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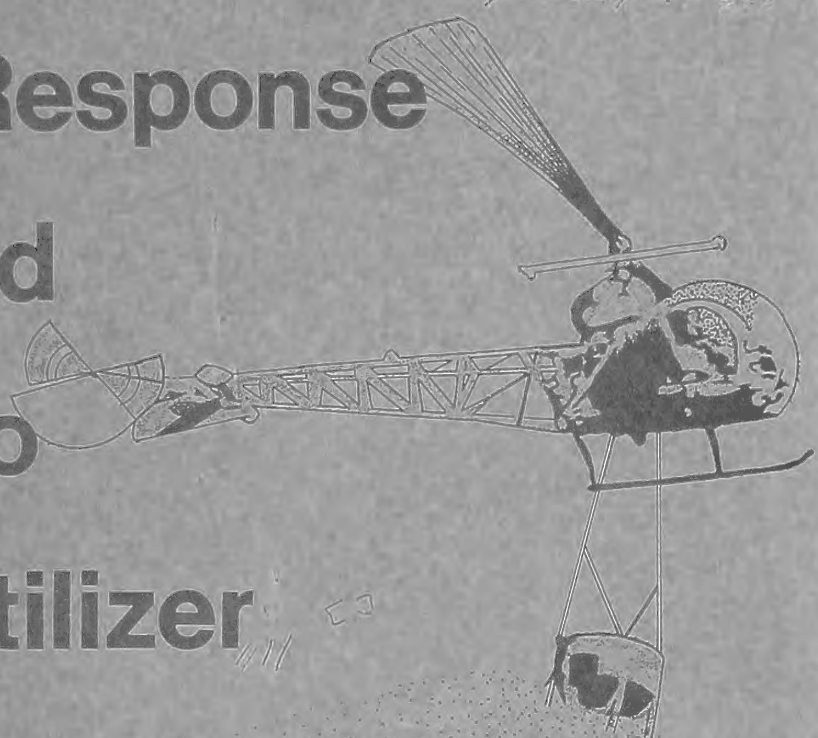
Seven-year Response of 35-year-old Douglas-fir to Nitrogen Fertilizer



R.E. Miller
and
L.V. Pienaar

Pacific Northwest Forest and Range Experiment Station
U. S. Department of Agriculture Forest Service
Portland, Oregon

415536

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ABSTRACT

Applying ammonium nitrate fertilizer to a Site V plantation resulted in significant increases in tree diameter, height growth, and in volume growth during the 7 years following treatment. Dosages of 140, 280, and 420 pounds of nitrogen per acre increased gross volume growth by 55, 92, and 109 percent,respectively (515, 852, and 1,012 cubic feet per acre); the increase with the 140 N dosage was equivalent to a temporary improvement of site quality by one site class (30 feet on a 100-year basis). Continued response in total and merchantable volume is likely, especially with higher dosages of nitrogen. The 280- and 420-pound-N dosages increased winter breakage, primarily in smaller trees, and at least doubled the number of trees and cubic volume lost to mortality. Thus far, net gain in total cubic volume of the live stand from fertilizing is as much as 83 percent (649 cubic feet), with maximum gain from the 280-pound-N treatment. Nitrogen fertilizer is a promising silvicultural tool for increasing wood production of Douglas-fir stands on similar soils of low natural productivity.

Keywords: Diameter increment, Douglas-fir, fertilizer response (forest tree), height increment, nitrogen fertilizer response, *Pseudotsuga menziesii*, silviculture, site productivity, volume increment, winter damage (forest).

R. E. Miller is Principal Soil Scientist at Forestry Sciences Laboratory, Pacific Northwest Forest and Range Experiment Station, Olympia, Washington.

L. V. Pienaar is Associate Professor of Forest Biometrics, School of Forestry, University of Georgia, Athens, Georgia.

INTRODUCTION

During the past 20 years, various fertilizers have been tested in Douglas-fir forests of western Washington and Oregon. In most tests, nitrogen has increased tree growth (Strand and Miller 1969). Some land managers have quickly adopted nitrogen fertilizing as a silvicultural tool for increasing production; other managers lack organizational or financial flexibility to implement a fertilizing program or lack sufficiently strong evidence of expected volume or value gains from their own lands.

Reliable data on volume response and its distribution by tree sizes are basic in any decision to implement or continue a forest fertilizing program. The major purpose of this paper is to provide such response data from a specific study area in a 37-year-old, Site V, Douglas-fir plantation on the Wind River Experimental Forest in southwestern Washington. In the initial report, Reukema (1968) reported substantial increases in height, diameter, and basal area growth per acre during the first 4 years after fertilizing. This present report describes the continuing effects of fertilizer on diameter and height of individual trees and cubic volume growth per acre.

In April 1964, ammonium nitrate (33.5 percent N) was applied to this plantation (fig. 1) at rates of 140, 280, and 420 pounds per acre. Trees were measured prior to treatment, after two growing seasons, and then annually through 1970. Additional details about the experimental stand, design, treatment, and data analysis are provided in the appendix.

Figure 1.--*An unfertilized plot in the study area.*

RESULTS AND DISCUSSION

TREE DAMAGE AND MORTALITY

During the 7 years after treatment, 12 to 37 percent of the initial trees died; more than twice as many trees died on plots treated with 280 and 420 pounds of nitrogen per acre as on untreated plots (table 1). Mortality was largely confined to smaller trees; only 5 percent were in the upper third of the diameter range, whereas 60 percent were in the lower third.

Winter Breakage Was the Major Cause of Damage and Mortality

Most mortality was caused by or associated with winter breakage, presumably the mixed effects of snow, ice, and wind. Serious winter damage to forests in the general study area occurs every 2 to 3 years.[1/] Winter breakage caused 78 to 79 percent of the total mortality on control and 140 N plots and 87 and 88 percent, respectively, on plots treated with 280 and 420 pounds of nitrogen per acre. Higher dosages of nitrogen led to increased mortality, because more trees were damaged and a higher percentage of damaged trees subsequently died (table 1). Mortality in given years was clustered, rather than randomly distributed, within the plot; this suggests that excessive winter breakage probably caused temporary loss of site occupancy and volume growth.

1/ Personal correspondence with David Jay, who was District Ranger, Gifford Pinchot National Forest, in February 1972.

Table 1.--Tree mortality after seven growing seasons by treatment and cause, per acre basis, average of three plots per treatment

Treatment[1/]	Live, 1963	Total dead, 1963-70		Winter breakage			Breakage mortality / Total mortality
				Total	Died		
	-------*Number*-------		*Percent*	------*Number*------		*Percent*[2/]	*Percent*
0	600	93	16	113	73	65	78
140	573	67	12	107	53	50	79
280	627	193	31	220	167	76	87
420	620	227	37	260	200	77	88

1/ Pounds of nitrogen per acre.

2/ Percent of damaged trees.

Why should nitrogen application to this stand lead to greater tree breakage and mortality, especially in smaller trees? The most plausible explanation is that the near doubling of needle length observed during the first growing season after fertilizing[2] resulted in greater accumulation of snow and ice and greater resistance to wind. The comparable height growth response of smaller trees to nitrogen suggests that their needle and twig length were also increased as much as those of larger trees. Although smaller trees are commonly sheltered by larger trees and presumably less subject to direct climate effects, these smaller trees can be targets for clumps of accumulated snow falling from larger trees. Similar increases in snow breakage after needle quantity was increased by greatly improved nitrogen nutrition on lower quality sites have been reported for Scots pine (Kreutzer 1967) and for Norway spruce (Nebe 1970).

It is unlikely that reduced wood strength could have been a major contributing factor to increased winter breakage, despite increases in ring width which occurred during the second growing season after treatment. Severe breakage occurred throughout the study area in the winter preceding fertilizing. During the second winter after treatment, however, numbers of trees damaged differed significantly among treatments and increased as fertilizer rates increased (Reukema 1968). It seems unlikely that the proportion of possibly weaker wood produced in the two growing seasons after fertilizing would sufficiently weaken the entire bole which was generally several inches in diameter at the breaking point.

D.B.H. GROWTH

We examined the effect of ammonium nitrate on (1) change in average d.b.h. (of plots), (2) average diameter growth of surviving trees, and (3) diameter growth by d.b.h. classes. The rate of diameter growth during the 7-year period increased progressively with increased dosages of fertilizer; continued response is indicated.

Average D.b.h. Growth Was Increased by Fertilizing

After seven growing seasons, increases in average d.b.h. of plots and d.b.h. growth of surviving trees were closely related to the amount of nitrogen applied (table 2). When compared with growth on untreated plots, average diameter growth was more than doubled by the 280-N and 420-N treatments.

In both fertilized and unfertilized stands, part of the increase in average d.b.h. was due to mortality. In addition to providing more growing space to surviving trees, mortality caused an immediate increase in average d.b.h. that was not a result of growth, but rather the result of losses of smaller-than-average trees.

Average diameter growth of surviving trees was linearly related to amounts of nitrogen applied (fig. 2). Although the response per pound of applied nitrogen appeared to lessen at the 420-pound dosage, there was no significant curvilinear component to

[2] Personal correspondence with Robert Tarrant, Research Forester, Pacific Northwest Forest and Range Experiment Station, in March 1972.

Table 2.--Changes in live trees per acre and average d.b.h.

Treatment[1/]	Live trees 1963	Live trees 1970	Average d.b.h., 1963	Increase in average d.b.h.[2/]	D.b.h. growth of surviving trees[3/]
	-----*Number*-----		------------------------*Inches*------------------------		
0	600	507	5.4	1.0	0.7
140	573	507	5.3	1.3	1.1
280	627	433	5.4	2.2	1.5
420	620	393	5.3	2.3	1.8

1/ Pounds of nitrogen per acre.

2/ Average d.b.h. of live trees in 1970 minus average d.b.h. of live trees in 1963; weighted average of three plots per treatment.

3/ Average d.b.h. growth of trees surviving in 1970, weighted average of three plots per treatment.

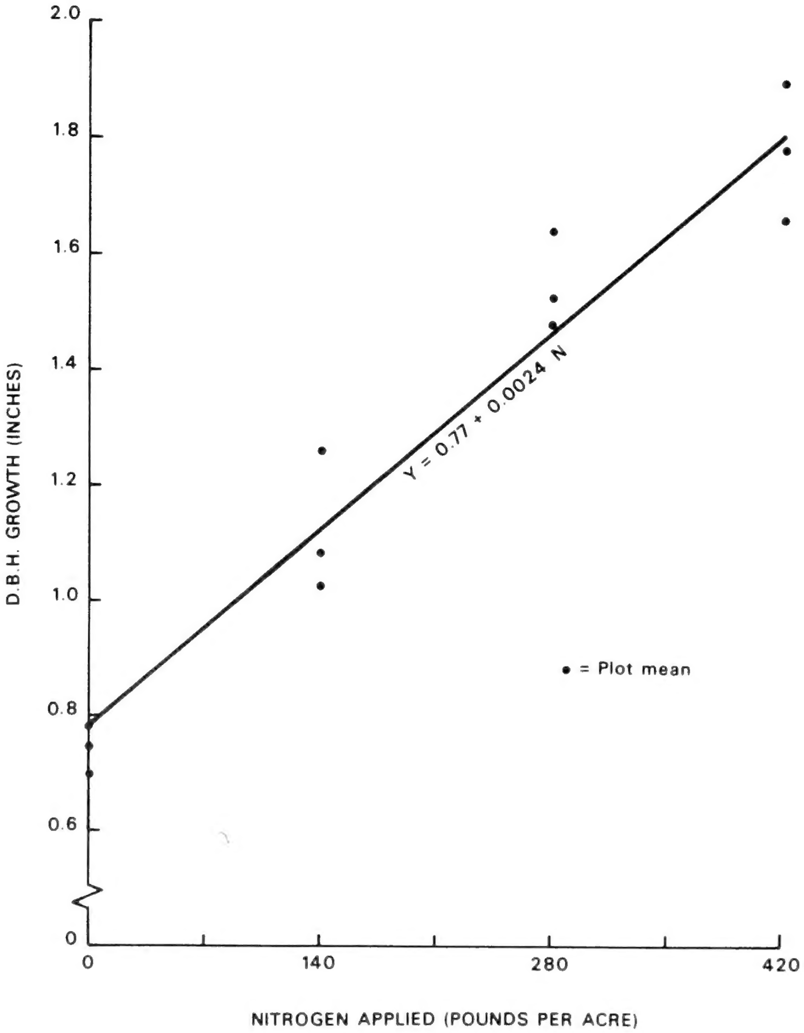


Figure 2.--*Average 7-year-d.b.h. growth after fertilizing. (Weighted average of three plots per treatment.)*

the response surface ($p < 0.11$). Thus the 420-pound-N treatment was not large enough to determine the dosage of N at which d.b.h. growth would have leveled off.

D.b.h. Growth of Larger Trees Particularly Stimulated by Nitrogen

In all plots, diameter growth of surviving trees was significantly related to initial tree size; largest trees grew most in d.b.h. Fertilizing enhanced this relationship. Additions of 280 and 420 pounds of nitrogen per acre significantly increased growth of larger trees more than that of smaller trees (fig. 3). The 140-N dosage also differentially increased the growth of larger trees but to a lesser extent than higher dosages. Because higher fertilizer dosages resulted in greater mortality, the increase in d.b.h. growth of larger trees following the 280- and 420-N treatments is explained in part by release as well as by improved nutrient status. The anticipated effects of this fertilization on future stand structure are increased average diameter and d.b.h. range, also continued advantage of large trees over small trees.

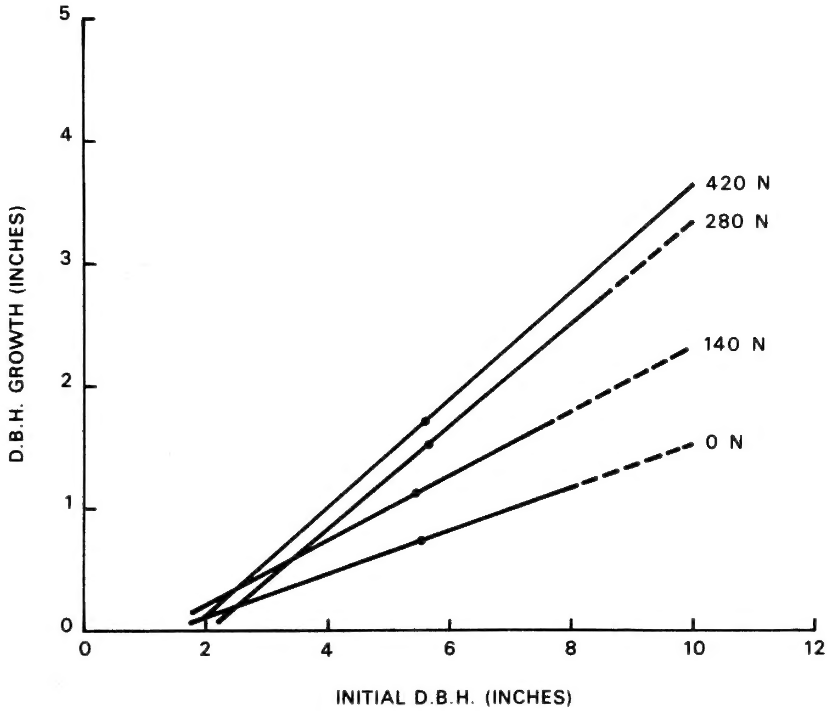


Figure 3.--*Average 7-year-d.b.h. growth of trees of varying initial d.b.h. and treatment.*

HEIGHT GROWTH

We examined fertilizer effects on total and periodic annual height growth during the 7-year period after treatment. Height growth was accelerated by fertilizer; continued response is indicated, particularly by trees treated with 280 and 420 pounds of N per acre.

Increasing Fertilizer Dosages Increased Response

We compared average height growth of 31 to 34 trees per dosage level; height of these trees had been measured at the start and end of the 7-year period. Approximately two-thirds of these sample trees were randomly drawn from trees with d.b.h. exceeding and one-third from trees less than the average of their respective plot. On 10 of the 12 plots, 7-year height growth was not significantly correlated with initial height; only one control plot and one plot treated with 140 pounds N were exceptions. Thus although average initial height of sample trees was somewhat greater on plots with the two highest dosages of N, it is unlikely that any serious bias was introduced.

Average 7-year height growth in fertilized plots was 34 to 89 percent greater than in unfertilized (table 3). Although there is some evidence that growth increases gradually diminished with higher levels of fertilizer (table 3), this tendency for curvilinearity was statistically nonsignificant ($p < 0.20$); analysis of variance supported a linear response surface ($p < 0.001$) for the range of dosages tested (fig. 4).

Continued Stimulation of Height Growth Is Likely

We examined the trends of mean annual height growth on 14 to 17 trees per treatment level. These trees, measured at each inventory, were of varying initial heights.

Annual height growth showed cyclic trends with no apparent relation to growing season precipitation (fig. 5). In general, fertilized and control trees had similar growth trends; however, growth of fertilized trees exceeded that of control trees in all years. Thus far, the yearly trend of height growth on plots treated with 280 pounds of nitrogen per acre is about the same as on those treated with 420 pounds. Height growth response following the 140-N treatment was consistently less than that following heavier dosages, yet was still evident in the seventh growing season. Continued response is likely, particularly by trees treated with 280 and 420 N.

CUBIC-VOLUME GROWTH

In this section, we examine the effects of fertilizing on:

1. Growth in total stem volume (including top and stump) of all trees 1.5 inches and larger (CVTS); this is our best estimate of total stand production.
2. Change in cubic volume to a 4.0-inch-top d.i.b. (but excluding a 1.5-foot stump) of all trees 5.6-inch d.b.h. and larger (CV4); this estimates merchantable volume production assuming intensive utilization standards.
3. Trend of annual volume growth to determine when response to fertilizer started, peaked, and ended.
4. Gross versus net growth.

Table 3.--Average[1] 7-year height growth by treatment and plot

Treatment[2] and plot[3]	Average initial height	Average growth	Gain from treatment	
	----------------*Feet*----------------			*Percent*
0:				
7	42.8	8.8	--	--
1	40.3	6.6	--	--
5	44.5	8.7	--	--
All plots	42.5	8.0	--	--
140:				
3	40.6	11.7	--	--
9	39.6	10.3	--	--
8	44.0	10.5	--	--
All plots	41.7	10.7	2.7	34
280:				
2	47.6	13.6	--	--
12	39.8	14.0	--	--
11	48.1	14.7	--	--
All plots	45.0	14.1	6.1	76
420:				
6	45.0	16.1	--	--
4	42.7	15.6	--	--
10	45.6	13.5	--	--
All plots	44.3	15.1	7.1	89

1/ Treatment averages are based on 31-34 trees.

2/ Pounds of nitrogen per acre.

3/ Plots are arranged within treatment in ascending order of initial total cubic volume.

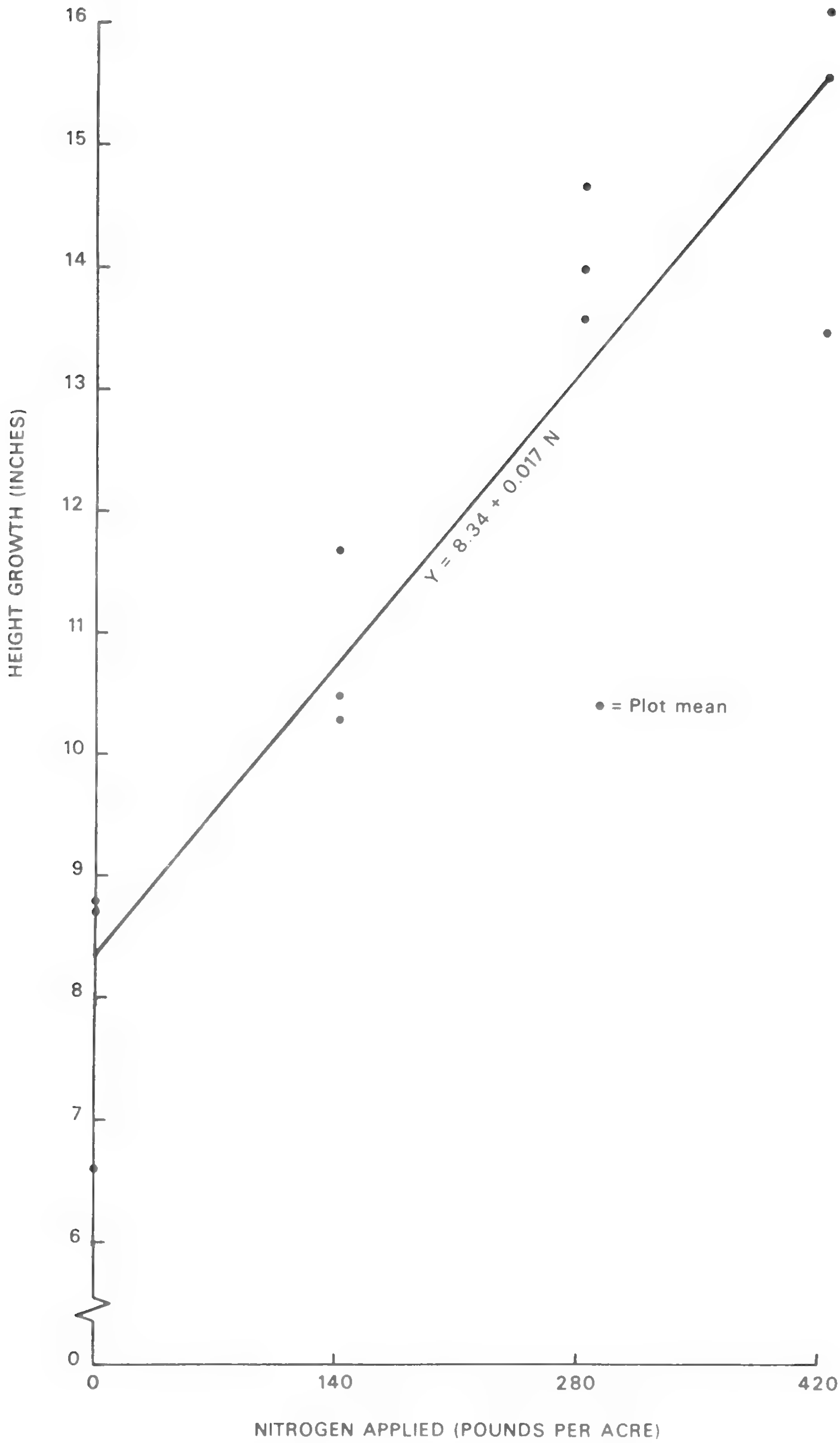


Figure 4.--*Average 7-year height growth after fertilizing. (Weighted average of three plots per treatment.)*

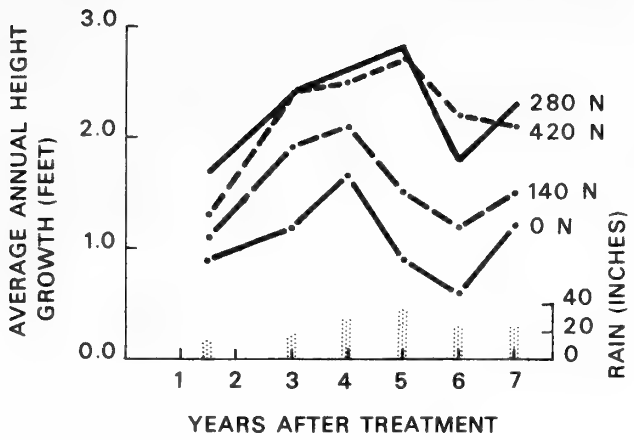


Figure 5.--*Average yearly height growth by treatment and year since treatment related to estimated rainfall during growing season.*

The method used to determine tree and plot volumes is detailed in the appendix. Although there were initial differences in both total (CVTS) and merchantable (CV4) volume among plots and treatment levels, subsequent volume growth in CVTS, but not CV4, was significantly correlated with volume of the initial growing stock ($p < 0.002$). Therefore, CVTS growth was adjusted by covariance to common initial volumes and adjusted growth used to determine fertilizer gain and trends of annual volume growth.

Gross Volume Growth per Acre Was Markedly Improved

Total volume growth.--During the 7 years following treatment, total cubic-volume growth of all trees, 1.5-inch d.b.h. and larger, was positively related to amount of nitrogen applied (table 4); the response surface was significantly curvilinear ($p < 0.06$) (fig. 6). Depending on fertilizer rate, gross growth on fertilized plots averaged 55 to 109 percent greater than that on control plots. Corresponding gains in volume growth averaged 515 to 1,012 cubic feet and increased with nitrogen dosage. The average increase following the 140-N dosage was equivalent to a temporary improvement of site quality by one site class (30 feet on a 100-year basis).

The response surface was better described by a curved than a straight line. For example, the adjusted treatment means before smoothing clearly showed that volumes gained from the three dosages gradually declined from 3.4 through 3.0 to 2.3 cubic feet per pound of nitrogen applied. Thus far, the optimum dosage of ammonium nitrate for gross volume production on this area is near 140 pounds of nitrogen per acre. To define the present or future response surface precisely will require another experiment using narrower intervals of dosage and, if possible, more replications per dosage.

Table 4.--Gross volume growth by treatment, 7-year period, per acre basis

Treatment1/ and plot2/	Initial stand		Volume growth			
	CVTS3/	CV44/	CVTS3/		CV44/	
			Unadjusted	Adjusted5/	Unadjusted6/	Adjusted5/
	------------	------------	------------	*Cubic feet*	------------	------------
0:						
7	1,617	781	772		685	
1	1,842	954	859		931	
5	2,282	1,087	1,125		1,296	
Mean	1,914	941	919	930	971	1,023
140:						
3	1,446	650	1,163		1,180	
9	1,878	811	1,249		1,331	
8	2,214	1,215	1,652		1,668	
Mean	1,846	892	1,355	1,445	1,393	1,412
280:						
2	1,793	839	1,583		1,694	
12	1,904	608	1,944		2,126	
11	2,470	1,560	2,133		2,172	
Mean	2,056	1,002	1,887	1,782	1,997	1,801
420:						
6	1,767	964	1,648		1,685	
4	1,807	668	1,841		2,042	
10	2,267	1,002	2,329		2,471	
Mean	1,947	878	1,939	1,942	2,066	2,190

1/ Pounds of nitrogen per acre.

2/ Cubic volume of total stem of all trees 1.5-inch d.b.h. and larger.

3/ Plots are arranged within treatment in ascending order of initial total cubic volume.

4/ Cubic volume to a 4.0-inch top d.i.b. of trees 5.6-inch d.b.h. and larger.

5/ Adjusted to a common initial plot volume for all treatments and smoothly curved over N dosage.

6/ Neither the covariate nor quadratic response surface proved significant; $p < 0.27$ and 0.27, respectively; smoothed by linear regression.

The volume increases after fertilizing this plantation exceed those predicted for comparable nitrogen dosages applied in similarly aged but natural stands on site class 82 (Site V) land in the Puget Sound lowlands (Gessel et al. 1969).

	Gessel et al. (1969)		This study	
Treatment	Growth	Gain	Growth	Gain
	(Cubic feet)		*(Cubic feet)*	
0	1,062	--	930	--
140	1,359	297	1,445	515
280	1,555	493	1,782	852
420	1,666	604	1,942	1,012

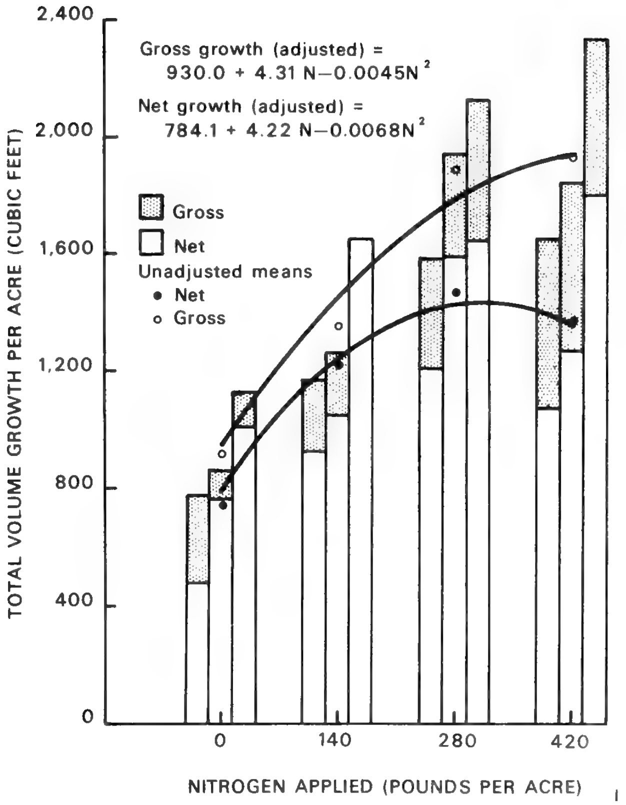


Figure 6.--*Total gross and net volume growth for a 7-year period by plot and treatment.*

Although predicted growth for their untreated stands (1,062 cubic feet) is unexplainably so much more than the 735 cubic feet predicted for normal, natural stands (Staebler 1955), this possible overestimate of growth should also apply to their growth estimates for treated stands. Average gains predicted by them for comparable rates of nitrogen and a comparable 7-year period are about 60 percent of those attained in this study.

Change in gross merchantable volume.-- Increase in CV4 (cubic volume to a 4.0-inch top d.i.b. of trees 5.6-inch d.b.h. and larger) was also accelerated by nitrogen (table 4). An additional 389 to 1,167 cubic feet of merchantable wood was produced in fertilized stands, relative to unfertilized stands, during the 7-year period:

Average gain in gross CV4 increment

Treatment	Cubic feet	Percent
140 N	389	38
280 N	778	76
420 N	1,167	114

The accumulation of merchantable volume accelerated from increased growth after treatment, as well as reclassification of nonmerchantable volume that existed before treatment. Potentially, treatment can accelerate merchantable volume accumulation when any of the following occurs. (1) More growth is added to portions of merchantable stems. (2) Diameter growth of nonmerchantable trees is increased, so they more quickly reach merchantable size (5.6-inch d.b.h. in this study); upon attaining this merchantable d.b.h., the total merchantable stem volume (about 2.7 cubic feet), not just growth since treatment, is classified as "growth." (3) Height growth is increased so a longer merchantable stem results; part of the gain in merchantable volume from increased length of merchantable stem is from reclassification of previous nonmerchantable wood. In this study, more merchantable volume undoubtedly resulted from accelerated height and diameter growth. It is doubtful, however, that fertilization accelerated movement into merchantable d.b.h. classes. Although more ingrowth into merchantable classes occurred on fertilized stands following the 280- and 420-N treatments, there were initially more such trees potentially available as ingrowth (table 5).

Table 5.--Number and proportion of larger than specified d.b.h. class trees at ages 37 and 44, by treatment[1/]

Treatment[2/]	Initial live stand		Merchantable ingrowth during 7 years				Final live stand[3/]	
	2-inch + d.b.h.	6-inch + d.b.h.	Potential	Actual	Died	Live	2-inch + d.b.h.	6-inch + d.b.h.
	Number of trees per acre							
0	600	273	327	107	7	100	507	373
140	573	273	300	107	7	100	507	367
280	627	213	413	160	13	147	433	353
420	620	233	387	160	40	120	393	333
	Percent of total number							
0		46		[4/] 33	[5/] 6			74
140		48		36	6			72
280		34		39	8			82
420		38		41	25			85

1/ Merchantable trees = trees 5.6-inch d.b.h. and larger; total trees = trees 1.5-inch d.b.h. and larger.

2/ Pounds of nitrogen per acre.

3/ Totals may not agree because some of the original 6-inch+ d.b.h. trees subsequently died.

4/ Percent of potential ingrowth.

5/ Percent of actual ingrowth.

Continued Response Is Predictable From Trends of Annual Volume Growth

Mean annual growth in CVTS of fertilized stands exceeded that of unfertilized stands during each measurement period after fertilizing (fig. 7).

When did response start?--A statistically significant response to all nitrogen dosages occurred during the 2-year period following fertilization. Although the trees were not remeasured after the first growing season, increment cores showed a definite response in radial growth during the first year after treatment.

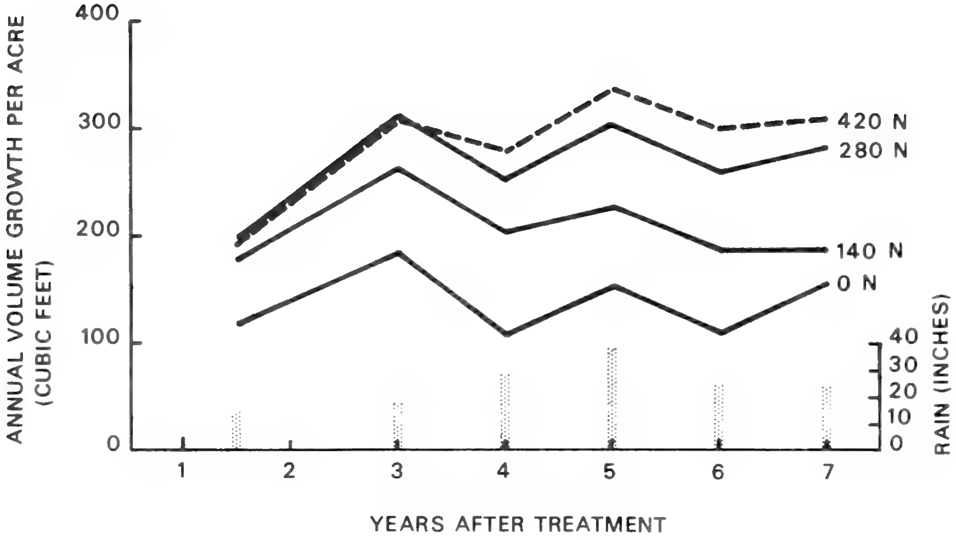
Why fluctuations in annual growth?-- Yearly volume growth on both treated and untreated stands progressed in a harmonic, up-down trend (fig. 7); years of minimum and maximum growth on fertilized plots corresponded to those of the control. Gessel et al. (1969) reported similar patterns of annual basal area growth in 40-year-old, Site IV Douglas-fir near Shelton, Washington. They regarded these as normal cyclic trends and also noted that growth of fertilized and unfertilized stands fluctuated similarly.

It seemed likely that fluctuations in cubic-volume growth in a given year should be related to growing season precipitation of that year. However, a comparison of yearly trends of growth on control plots and rainfall during April through October as measured at the nearest weather station failed to reveal a simple relationship (fig. 7). Unfortunately, we have insufficient information to evaluate precisely other explanations.

When did response peak?--Volume responses apparently peaked 2 years earlier with 140 pounds N per acre than those with heavier applications (fig. 7). With 140 N, peak annual growth occurred in the third year and peak gain (over the control), in the fourth year. With 280 and 420 pounds N per acre, peak annual growth was in the fifth growing season, and gain was as great or greater in the sixth year as in the fourth. Thus, with higher dosages, growth continued at near-peak levels for several years; in contrast, growth with the 140-N treatment declined rapidly after culmination.

Peak response after heavy dosage of N in this study area was more prolonged than that in a 40-year-old stand on gravelly soil of the Puget Sound lowlands (Gessel et al. 1969). Following application of 300 pounds N per acre, volume response culminated in years 4 and 5 and declined rapidly thereafter. There was practically no further response in years 7 and 8.

What is the duration of response?-- The duration, as well as magnitude, of response to nitrogen fertilizer in this stand will probably depend on the nitrogen dosage (fig. 7). Seven years after treatment, the response is still evident; the gain in the seventh growing season was 19, 82, and 99 percent with 140, 280, and 420 pounds of nitrogen per acre, respectively. Although the effects of fertilizing with 140 N are likely to end within 10 years after treatment, those with heavier applications are likely to continue several years longer.



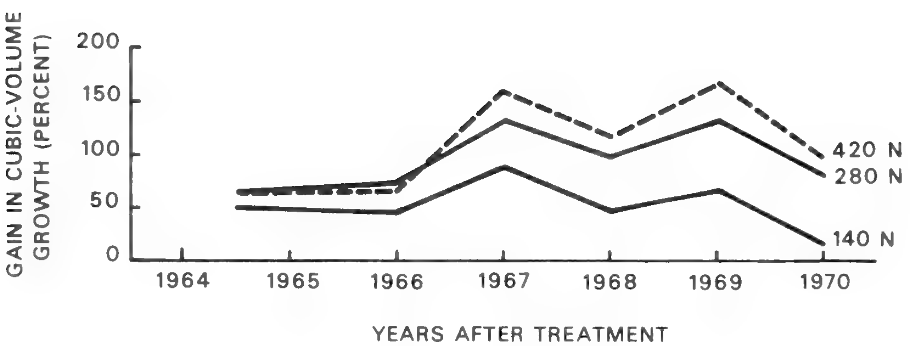


Figure 7.--*Trends of gross total volume growth and estimated rainfall during the growing season: Top, Growth adjusted for differences in initial volume, total stand in axis;* bottom, *percent gain.*

Response to nitrogen at this study area may last longer than that in Douglas-fir stands on gravelly soils of the Puget Sound lowlands, where durations exceeding 12 years following a single application of nitrogen fertilizer have been measured (Handley and Pienaar 1972).[3/] Heilman (1971) also found that duration of response depended on the amount of fertilizer applied. For nine areas in southwest Washington, he estimated that duration of response to a single application averaged 5 years with 200 N and 7 years with 400 N.

Summary.-- Ammonium nitrate fertilizer increased gross cubic volume growth each year during the 7 years following treatment. As the dosage increased from 140 through 280 to 420 pounds of nitrogen per acre, (1) annual increment increased, (2) peak annual growth occurred later and continued longer, and (3) duration of response will probably be extended by several years.

Mortality Volume Was Increased by Heavy Dosages of N

Application of 280 or more pounds of nitrogen increased mortality losses in total and merchantable volume (table 6). Following treatment with 280 or 420 pounds N, there was a two- and four-fold increase, respectively, in total mortality volume (CVTS) during the 7-year period. Most losses occurred in nonmerchantable volume. An average of less than 1 percent of mortality was merchantable volume on control plots compared with 22 to 28 percent on fertilized plots.

Net Cubic-Volume Growth Was Greatest With 280 Pounds N

Although gross growth in CVTS and CV4 increased with increasing nitrogen dosage, so did mortality. Consequently, net growth in both volume standards was greatest with 280 pounds N.

[3/] Personal communication with Stanley P. Gessel, Professor, University of Washington, in March 1972.

Table 6.--Average volume of mortality, 1964 through 1970, per acre basis

Treatment[1/]	CVTS[2/]			CV4[3/]		
	Cubic feet	Percent of unfertilized	Percent of gross growth	Cubic feet	Percent of unfertilized	Percent of gross change
0	146	100	16	[4/]0	100	0
140	203	139	14	44	∞	3
280	349	239	20	96	∞	5
420	583	399	30	148	∞	7

[1/] Pounds of nitrogen per acre.

[2/] Cubic volume of total stem, trees 1.5-inch d.b.h. and larger, mortality volume based on adjusted gross and net CVTS.

[3/] Cubic volume to a 4.0-inch top d.i.b., trees 5.6-inch d.b.h. and larger.

[4/] Some mortality in CV4 did occur in 0-N plots; however, the mathematical, linear fit to treatment means removed this.

Net volume growth of the total stand.--Depending on amount of applied nitrogen, net CVTS growth on fertilized plots averaged 458 to 649 cubic feet per acre or 58 to 83 percent more than that on control plots during the 7-year period (fig. 6). The response surface was significantly curvilinear ($p < 0.03$).

Net change in merchantable volume.--CV4 volume of the live stand increased by an additional 336 to 1,010 cubic feet per acre or 33 to 98 percent after fertilizing:

Treatment	Net gain in CV4	
	Cubic feet	Percent
140 N	336	33
280 N	673	65
420 N	1,010	98

CONSIDERATIONS FOR THE LAND MANAGER

WHAT RATES OF NITROGEN SHOULD BE USED?

In this study area, magnitude and duration of response in gross cubic volume were related positively to amount of ammonium nitrate applied. Response to the 140-N treatment appears nearly complete after seven growing seasons; however, response to double and triple dosages have not yet ended, so we cannot yet accurately compute fertilizer efficiency and thus optimum dosage.

Intensity of stand management or risk from winter breakage may be other bases for deciding the appropriate nitrogen dosage for specific stands. One could use small dosages in accessible, intensively managed stands and larger dosages in less accessible stands. In this study area, dosages of 280 and especially 420 pounds of N per acre increased risk of winter breakage and mortality. In similar areas prone to winter breakage, foresters may choose to adjust nitrogen dosage to increase or decrease winter breakage and mortality; they may wish to increase this breakage in overstocked stands and minimize it in understocked stands. To minimize winter breakage, Nebe (1970) suggested restricting fertilizing to stands having a uniform crown canopy and regularly shaped crowns. Even when such stand conditions do exist--as in our plantation--silviculturists should avoid sudden stimulation of a heavy foliage complement by heavy dosages of nitrogen.

Treatment cost, per pound of nitrogen applied, is likely to decline slightly, if dosage per application is increased from 140 to 420 pounds N per acre. At dosages of 150 and 200 pounds N per acre as urea prill, contractors will commonly supply fertilizer and helicopters to fertilize large forested areas (approximately 1,000 acres or more) for about $0.11 per pound of N (Strand and Miller 1969). Increasing dosage would increase construction and operational costs of each heliport; however, these costs would be apportioned to a larger tonnage of fertilizer. The increase in costs are likely to be proportionately less than the increase in dosage; therefore, costs per pound of N applied from each heliport would decrease as dosage increased. Assuming that increased dosage would not affect the acreage treated from each heliport, and thus the number of heliports needed, then costs of changing heliports would be apportioned to a larger tonnage of fertilizer and further reductions in costs per unit of N would result. More reduction is possible if increasing dosage encouraged use of more efficient equipment or increased competition among bidders. [4]

WHAT SOURCE OF NITROGEN SHOULD BE USED?

We do not know if comparable gains in volume growth would have been obtained in this study had a nitrogen source other than ammonium nitrate been used. Most nitrogen fertilizer currently applied to forests in the Pacific Northwest is urea, primarily because its higher concentration (46-percent N) insures a greater net payload than do other fertilizers such as ammonium nitrate (34-percent N). There is concern, however, that urea applications during dry, warm weather can lead to gaseous losses of N (Watkins et al. 1972) and reductions in the amount available for growth. Currently, there is insufficient evidence from tests in Douglas-fir to specify circumstances where the various nitrogen fertilizers will differ in response per pound of nitrogen applied.

FERTILIZER CAN INCREASE USABLE YIELDS

Where natural productivity is restricted by nutrient deficiencies, fertilizers can increase usable yields per acre and enable the land manager to make earlier commercial thinnings or final harvests. Fertilizer can increase the amount and advance the timing of yields in several ways.

1. By supplying a growth-limiting factor and thus improving natural site productivity. Field trials have demonstrated that insufficient available nitrogen can limit maximum growth on Sites I through V (Strand and Miller 1969).
2. By stimulating growth of upper crown classes more than that of lower classes. We found this in our diameter growth analysis.
3. By accelerating diameter growth of small trees and thus rate of ingrowth into merchantable size classes. We found no strong evidence for this in our study.
4. By accelerating the natural rate of mortality of smaller trees in Douglas-fir stands through suppression (Crossin et al. 1966)[5] or through differential winter breakage and mortality, as found in this study. Even on nutrient-deficient sites, however, it is unlikely that the release provided by fertilizer- induced mortality will be as effective in stimulating growth of crop trees as that provided by mechanical or chemical thinning methods.

Besides affecting volume growth, fertilizer can also affect wood quality. A major concern is that increasing tree ring width lowers specific gravity of the wood. Potentially, reduced specific gravity lowers structural strength and pulp yield per unit volume (Larson 1968). In Douglas-fir, average specific gravity is generally

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[4] Personal correspondence with Robert Bergland, Forester, Washington Department of Natural Resources, in June 1972.

[5] Unpublished data (Black Rock Fertilizer Study) on file at the Forestry Sciences Laboratory, Olympia, Washington.

reduced after fertilization with nitrogen alone or in combination with other elements. Maximum reductions of 8 percent (Erickson and Lambert 1958) and 10 percent (Siddiqui et al. 1972) have been reported. Two recent studies in Douglas-fir have shown that fertilization improved fiber and paper quality despite substantial increases in volume growth (Gladstone and Gray 1973). In assessing the effects of fertilization on wood quality and quantity, the net effects of changes in wood quality must be offset by the value of additional wood volume beyond that necessary to cover the cost of fertilization. If pulp yields or pulp properties, or lumber grades and recoveries, are not affected adversely by treatment, then volume increases due to fertilizer may be accepted as a valid measure of gain from treatment (Gladstone and Gray 1973).

COMBINATION OF FERTILIZING AND THINNING HOLDS PARTICULAR PROMISE

Some of the growth increases from fertilization will be in trees or portions of trees which remain nonmerchantable. This is particularly true in young, natural stands on low quality sites. To increase the usable gains from fertilizing, there is a need to concentrate growth on fewer trees. The land manager can accomplish this by combining fertilizing and thinning.

Similarly, the benefits from thinning can be increased by combining this practice with fertilizing. Thinning generally results in a temporary loss of full site occupancy; however, foresters believe that this reduction in total growth per acre is usually offset by the increased growth added to crop trees. One extreme case of growth reduction following thinning occurred within 0.1 mile of our study area and in a portion of the same plantation. For 6 years after the stand was thinned from 650 to 350 or fewer stems per acre, basal area growth per acre was roughly proportional to growing stock; growth on the most lightly thinned plots averaged 63 percent of control growth.[6/] Based on our study results in the same plantation, we assume that application of nitrogen fertilizer before or after thinning would have stimulated growth of residual trees and increased per acre production.

In another study area on the Olympic National Forest, we fertilized previously thinned portions of a Site IV stand of Douglas-fir. During the 2 years after fertilizing, basal area growth of the thinned and fertilized stand was nearly equal to, and that of the thinned-only stand only one-half, that of the unthinned stand.[7/] Thus, on nutrient-deficient sites, fertilizer is a means for lessening temporary reductions in total growth following thinning as well as for further increasing the growth added to released crop trees.

[6/] D. L. Reukema. 1959. Unpublished report on the Planting Creek increment spacing study. Copy on file at the Forestry Sciences Laboratory, Olympia, Washington. 10 p.

[7/] Unpublished data (Rocky Brook Fertilizing-Thinning Study) on file at the Forestry Sciences Laboratory, Olympia, Washington.

EFFECT OF NITROGEN FERTILIZATION ON WATER QUALITY

The increasing use of nitrogen fertilizers in the Pacific Northwest to increase forest growth has triggered concerns about the effects of this practice on environmental quality, specifically a concern for excessive nitrogen in surface and ground water. In response to this concern, stream waters flowing from numerous forested watersheds in western Washington and Oregon have been analyzed before and after applications of 150 to 200 pounds of N per acre as urea fertilizer. Such applications have not resulted in toxic levels of urea-, ammonia-, nitrite-, or nitrate-nitrogen in streams draining treated areas during the first year after treatment (Moore 1972). Most research results indicate that direct application to surface waters is the principal means of entry of fertilizers and other chemicals to forest streams (Norris and Moore 1972). Although additional information is needed about the effects of repeated fertilization to the same area and other nitrogen carriers, such as ammonium nitrate, available information suggests that little environmental damage appears possible if fertilizer is carefully broadcast at current dosages and intervals on the forested lands (Tarrant et al. 1973).

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APPENDIX

PRETREATMENT CONDITIONS

Stand.--Planted in spring 1929 with 1-1 Douglas-fir from an offsite, Roy, Washington, seed source,[8] the stand was 37 years old when fertilized in April 1964. Spacing in the original planting averaged 8 by 8 feet or about 680 trees per acre. Prior to fertilizing, plots averaged 604 live trees per acre and 94.5 square feet of basal area (table 7). Site index averaged 82 and ranged from 75 to 90 feet (height at age 100). Basal area per acre in all of these plots was below normal standards (McArdle et al. 1961). Expressed as a percent of normal for the indicated site index for each plot, stocking among plots before 1964 growing season ranged from 65 to 98 percent of full stocking, averaging 80 percent.

8/ Written correspondence with Tom Atzet, District Forester, Gifford Pinchot National Forest, on February 23, 1973.

Table 7.--Stand conditions prior to fertilizing, total stand, per acre basis

Treatment[1] and plot[2]	Number of live trees	Site index (feet)	Basal area (sq. ft.)	Basal area, percent normal[3]
0:				
7	540	79	81.9	73
1	580	75	91.9	90
5	680	81	113.5	98
Mean	600	78	95.8	88
140:				
3	480	75	71.4	70
9	600	85	91.9	74
8	640	82	106.1	90
Mean	573	81	89.8	77
280:				
2	580	90	86.4	65
12	720	77	95.4	89
11	580	88	112.8	87
Mean	627	85	98.2	79
420:				
6	540	84	84.8	70
4	620	81	89.1	77
10	700	88	109.2	85
Mean	620	84	94.4	77
All treatments:				
Mean	604	82	94.5	80

1/ Pounds of nitrogen per acre.

2/ Plots are arranged within treatment in ascending order of initial cubic volume.

3/ Richard E. McArdle, Walter H. Meyer, and Donald Bruce. The yield of Douglas fir in the Pacific Northwest. U.S. Dep. Agric. Tech. Bull. 201, 74 p., illus., 1961.

Location.--The study area is located 3.5 miles northwest of the Wind River Ranger Station near Carson, Washington, at an elevation of approximately 2,000 feet. Topography is relatively uniform, with northwest aspect and slopes ranging from 15 to 30 percent. The plantation lies on the east edge of the 294,000-acre Yacolt Burn in an area that was swept by wildfires in 1902 and 1927.

Climate.-- Based on weather records (1956 through 1965) from the Wind River Ranger Station, 900 feet lower in elevation than the study area, annual precipitation averages 96 inches with 26 percent falling during the April through October period (Pacific Northwest River Basins Commission Meteorology Committee 1969). Potential evaporation during the summer months greatly exceeds summer precipitation, so trees in the study area are subjected to summer moisture stress characteristic of western Washington and Oregon.

Most precipitation falls between growing seasons as rain, snow, or a mixture. Winter temperature is normally near or above freezing; thus ice accretion as glaze or rime is likely to occur.

Soils.-- The soil in the study area is moderately deep and well-drained; it is derived from andesitic or rhyodacitic pyroclastic rocks of the Ohanapecosh Formation from early Tertiary times (Wise 1970). Surface horizons contain some pumice and basaltic gravel from recent Pleistocene time. This soil (Number 87) has been mapped on nearly 10,000 acres of the Gifford Pinchot National Forest.[9/] Morphologically related soils cover an additional 23,000 acres of the Forest.

Surface soil on the study plots has fine gravelly loam texture and granular structure; below the 6- to 17-inch depth, the soil has a clay-loam texture and strong, subangular blocky structure. Roots are abundant in the surface layer, but sparse below 3 feet. The soil contains approximately 3,000 pounds of total nitrogen per acre to a 3-foot depth (Tarrant and Miller 1963). This amount is about average for low productivity lands in western Washington; probably less than 5 percent of this total is available for vegetative use each year (Stevenson 1964, Pesek et al. 1971).

EXPERIMENTAL DESIGN AND TREATMENT

In April 1964, ammonium nitrate (33.5-percent N) was applied to 0.15-acre circular plots at rates of 140, 280, and 420 pounds of N per acre.[10/] Each treatment was replicated on three plots. Three control plots were also included in this completely randomized experimental design.

9/ Written correspondence with LeRoy Meyers, Soil Scientist, U.S. Forest Service Region 6, on December 28, 1971.

10/ Rates of nitrogen application were previously reported (Reukema 1968) as 200, 400, and 600 pounds of nitrogen per acre. Subsequently, we found that a larger plot area had been actually treated and thus rates were 140, 280, and 420 pounds.

MEASUREMENTS AND VOLUME DETERMINATION

Trees were measured on a 0.05-acre circular plot centered within the treated plot. Trees were initially measured after the 1963 growing season, subsequently measured after two growing seasons, and then measured annually through 1970. At each measurement, d.b.h. was measured on all trees and total height determined on a subsample of seven to 15 trees per plot distributed over the range of diameters,[11/] but with two-thirds of the subsample larger than average d.b.h.

Local volume tables for plot volume estimation were derived by means of the tarif system (Turnbull et al. 1963). Tarif numbers[12/] were obtained from Hoyer (1966). For each treatment level, an average tarif number was computed based on more than 30 trees which had been measured for total height in 1963, 1967, and 1970. Average tarif numbers for intervening years were obtained by graphic interpolation. The average tarif number of each treatment level was used to calculate plot volumes at each inventory. Initially, the average tarif numbers among treatment levels ranged between 24.3 and 25.5. By the end of the seventh growing season after treatment, the range had widened to between 26.8 and 28.9, with larger increases associated with the higher fertilizer levels.

11/ Initially, height was measured on seven trees per plot. After the 1967 growing season, the height sample was increased to 15 trees per plot and the 1963 height of the supplemental trees was measured when possible.

12/ Tarif-volume equations provide a series of harmonized volume/d.b.h. curves, each indexed by a tarif number. The tarif number is the cubic volume (from stump to a 4-inch top) for a tree of 1.0 square foot of basal area.

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