Forest Sci., Vol. 29, No. 1, 1983, pp. 127–137

Long-term Growth Response of Douglas-fir to Ammonium Nitrate Fertilizer

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ABSTRACT. The effect of a single application of ammonium nitrate fertilizer on diameter, height, and volume growth of a Site IV plantation of *Pseudotsuga menziesii* was measured repeatedly during a 15-year period. Fertilizer dosages of 157, 314, and 471 kg N/ha increased gross volume growth during the 15-year period by an average of 51, 88, and 111 percent, respectively (67, 116, and 146 m^3/ha). Quadratic equations best described the relationship between fertilizer dosage and gross and net volume growth during the entire period and during three intermediate periods. Volume growth on fertilized plots exceeded that on unfertilized plots in all periods. Response to all N dosages did not change significantly during the 15-year period of observation. The positive, long-term effect of fertilizer on stand growth is attributed both to improved tree nutrition and to secondary effects of increased tree growth on stand structure. FOREST SCI. 29:127–137.

ADDITIONAL KEY WORDS. *Pseudotsuga menziesii,* forest fertilization, silviculture.

IN APRIL 1964, we applied ammonium nitrate to experimental plots in a 37-year-old Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] plantation growing on Site IV land in the Wind River Experimental Forest near Carson, Washington. The purpose of the study was to observe the effectiveness of a chemical fertilizer in the same Douglas-fir plantation which had responded strongly to a biological source of N (Tarrant 1961). In this paper, we report and discuss an unusually strong effect of ammonium nitrate on tree and stand growth over a 15-year period after treatment.

Until recently, ammonium nitrate has been generally ignored for forest use in the Douglas-fir region largely because of its lower N concentration (34 percent N) and thus, greater application cost vs. urea (46 percent N). The few studies in which ammonium nitrate had been used in Pacific Northwest forest fertilization either involved two or more fertilizers in combination (Gessel and others 1969) or emphasized effects on cone production (Ebell 1962). During the time this study has been underway, however, additional research has been reported (Harrington and Miller 1979, Miller and Harrington 1979, Miller and Reukema 1974, Brix 1981). Further, research over the past decade or more (Marshall and DeBell 1980) indicates that under certain conditions, ammonia can be volatilized from urea and lost to the atmosphere, thus lessening the cost advantage of urea.

Scandinavian foresters also have developed a strong interest in ammonium nitrate. In northern latitudes, primarily on shallow, infertile mineral soils, fertilizing forests with ammonium nitrate produces greater tree growth response than that gained from urea (Bengtson 1977). As of 1967, almost all forest fertilization

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FIGURE 1. An unfertilized plot in the study area (1971 photo).

in Sweden was with urea, but by 1975, about 80 percent of all N fertilizer so used was ammonium nitrate (Moller 1974).

MATERIALS AND METHODS

Study Site.—The study site (Fig. 1) was planted in 1929 with 1-1 Douglas-fir seedlings from a nonlocal seed source. Initial spacing was 2.4 by 2.4 m (8 by 8 ft), or about 1,680 trees/ha. At fertilization in 1964, the 12 plots in the study averaged 1,547 trees/ha, 123.2 m^3/ha in total stem volume and 26.2 m in site index (100-year base).

Elevation of the study area is about 600 meters. Annual precipitation averages about 2,500 mm, only a quarter of which falls during April–October, the approximate growing season. Potential evaporation greatly exceeds summer precipitation, so vegetation at the study site annually undergoes several months of moisture stress.

The unclassified soil here is derived from early Tertiary andesitic or rhyodacitic rock. The gravelly loam surface horizons also contain pumice and basaltic gravel of Pleistocene origin. Below 15- to 40-cm depths, the soil is of clay loam texture and has a strong, subangular blocky structure. Roots abound in the surface layer, but few extend below 1 m. The soil contains approximately 3,400 kg N/ha to a depth of 1 m (Tarrant and Miller 1963), about average for forestlands of low to moderate productivity in western Washington.

Treatments.—Ammonium nitrate was broadcast by hand in April 1964 over 0.06-ha (0.15-acre) circular plots at rates of 157, 314, and 471 kg/ha. Treatments, including unfertilized controls, were replicated three times in a completely randomized experimental design.

Measurements.—Diameter at breast height (dbh) was measured at 1.4 m above ground on all trees 4.1 cm (1.6 inches) and larger on 0.02-ha (0.05-acre) circular

TABLE 1. Average change in dbh during 15 years after fertilization.

Fertilizer application (kg N/ha)	Average dbh			Annual adjusted growth of surviving trees[2]
	1963	1978	Annual change[1]	
	cm			
0	13.7	18.5	0.32	0.28
157	13.5	19.3	0.39	0.38
314	13.5	22.1	0.57	0.47
471	13.7	23.1	0.63	0.56

[1] Average dbh of live trees in 1978 minus average dbh of live trees in 1963; weighted average (by basal area) of three plots per treatment.

[2] Average dbh growth of surviving trees in each treatment was adjusted for differences among the treatments in initial dbh. The adjusted means were linearly regressed over N dosage; the quadratic response was nonsignificant ($P < 0.425$).

plots centered within each treatment area. Total height was determined on a subsample of 14 to 17 trees per plot (plots averaged 30 trees in 1963). These trees were distributed over the dbh range, but two-thirds of the subsample had larger-than-average dbh. First measurements of both height and dbh were made after the 1963 growing season and before fertilization. After-treatment measurements were made after year 2, then at 1- to 4-year intervals through 1978, 15 years after fertilization.

Volume Growth Determination.—Total stem volume, including top and stump of each height-sample tree was estimated from a regional volume equation for Douglas-fir (Bruce and DeMars 1974). These sample tree volumes were then used to calculate a separate volume equation for each plot and measurement year. The form of the equation was

$$\log V = a + b \log D$$

where V = cubic-foot volume of total stem and D = dbh (inches). The volume of each tree in each measurement year was computed by specific equations for each plot and year. The difference between the combined volume of live and of dead trees at one inventory and the volume of the live stand at the previous inventory is gross growth. The difference in volume of live trees at successive inventories is net growth—gross growth minus the total volume in trees that died between inventories.

Statistical Analyses.—Analysis of covariance with orthogonal polynomials was used to estimate a response surface or curves of change in average dbh, height,

TABLE 2. Average change in numbers of live trees during 15 years after fertilization.

Fertilizer application (kg N/ha)	1963	1978	Loss
	live trees/ha		
0	1,515	1,087	428
157	1,515	1,137	378
314	1,614	1,038	576
471	1,549	907	642

TABLE 3. Average annual height growth of surviving trees during 15 years after fertilization.[1]

Fertilizer application (kg N/ha)	Average height 1963	Adjusted average heights[2]			
		1978	Height growth	Gain from treatment	
	m	*m*	*m/yr*	*m/yr*	*percent*
0	13.4	18.1	0.31	—	—
157	13.0	19.0	0.40	0.09	30
314	13.8	21.3	0.50	0.19	61
471	13.7	22.6	0.59	0.28	90

[1] Treatment averages are based on 30–34 trees.

[2] Treatment averages were adjusted for initial differences in height then linearly regressed over N dosage; the quadratic response surface was nonsignificant ($P < 0.228$).

and stand cubic volume during the 15-year period. The covariate for computing adjusted treatment means was initial dbh, height, or volume, respectively. To compare trends of growth, the 15-year period was divided into periods of 5, 4, and 6 years; the average annual volume growth during each of these periods was compared as the split-plot effect in covariance analyses. Using time-after-treatment as the split-plot is suggested by Bliss (1967). In all analyses, we used the 5-percent probability level to judge statistical significance of results; we also offer the actual level of significance for each test.

Results and Discussion

Diameter Growth.—During the 15-year period after the fertilizer application, increases in stand average dbh and growth in dbh of surviving trees were linearly related to the amount of N applied (Table 1). Part of the increase in average dbh of both the unfertilized and the especially heavily fertilized stands was due to mortality (Table 2). Mortality not only provided more growing space for surviving trees, which increased their rate of growth, but it also removed many smaller-than-average trees which arithmetically increased average dbh of the stand. For example, more than twice as many trees of below-average dbh died during the first 7 years after fertilization with 314 and 471 kg N/ha (Miller and Pienaar 1973).

TABLE 4. Average annual gross growth and mortality by treatment during 15 years after fertilization.

Fertilizer application (kg N/ha)	Initial volume	Gross growth		Mortality	
		Unadjusted	Adjusted[1]	Unadjusted	Adjusted
	m^3/ha[2]				
0	119.4	8.6	8.8	2.0	1.9
157	119.6	12.2	13.2	1.9	1.8
314	131.5	17.9	16.5	1.9	2.1
471	122.3	18.1	18.4	2.9	2.1

[1] Treatment averages were adjusted for initial differences in stand volume and smoothly curved over N dosage. The covariate and the quadratic response surface for gross growth were significant: $P < 0.000$ and 0.039, respectively. Those for net growth were also significant: $P < 0.000$ and 0.034, respectively.

[2] Total stem volume of all trees 4.1-cm dbh and larger.

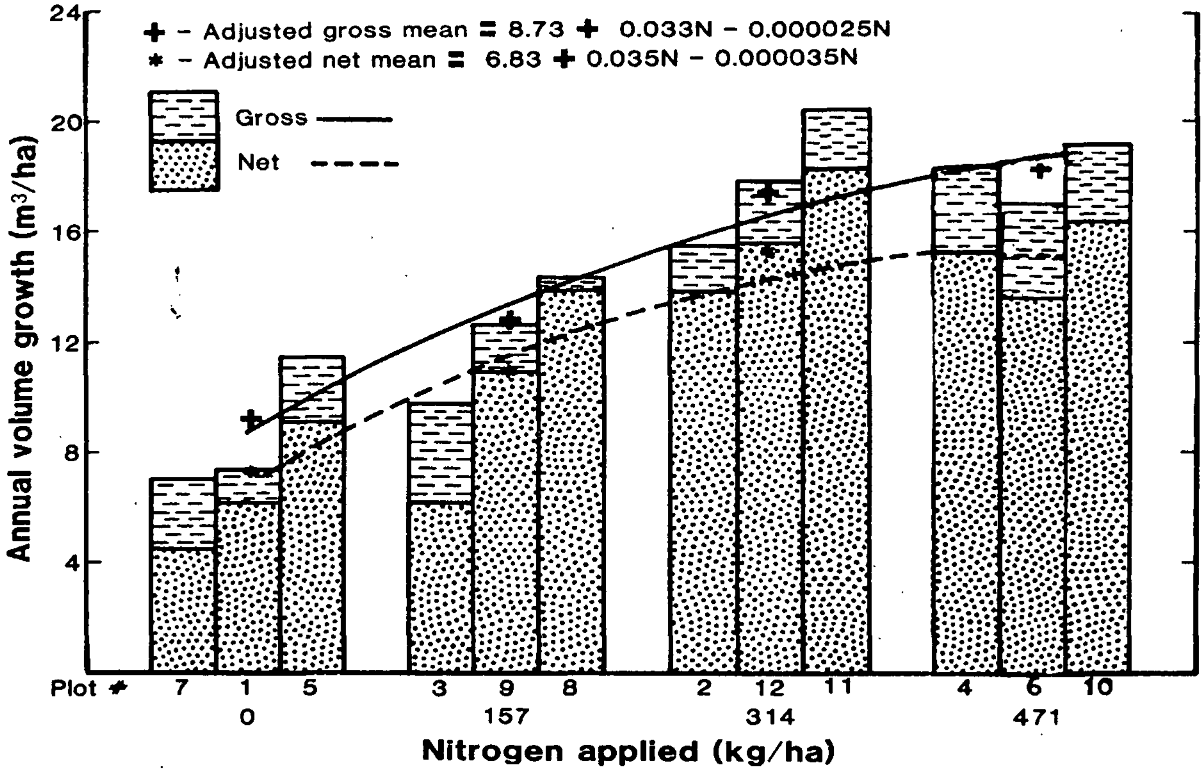

FIGURE 2. Average annual gross and net volume growth during a 15-year period by plots and treatment; plots are arranged within treatment in ascending order of initial stand volume.

Average annual dbh growth of surviving trees was doubled by the 471 kg N/ha treatment, presumably a result of the combined effect of reduced number of stems (or reduced competition) and of improved nutrition afforded by the highest N dosage. Although the response per pound of N appeared greatest at the 157-kg-N/ha dosage, the response surface was not significantly curvilinear. Thus, even the heaviest fertilizer application apparently was not sufficiently large to establish the dosage which would provide maximum dbh growth.

Height Growth.—Average height growth of surviving fertilized trees was 30 to 90 percent greater than that of unfertilized trees during the 15-year period (Table 3). Mortality or damage to nonsurviving trees did not remove more smaller-than-average height trees on the fertilized plots and thus did not arithmetically exaggerate the greater height growth after fertilization. Again, as with diameter, growth was linearly related to the amount of N applied ($P < 0.001$).

Volume Growth (Gross).—During the 15 years after fertilization, total cubic volume growth per hectare of all trees 4.1-cm dbh and larger was positively related to the amount of N applied (Table 4).

Gross growth on fertilized plots averaged 50 to 109 percent greater than that on control plots; corresponding gains in volume growth during the 15-year period averaged 67.4 to 145.5 m^3/ha. The response surface was significantly curvilinear ($P < 0.039$). This fall-off in volume response at the highest N dosage probably reflects the combined effect of (1) small but statistically nonsignificant fall-off in both dbh and height response of surviving trees with 471 kg N/ha and (2) the greater number of trees lost to mortality (Table 2) largely from increased winter damage in the first few years after fertilization (Miller and Pienaar 1973).

Average annual volume growth during the 15-year period varied among the three replications of each treatment (Fig. 2). Some of this within-treatment vari-

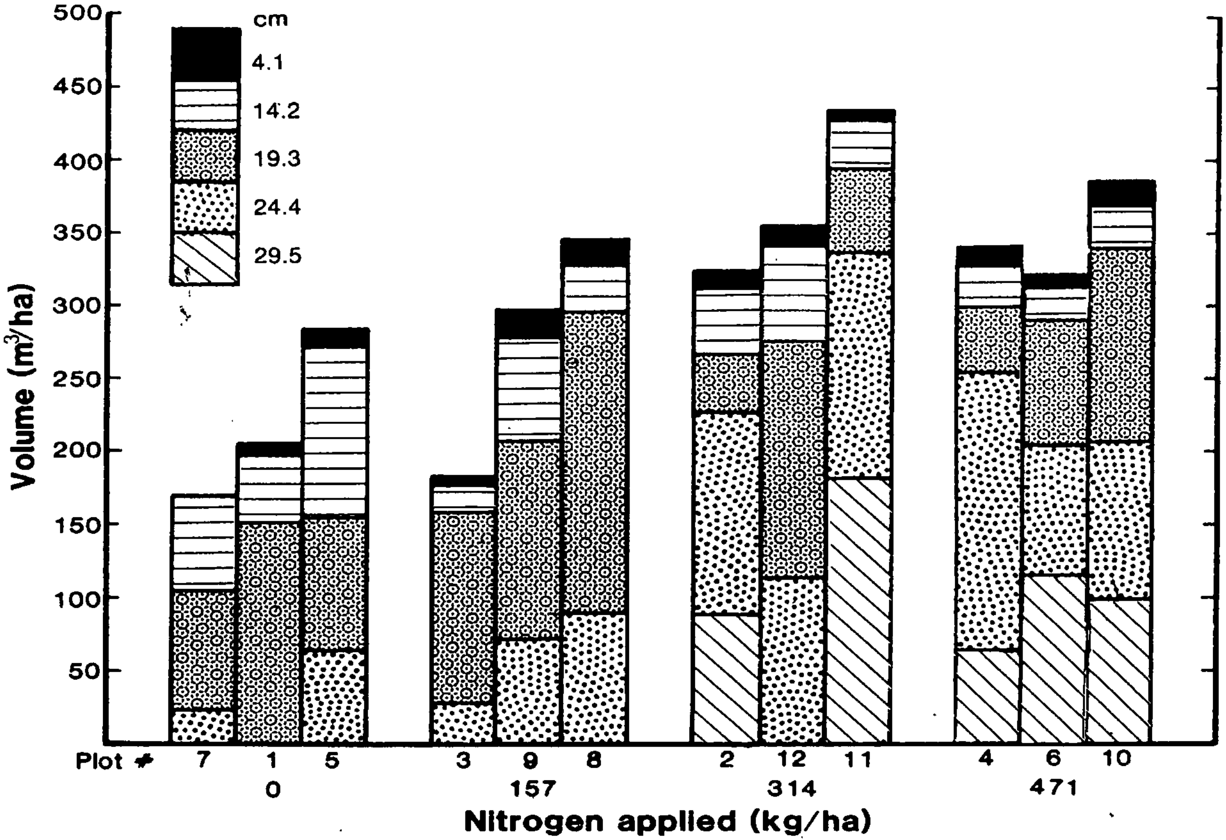

FIGURE 3. Volume of trees exceeding specified dbh at age 52 years by plot and treatment. Unadjusted for initial diffferences before fertilization.

ation in growth was evidently related to differences in beginning volume; replicates with greatest initial volume also had greatest growth. Covariance analysis substantiated that growth was positively related to stand volume (for gross and net growth, $P < 0.000$).

Volume Growth (Net).—Depending on the amount of N applied, adjusted net volume growth on fertilized plots averaged 4.5 to 8.6 m^3/ha/yr or 65 to 125 percent more than on control plots during the 15 years after fertilization. The response surface was significantly curvilinear ($P < 0.034$), again indicating that the dosage for maximum volume production during the first 15 years was less than 471 kg N/ha (Fig. 2).

Current Volume By Tree Size.—Fifteen years after fertilization, and without adjustment for relatively small differences in tree sizes and numbers prior to fertilization, total stand volume on fertilized plots averaged 25 to 69 percent greater than that on control plots; moreover, a much larger proportion of this volume was in larger dbh classes (Fig. 3). For example, an average of 24 and 27 percent of total stand volume on plots fertilized with 314 and 471 kg N/ha, respectively, was in trees of 29.5-cm (11.6-inches) and larger dbh. In contrast, 0-N and 157-N plots contained no volume in these sawtimber-size classes. Clearly, fertilization increased merchantable yields and economic value of this Douglas-fir plantation. Moreover, the trends indicate that further enhancement of both stand volume and value are likely.

Growth Response Trends.—Although the trees were not remeasured after the first growing season, increment cores revealed a definite response in dbh growth during

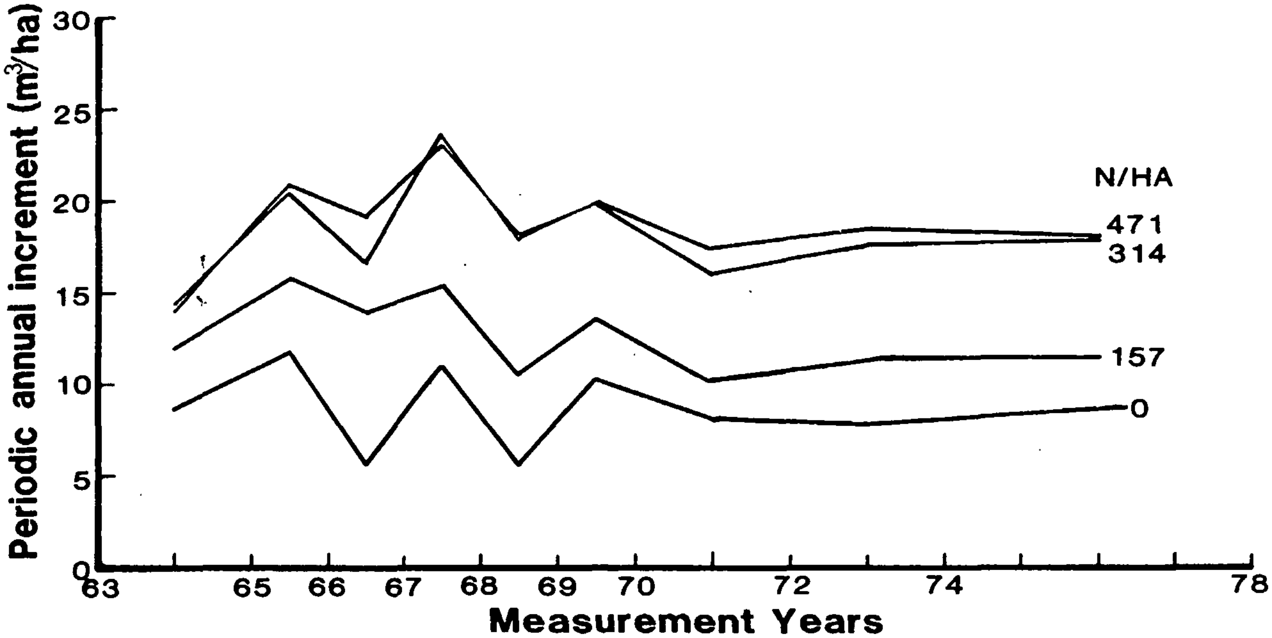

FIGURE 4. Trends of average gross periodic annual growth, all species trees 4.1-cm dbh and larger. Unadjusted for initial differences before fertilization.

the 1st year after fertilization. Two growing seasons after treatment, a statistically significant response in volume growth was evident for all levels of ammonium nitrate (Miller and Pienaar 1973).

The 1st year response of this stand to fertilization is likely related to improved photosynthetic activity per unit of foliage rather than to increased mass of foliage which was still evident 15 years after fertilization. H. Brix[1] has concluded from his investigations of N fertilization of Douglas-fir that both photosynthetic efficiency and the amount and distribution of foliage in the crowns can be affected by fertilization. On N-deficient sites, Brix found that increased growth during the first 2–3 years after fertilization was related mainly to improvement of foliage efficiency. Therefore, foliage efficiency declined to that of untreated levels, or even less, by year 7. The growth response which still existed was caused solely by the difference in foliage mass.

During the 15 years after fertilization, volume response to 157 kg N/ha was not as rapid nor as large as that after 314 or 471 kg N/ha (Fig. 4). Moreover, volume response to 157 kg N/ha may have peaked at year 3 or about 2 years before peak response to higher N dosages.

These growth trends from measurements at 1- to 4-year intervals, however, contain erratic fluctuations and do not reflect initial differences in stand volume before fertilization. To facilitate statistical analysis of these trends, we combined data from several short intervals between measurements to divide the 15-year period into 4- to 6-year parts. In a subsequent covariance analysis in which time-after-treatment was treated as a split-plot effect and stand volume prior to fertilization was the covariate, the response surface was quadratic ($P < 0.045$). Moreover, both period and period-×-treatment interaction were nonsignificant ($P < 0.069$ and $P < 0.191$, respectively). This indicated that response trends of the three dosages did not vary significantly over time (Fig. 5A).

[1] Personal communication with H. Brix, Canadian Forestry Service, Victoria, B.C., April 1982.

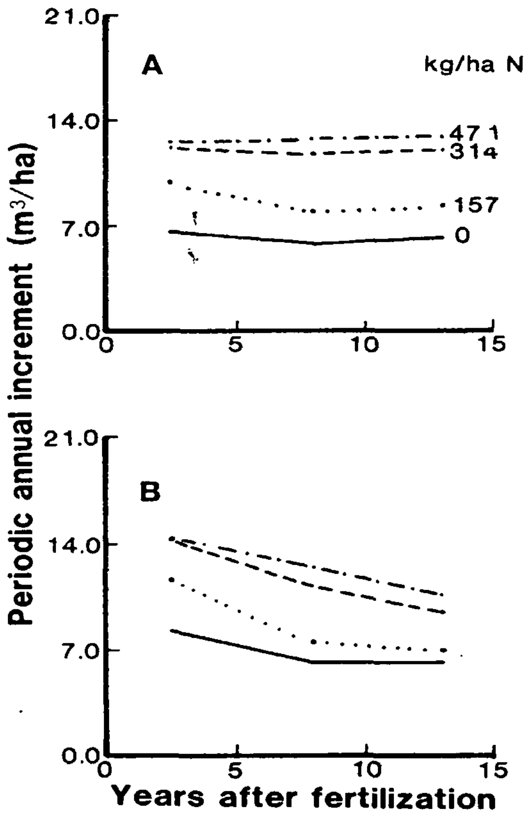

FIGURE 5. Trends in adjusted gross periodic annual increment by treatment: (A) P.A.I. in each period adjusted to a common 1963 (initial) volume; (B) P.A.I. in each period adjusted to a common volume at the start of each period.

Duration of Growth Response.—Response is clearly evident during the 15 years after treatment (Fig. 4). In years 10 through 15 after fertilization, the gain in gross volume growth averaged 34, 93, and 107 percent, respectively, with increasing N dosage.

Based on the trends of past growth and the more vigorous crowns observed on fertilized trees after year 15, we believe response will continue beyond the period we have observed. Although increased N dosage increased the amount of response during the 15-year period, we must await future measurement to determine whether duration of response will vary by N dosage.

Dosage Efficiency.—Although the response surface computed for the three periods after fertilization has been curvilinear, the most efficient dosage (that providing the greatest amount of additional wood per kilogram N) may have shifted slightly toward the higher application rates (Fig. 6). Based on cumulative gross volume growth during the first 5 years after treatment, the most efficient dosage for volume response was about 157 kg N/ha. By the second and third periods after fertilization, however, the efficient dosage of ammonium nitrate was near 314 kg N/ha.

It obviously would be premature to draw a conclusion as to best dosage before the treatment effect has ceased. The efficient dosage for volume production or gain per kilogram N clearly depends on the period of observation and the duration of response. Moreover, the most efficient dosage for maximizing the net economic returns from fertilization will further depend on tree size and quality of this increased volume and on the fertilization costs per kilogram N.

Relative Influence on Growth—Improved Nutrition vs. Altered Stocking.—To understand the nature of response to fertilizer, we believe it necessary to recognize the interaction between improved tree nutrition and alteration in stand stocking after supplemental nutrients have been added. Fertilizer can temporarily reduce

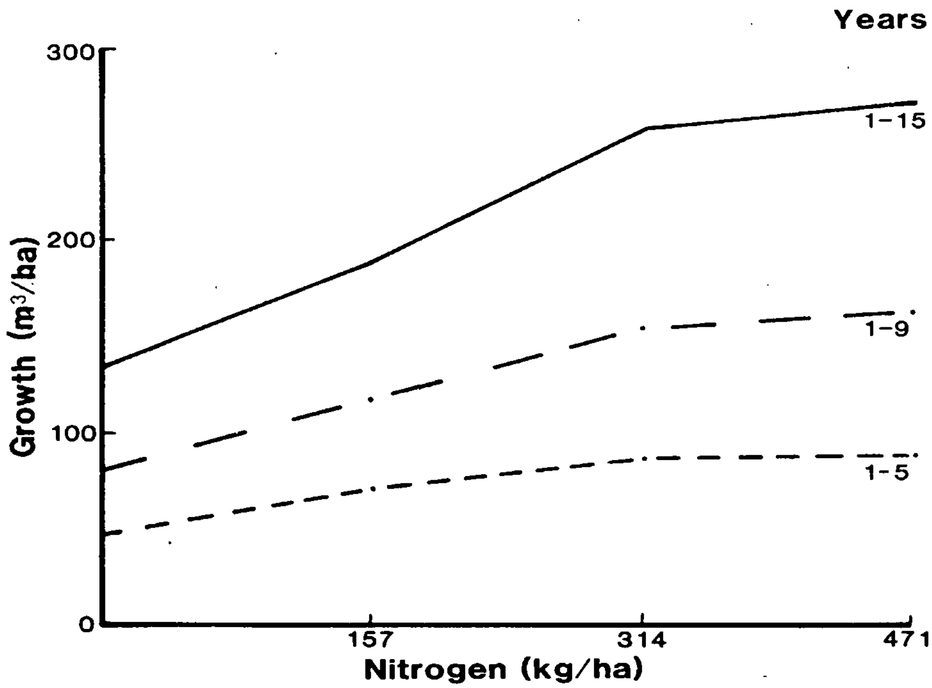

FIGURE 6. Average cumulative gross growth at specified years after fertilization. Adjusted for differences in initial stand volume before fertilization.

or eliminate nutrient deficiencies that limit tree growth (nutritional effect) and can also permanently alter the number and size of trees in the stand (stocking effect). Changes in stand stocking that may result from forest fertilization are more subtle than those created by physical thinning, yet the consequences are the same—a new stand structure is created and the capacity for future growth is affected.

In our study area, biological changes induced by fertilization affected tree growth rate and, therefore, competitive relations between trees. Large trees responded in dbh growth more strongly than did small trees. Further, in plots treated with 314 or 471 kg N/ha, more than twice as many trees of below-average dbh died during the first 7 years after fertilization. This thinning effect at this location was due primarily to increased snow and ice breakage, not to suppression (Miller and Pienaar 1973). Because of these changes, the variously treated stands became different in number and size of trees which affected subsequent stand volume

TABLE 5. Split-plot covariance analysis.

Source of variation	D.F.	$P<$
Whole plot error	7	
Regression	1	0.000
Treatment		
Linear	1	.000
Quadratic	1	.206
Cubic	1	.082
Split plot error	15	
Regression	1	.458
Period	2	.219
P × T	6	.171

growth in a manner independent of current nutritional status of the trees. Thus, if we are to understand the growth response from altered nutritional status vs. that from physical changes in stand structure, the two sources of altered production must be considered separately.

In the plantation we studied, growth on the variously treated plots was positively related to stand volume before fertilization (Fig. 2). Likewise, the greater volume growth attained in fertilized stands presumably resulted in part from progressively greater stand volume or tree size in these stands. Therefore, for each of the three growth periods of the total 15 years we adjusted average periodic growth of each treatment to an average volume of all treatments at the beginning of each period (Fig. 5B). Thus, we mathematically removed some of the effects of greater cumulative stand volume in fertilized plots. The "residual," then, is considered to be the contribution of continued improved nutrition on fertilized plots. Form of the split-plot covariance analysis is shown in Table 5.

Results of this analysis support three inferences:

(1) Growth was linearly related to N dosage, both when the average annual volume growth for each N dosage was pooled for all periods and when growth was adjusted to the same stand volume at the start of each period. This indicates that the greater cumulative tree volume on fertilized plots only partially explained the long-continued growth response.

In previous covariance analyses of gross volume growth during the 15-year period (Figs. 2, 5A), the response surface was quadratic when the treatment means were adjusted only for prefertilization differences in stand volume. We attribute the linear response surface in the subsequent analysis to our having removed the effects of changes in cumulative live stand volume that occurred after fertilization. Thus, growth after the 314-kg N/ha dosage was mathematically adjusted downward in the second and third measurement periods because cumulative live stand volume was highest after that treatment. For the 471-kg N/ha treatment, however, growth was adjusted upward in these same periods because of greater losses in tree numbers and volume following this treatment (Table 4).

(2) Growth did not differ significantly among periods ($P < 0.219$) when average growth of all treatments was pooled for each period.

(3) The shape of the response surface did not change significantly during the 15-year period of observation (P × T interaction was statistically nonsignificant). We interpret this to mean that improved nutrition contributed significantly to response in all three measurement periods.

Conclusions

Applying ammonium nitrate fertilizer to a 35-year-old Douglas-fir plantation resulted in significant increases in diameter, height, and volume growth. Response to one application of 157, 314, and 471 kg N/ha was still evident 15 years after treatment. During the 10- to 15-year period after treatment, fertilized stands were still producing 35 to 107 percent more cubic volume than were unfertilized stands. Both the trend of response data and the vigorous crowns observed on fertilized trees suggest to us that growth response will continue beyond the 15 years thus far observed.

A quadratic equation best described the response surface for gross and net volume growth by 5, 9, and 15 years after fertilization. Until growth response has ceased, however, a reliable estimate of optimum level of application for volume production cannot be offered.

The long-term effects of a single fertilization at this location are explained by initial and continued improvement in tree nutrition and by major changes in stand stocking and structure that resulted from this improved nutrition.

In view of the unusually strong and long-continuing response of Douglas-fir to ammonium nitrate fertilizer at this study area, it appears necessary here and elsewhere in the Pacific Northwest to systematically compare the efficiency of various fertilizer N sources.

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