Table 39 Net nutrient removed from the forest floor by the total vegetation, based on nutrient budget calculations (% of total uptake) (Cole et al., 1975).

Age class*	N	K	Ca
0-20	55	15	25
20-60	65	-5	35
60-90	100	0	55
Average	70	5	40

* Douglas-fir (site IV).

Figure 26

Flow diagram for nitrogen dynamics model
(Riggan, 1976)

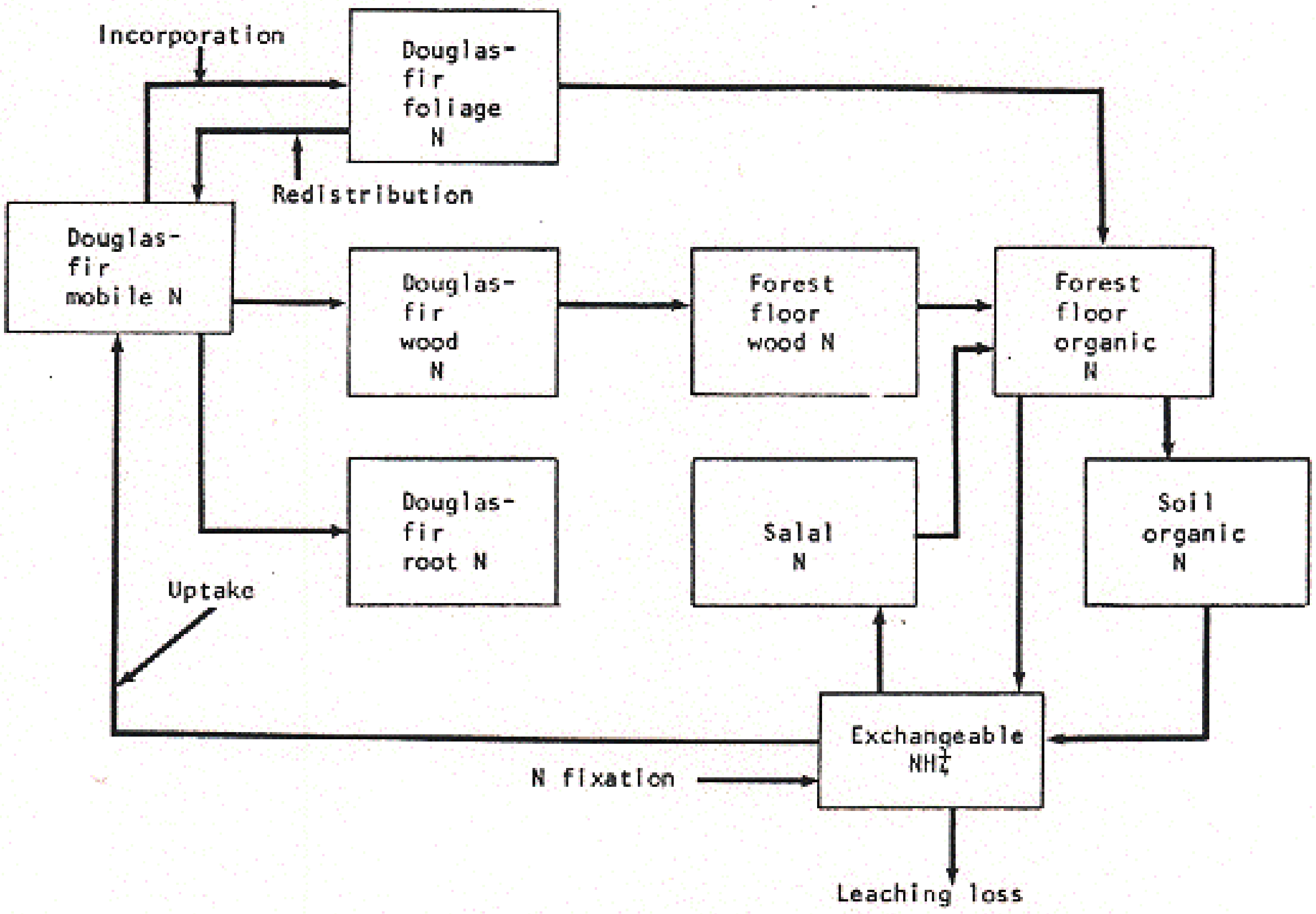
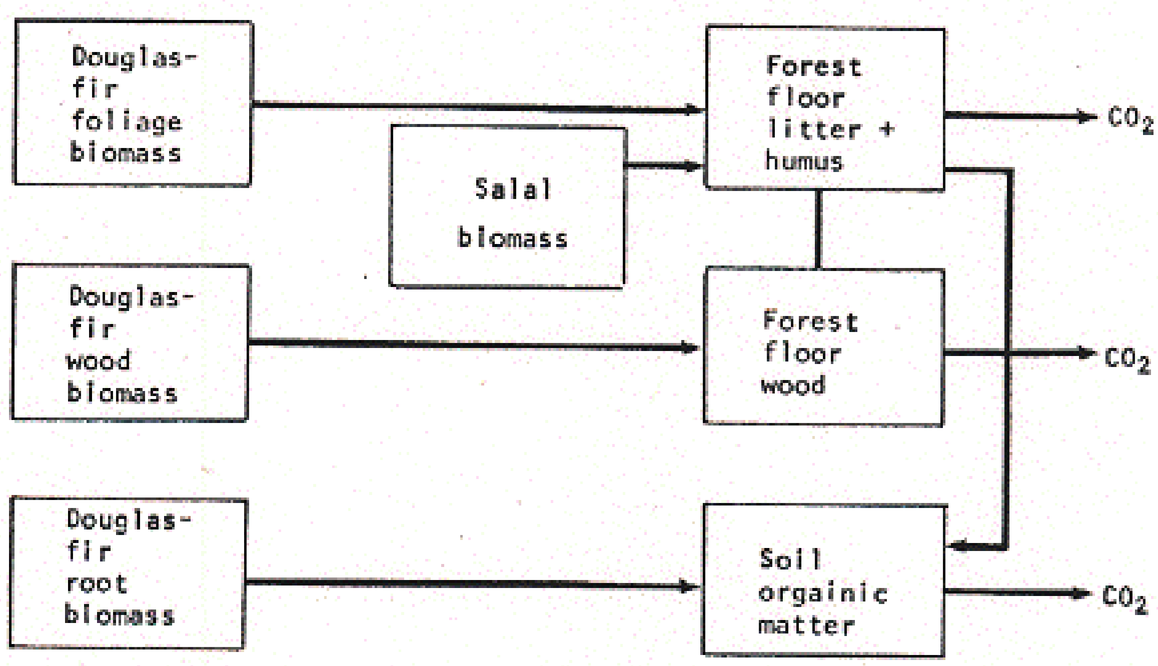


Figure 27

Flow diagram for biomass dynamics model
(Riggan, 1976)



Movement and Storage of Available N in the Ecosystem

A. Soil N and Leaching Processes

The nitrogen cycle depicted in Figure 20 shows that nearly all of this ecosystem's nitrogen capital lies in the soil (2809 kg out of 3311 kg). Considering this and the fact that annual uptake is a small fraction of total soil N, it might be asked why this forest responded significantly to a mere 200 kg/ha fertilizer addition--only a 10% increase in soil nitrogen (N). The answer lies in the fact that a very small fraction of the total store of soil N exists in forms available to trees, specifically the ammonium (NH_4+) and nitrate (NO_3-) forms. As shown in Table 40, NH_4+ and NO_3- constitute only a small fraction (0.11%) of total soil N. Using this percentage only 3 kg/ha of the 2809 kg/ha total N in Figure 20 are available for uptake. Since uptake in this example was determined to be 21 kg/ha/yr, a rapid turnover of available N in the soil is indicated. Amino sugar N is thought to be a precurser to NH_4+ (Baker, 1973), and the values given in Table 40 show that this fraction constitutes about 20-25% of total soil N. It is not known how rapidly this form is made available as NH_4+, nor what fraction of the NH_4+ so released is taken up by soil microorganisms, but the level of this fraction plus the NH_4+ and NO_3- fractions may be useful in diagnosing soil N fertility.

Since so little soil N is in available forms, it is important to understand what processes can remove available N from the soil and how these processes operate. Volatilization into the atmosphere of various forms of N is one process by which loss can occur. This process is highly complex and difficult to measure, and is only alluded to in this report.

Soil leaching is another means by which dissolved nutrients can leave the forest ecosystem and it is relatively easy to study using lysimeter techniques. In order for leaching to take place, it is necessary to have a cation that will displace native exchangeable cations and an anion that is mobile in the soil. McColl and Cole (1968) showed that carbonic acid, which is produced from carbon dioxide in the soil, provides both the displacing cation (H+) and mobile anion (HCO_3-) necessary for soil leaching under natural conditions in a second growth Douglas-fir stand.

The events associated with carbonic acid leaching are depicted in Figure 28 (Cole et al., 1975). If nitrogen is in the ammonium (NH_4+) form, the carbonic acid mechanism is the primary means by which it can be leached. When soil organisms cause nitrification to occur, however, both the hydrogen (H+) and the highly mobile nitrate (NO_3-) ion are produced, and the potential for leaching intensifies accordinaly (Figure 29). Nitrification is therefore a key process for determining the rate of soil nitrogen loss by leaching, as well as leaching of cations including NH_4+. This has been conclusively demonstrated in studies conducted by Cole and Breuer on sewage effluent application to forest soil. In this study, massive amounts of NH_4+ were applied under favorable conditions for nitrification, and massive nitrate leaching occurred (Figure 30).

Table 40

Some nitrogen fractions in two forest soils. NH_4+ and NO_3^- are available for plant uptake, and amino sugar is easily broken down to those forms (Johnson, unpubl. data)

Depth (cm)	Total N ppm	Amino sugar* ppm	Amino sugar* % of total	NH_4^+-N ppm	NH_4^+-N % of total	NO_3^--N ppm	NO_3^--N % of total
			Everett Soil				
0-15	1770	310	17.5	2.4	0.1	0.2	0.01
15-30	1470	390	26.5	2.2	0.1	0.2	0.01
			Alderwood Soil				
0-15	1430	370	25.8	1.8	0.1	0.1	0.01
15-30	1390	330	23.7	1.2	0.1	0.1	0.01

*This fraction includes a more labile form in addition to amino sugar called hydrolyzed NH_4+ by Cheng and Kurtz (1963).

Figure 28

Role of the bicarbonate ion, pH, and CO_2 in the leaching process (Cole et al., 1975)

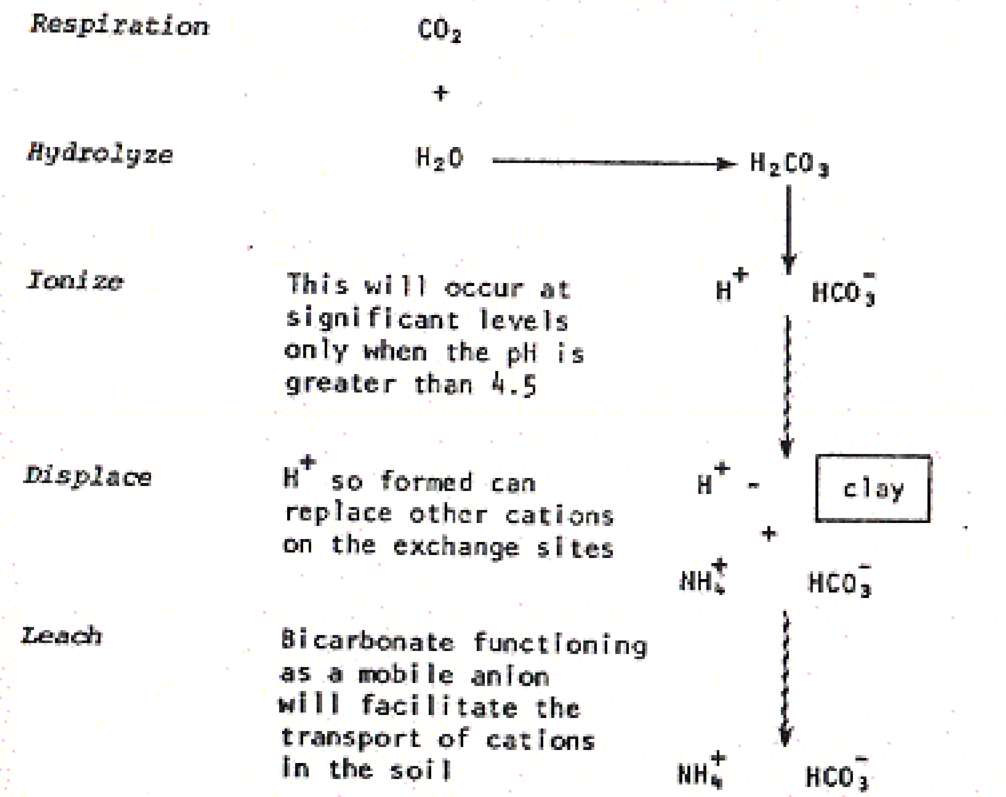


Figure 29

Nitrification as a soil leaching mechanism (Cole et al., 1976)

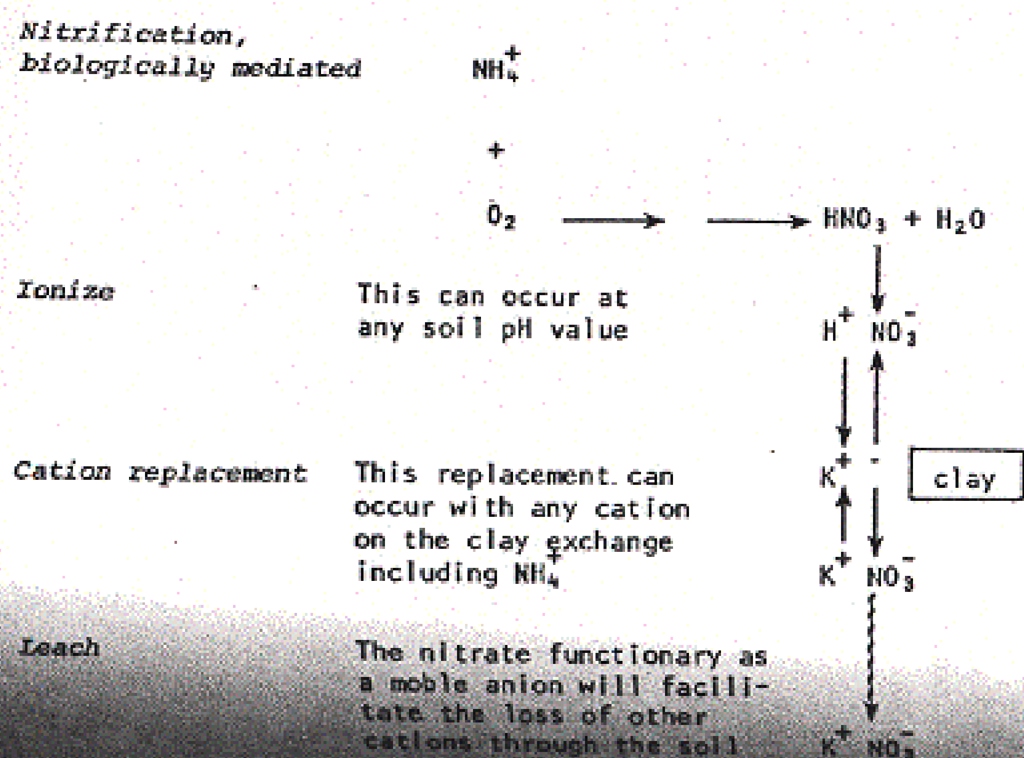
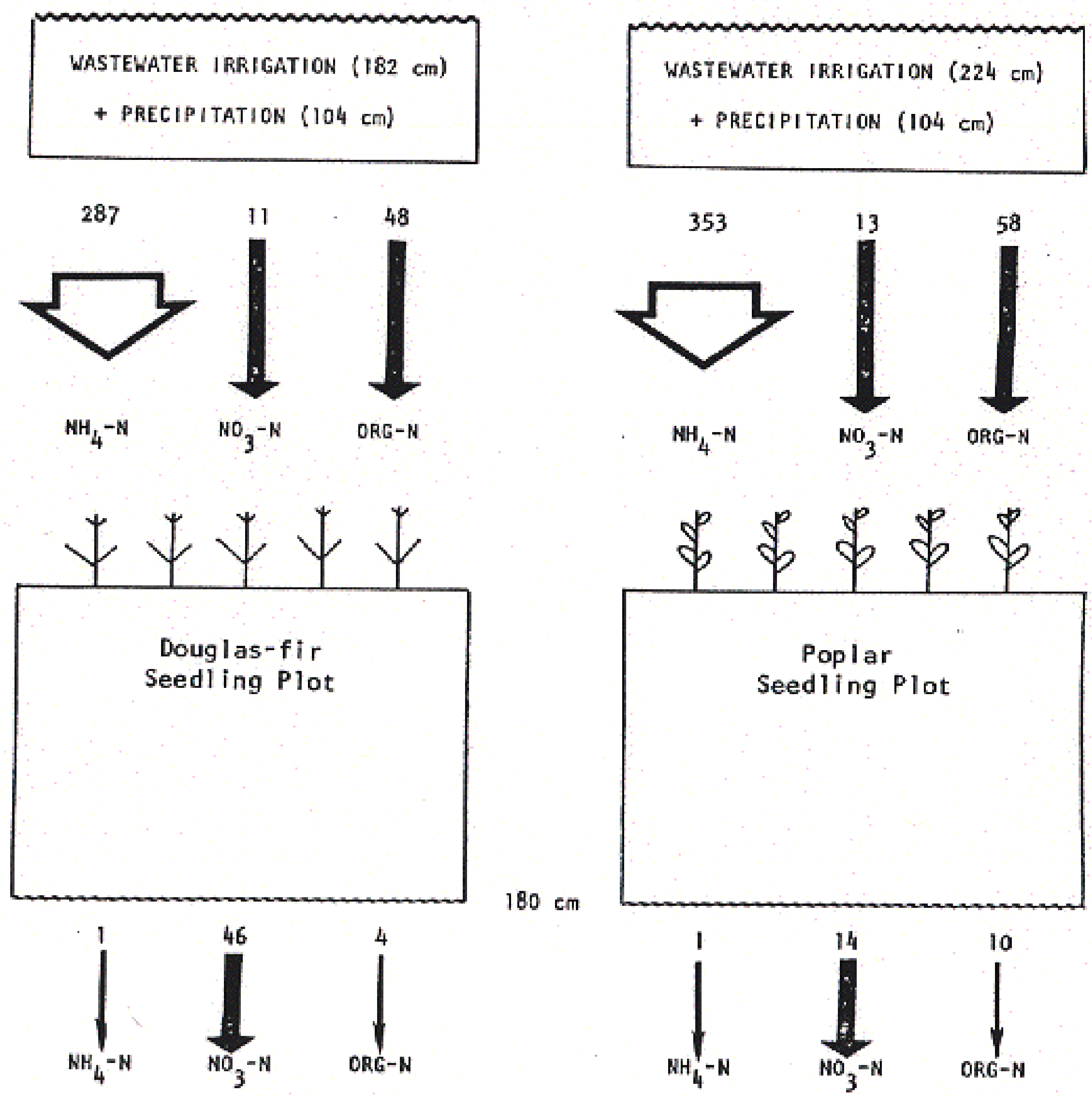


Figure 30

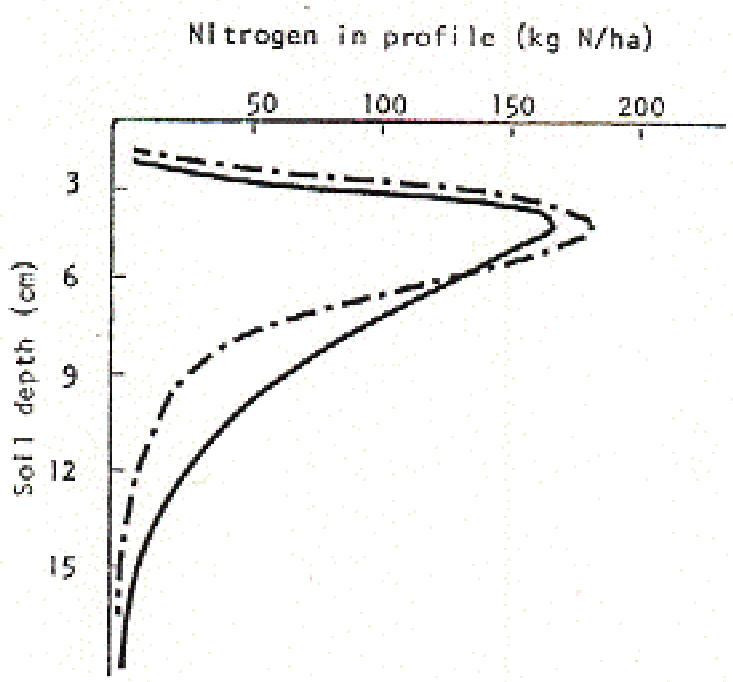
Nitrogen transfers (kg/ha) during the second year of municipal wastewater irrigation (Cole et al., 1976)



Fortunately, experiments in forest fertilization have shown that fertilizer N applied in normal dosages does not nitrify to a substantial degree but remains in the soil after fertilization. The reasons for this are unknown. Under support of the Regional Forest Nutrition Research Project, Crane (1972) showed that applied urea-N converted rapidly to ammonium bicarbonate, but very little nitrification occurred and most of the applied nitrogen remained in the top 15 cm of the soil (Figure 31). (See Cole et al., 1975 for details on leaching reactions.) Crane also experimented with gas collection techniques and concluded volatilization loss to be small. In follow-up studies conducted by Johnson (unpublished data) on the same site it was found that applied urea was immediately detected as NH_4^+ in the soil, thus greatly increasing the level of available N to the forest (Table 41). Following this, the NH_4^+ was rapidly taken up by trees and soil micro-organisms so that 220 days after fertilization there was no significant difference in NH_4^+ and NO_3^- levels between fertilized and unfertilized soils (Table 41). Preliminary indications suggest that the amino acid fraction of the soil nitrogen increased significantly after 220 days, implying that the reserve of potentially available N had been increased by fertilization.

Figure 31

Nitrogen distribution in the soil profile following urea fertilization. Solid line shows results after heavy irrigation, dashed line is after light irrigation (from Crane, 1972)



The role of such species as red alder (*Alnus rubra*) and snowbush (*Ceanothus velutinus*) as nitrogen fixers following harvesting also deserves careful consideration. These species can add considerable amounts of N to the soil. Tarrant and Miller (1963) estimate that red alder added an average of 41 kg/ha/yr of N over 30 years of occupancy relative to Douglas-fir occupancy, and Youngberg and Wollum (1976) estimate that 10 years of snowbush occupancy resulted in a N accretion of 1081 kg/ha (or 108.1 kg/ha/yr) in a burned Douglas-fir clearcut and 715 kg/ha (or 71.5 kg/ha/yr) in a Ponderosa pine clearcut. They suggested cultivating snowbush in early stages of clearcut recovery and spraying to release Douglas-fir regeneration at ages 7-10.

B. Available N in the Trees

The fraction taken up by the forest is stored in various available pools as well. Turner (1975) showed that Douglas-fir has a remarkable ability to deal with changes in nitrogen nutritional status. It has long been known that nitrogen can be translocated from old foliage to new foliage to meet growth requirements, but Turner showed that the amount of nitrogen translocated varies

Table 41 Soil NH_4^+ and NO_3^- 3 days and 220 days after urea fertilization (Johnson, unpubl. data) (ppm N in soil).

Depth (cm)	3 Days After Fertilization						220 Days After Fertilization					
	Fertilized		Control		Diff.		Fertilized		Control		Diff.	
	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-
						ALDERWOOD SOIL						
0-15	221±95	0.2±0.1	1.5±0.6	0.08±0.01	220	0.1	7.2±5.7	0.2 ±0.3	1.8±0.6	0.06±0.02	N.S.	N.S.
15-30	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	3.2±1.5	0.2 ±0.2	1.2±1.0	0.09±0.03	N.S.	N.S.
						EVERETT SOIL						
0-15	279±86	0.2±0.03	1.3±0.6	0.08±0.04	278	0.1	4.5±2.0	0.16±0.10	2.4±0.8	0.16±0.09	N.S.	N.S.
15-30	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	4.5±3.3	0.29±0.25	2.2±0.6	0.19±0.08	N.S.	N.S.

N.D. - No data.

N.S. - Not significant (t - test, α = .05).

according to the nitrogen status of the soil. Using 5 plots, he applied 880 kg/ha of urea-N to one, 220 kg/ha of urea-N to one, no treatment to one (control), carbohydrate to one, and carbohydrate plus N, P (phosphorus), K (potassium), and S (sulphur) to the fifth. The latter treatments were designed to create nitrogen stress by tying up available soil N. As Figure 32 shows, internal translocation increased as nitrogen availability decreased. In the 880 kg/ha plot, the trees took up luxury amounts of N and stored it in older foliage, giving a negative value to translocation. This experiment thus showed that Douglas-fir has not only adapted to survive in nitrogen-poor conditions, but also that Douglas-fir can take advantage of nitrogen-rich conditions by storing N in foliage.

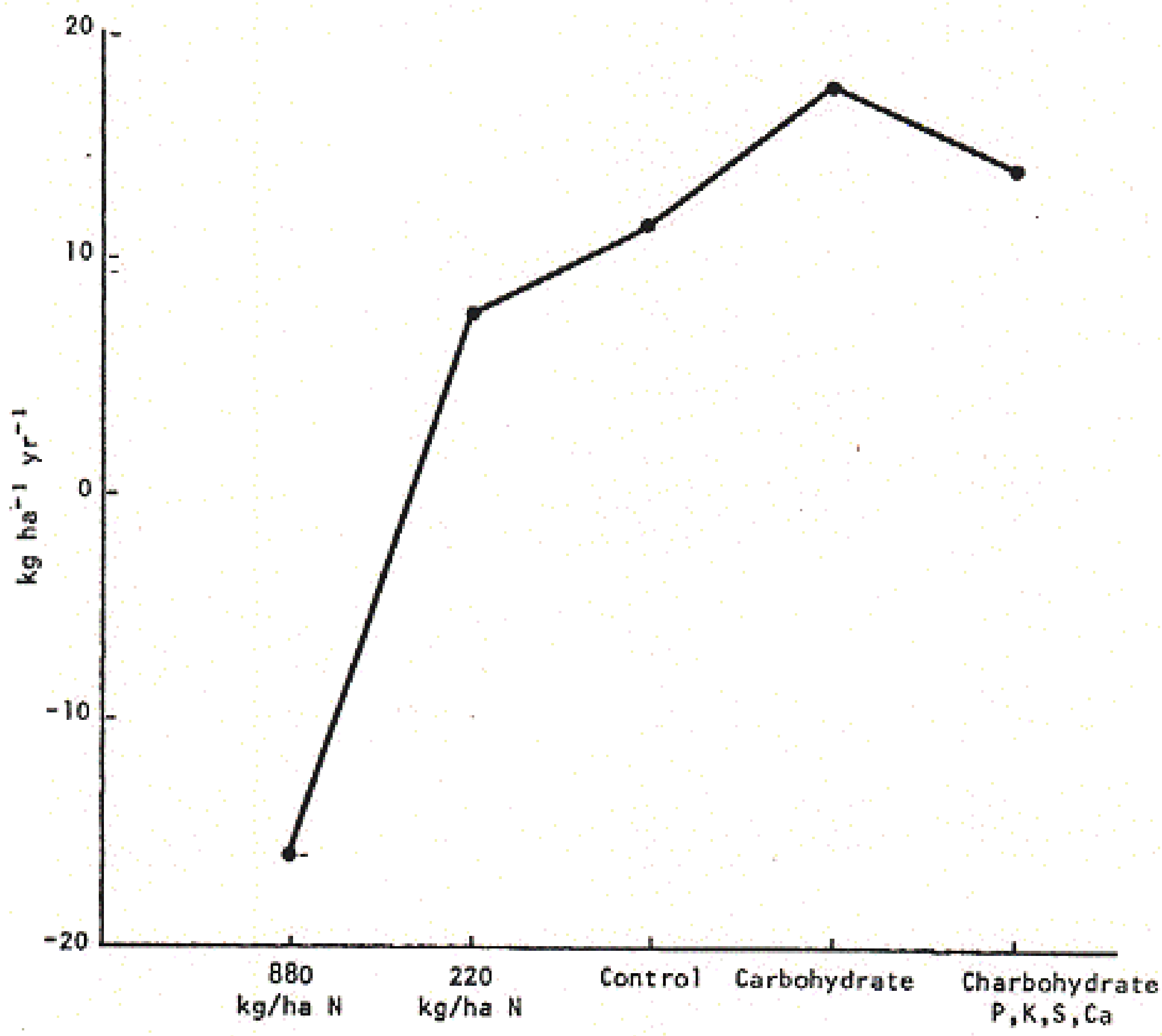
Summary and Conclusions

In summary, forest fertilization adds available nitrogen to the soil (primarily as NH_4^+) and this explains why a small addition to total N often results in a marked growth response. The NH_4^+ is taken up both by trees and soil organisms and much of it is stored in other available or potentially available forms in tree foliage and the soil. From a management perspective, it would seem most profitable to concentrate fertilization efforts on stands with low available N in the soil. This requires a determination of which soils have low inherent available N.

It is important to remember the dynamic and cycling nature of forest nitrogen nutrition, however, and storage of fertilizer N in one form or another cannot be considered permanent. Nitrogen stored in foliage can be translocated to meet growth requirements and

Figure 32

Internal retranslocation of nitrogen in Douglas-fir stands subjected to various nitrogen regimes (Data source: Turner, 1975)



thus nitrogen growth response may last longer than soil NH_4^+ levels would indicate. Eventually much foliar N reaches the forest floor as litterfall whereupon it is mineralized and routed either back to the tree or to soil organisms. Since trees are perennial, fertilizer nitrogen enters an ever-changing system that must be viewed in a dynamic perspective. Apparently the Douglas-fir ecosystems investigated have evolved strategies for conserving nitrogen very efficiently by blocking certain exit routes, such as nitrification.

Certain management practices can result in a drain on ecosystem N stores. For instance, according to figures given by Cole et al. (1968) and Grier et al. (1974), removal of the bole in harvesting a second-growth or an old-growth Douglas-fir stand removes only about 3-4% of the total nitrogen capital (Table 42). If the site is burned after harvesting, most of the N remaining in the forest floor, foliage, and branches would be lost by volatilization (Grier, 1976). This would result in a 10-15% removal of the total N, since most N capital lies in the soil. However, changes in available N following these manipulations is not known as yet.

Table 42 Nitrogen distribution in two Douglas-fir ecosystems.

Component	Nitrogen Content kg/ha	% of Total
Site IV, 36 years old (Cole et al., 1968)		
Foliage	102	3.2
Branches	61	1.8
Bole	125	3.8
Roots	32	0.9
Subordinate vegetation	6	0.1
Forest floor	175	5.4
Soil	2809	84.5
TOTAL	3310	
Site II, 450 years old (Grier, 1975)		
Foliage	75	1.3
Branches	49	0.9
Bole	189	3.3
Subordinate vegetation	58	1.0
Forest floor	132	2.3
Soil	5200	91.1
TOTAL	5703	

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BUDGET SUMMARY

Since the initiation of R.F.N.R.P. in April, 1969, a total of $777,538.78 of Cooperators' funds was expended up to the end of year 07: June 30, 1976. The category breakdown is:

Salaries and Wages	$375,255.93
Employee Benefits	35,507.50
Indirect Costs	79,252.48
Supplies, Equipment, & Services	165,817.11
Travel	121,705.76
Total	$777,538.78

In the 7-year period ending June 30, 1976, a total of $794,761.90 had been invested by the cooperators in the Project. Of this amount $488,162.00 was for Phase I (which terminated June 30, 1975), $190,673.90 was for the first five years of Phase II (which will terminate June 30, 1977), and $115,926.00 was for the first year of Phase III. Hence, during the period ending June 30, 1976, available funds exceeded expenditures by approximately $17,200. This residual will be carried into future budget periods to offset the effects of inflation.

Future funding for the Project includes:

Phase II (July 1, 1976 to June 30, 1977)	$ 36,000
Phase III (July 1, 1976 to June 30, 1980)	575,000
Miscellaneous Income from contract installations	20,120
Total:	$631,120

Cooperators Liaison Committee

E. C. Scheider	Boise Cascade Corporation
K. E. Karlsson	Broughton Lumber Company
Byron Thomas	Bureau of Land Management
R. D. Johnson	Chevron Chemical Company
W. E. Duggins	Collier Carbon & Chemical Corp.
M. E. Switzer	Cominco American, Inc.
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Paul Rooney	Fruit Growers' Supply Company
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