United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-533
April 2001

Detecting Response of Douglas-Fir Plantations to Urea Fertilizer at Three Locations in the Oregon Coast Range

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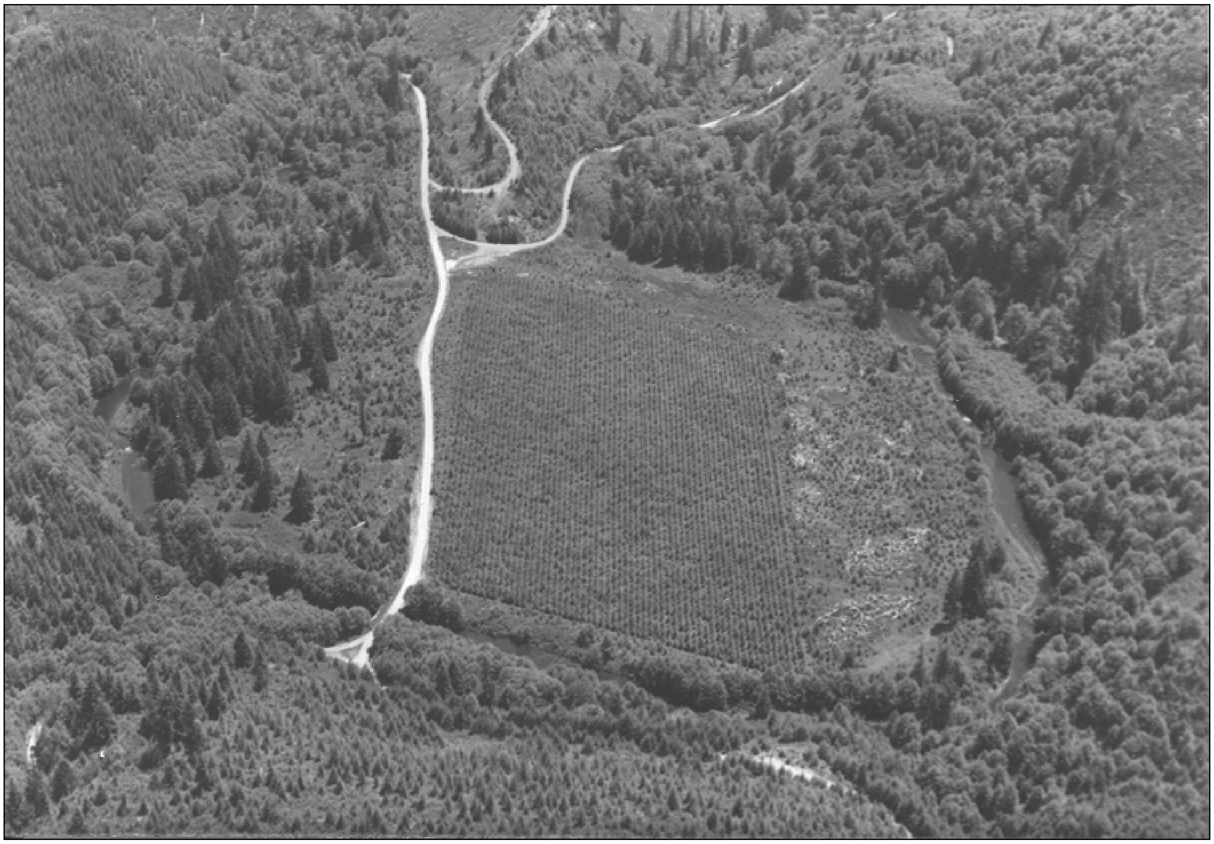

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Abstract

Miller, Richard E.; Smith, Jim; Anderson, Harry. 2001. Detecting response of Douglas-fir plantations to urea fertilizer at three locations in the Oregon Coast Range. Res. Pap. PNW-RP-533. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 20 p.

Fertilizer trials in coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) in the Oregon Coast Range usually indicate small and statistically nonsignificant response to nitrogen (N) fertilizers. Inherently weak experimental designs of past trials could make them too insensitive to detect growth differences that actually exist. Ability to detect real differences among treatments should be improved by having more than two replications per treatment and by using covariance analysis to adjust observed treatment means for unequal starting conditions among experimental treatments. To demonstrate these assumptions, we used size at fertilization and a prefertilization (calibration) period of growth as covariates when analyzing data from five coastal plantations. The trials had three to six replications per treatment and calibration periods of 6 or 7 years. Nitrogen fertilizer was assigned randomly to half the plots at each location when trees were 16 or 17 years old from seed. Our objectives were to quantify 4- or 7-year response to N fertilizer and to demonstrate practical means for detecting response. Effects of fertilization on tree diameter and height, and on basal area and volume growth per acre were estimated. Among the five nonthinned plantations, observed gross basal area growth was changed by -2 to 13 percent in the 4 or 7 years after fertilization. Observed responses were increased substantially by covariance analyses at some plantations but decreased at others. Random assignment of three to six plots per treatment did not ensure balanced or comparable plots for fertilized and nonfertilized treatments.

Keywords: Douglas-fir, *Pseudotsuga menziesii*, nitrogen, fertilization, urea, tree growth, stand growth.

Summary

Most fertilizer trials in coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) stands in the Oregon Coast Range indicate small and statistically nonsignificant response to urea or ammonium nitrate. Small response to nitrogen (N) could be explained by nitrogen sufficiency in this area as suggested by above-average site quality. Alternatively, weakly replicated experimental designs of past trials could make them too insensitive to detect differences that actually existed among treatments. We speculated that ability of field trials to detect real differences among treatments could be improved by more replications per treatment and by using covariance analysis to adjust observed treatment means for unequal starting conditions among experimental treatments. Accordingly, we used stand basal area and volume at fertilization and prefertilization (calibration) growth as covariates when analyzing data from a total of five plantations at three locations in the Oregon Coast Range. These plantations of 30 half-sib families (from 30 open-pollinated mother trees) had three to six replicate plots per treatment and a calibration period of 6 or 7 years before fertilization. Nitrogen fertilizer was assigned randomly to half the plots at each location when trees were 16 or 17 years old from seed. Our objectives were to quantify tree response to N fertilizer and to demonstrate practical means for detecting response. Effects of fertilization on tree diameter and height, and on basal area and volume growth per acre, were estimated.

With few exceptions, means of tree and stand attributes before fertilization appeared similar for fertilized and control groups at the five plantations. Coefficients of variation expressing variation among replicate plots within fertilized and control groups seldom exceeded 10 percent.

Tree losses were similar on fertilized and nonfertilized plots in the 4- or 7-year period after fertilization. Among the five nonthinned plantations, change in quadratic mean diameter at breast height was accelerated by fertilization at most plantations. Observed (unadjusted) gross basal area growth on fertilized plots in the 4- or 7-year period ranged from 1.7 percent less to 13.1 percent greater than on nonfertilized plots. Analysis of variance indicated that mean observed responses of 10 percent or more were statistically significant ($P \leq 0.10$). With covariance adjustment, however, both absolute and percentage response were decreased at four of five plantations. This indicates (1) that prefertilization conditions on fertilized plots averaged more favorable than those on control plots and (2) that using unadjusted means could lead one to overestimate response at four of the five locations. Of the two covariates, basal area growth in the 6- to 7-year period before fertilization was more frequently related to growth than was basal area per acre at fertilization.

We observed small, so-called “negative response” (-1.7 percent) in basal area growth to 200 lb N/acre at one plantation (with six replications of each treatment). This negative response in both observed and adjusted means, however, was statistically nonsignificant ($P = 0.49$ or 0.59, respectively); therefore, likely due to chance and validly interpreted as “no effect” rather than a “negative effect” of fertilization. Although this interpretation warranted our using one-tail testing, we remained with conventional two-tail tests.

Portions of only one plantation were concurrently thinned and fertilized. About 60 percent of live trees before thinning were retained and this included at least two trees of each half-sib family on each plot. Relative density averaged about 46 before thinning and 28 after thinning. Thinning removed slightly smaller-than-average trees. When data of this plantation (set E) were analyzed as a 2 × 2 factorial, (1) the thinning × fertilizing interaction was nonsignificant so that one could generalize separately about the effects of thinning and fertilization; (2) mean height growth for all measured trees that survived the 7-year period was similar for thinned and nonthinned trees; (3) stand basal area growth in thinned plots was similar to that in nonthinned; (4) yet, periodic annual volume growth of thinned plots averaged 286 cubic feet per acre compared to 355 cubic feet per acre for nonthinned plots (This shortfall of 68 ft^3/year [19 percent] is the expected consequence of the reduced basal area growing stock [40 percent) after thinning]; and (5) N fertilization (200 lb N/acre) increased 7-year basal area growth by 9 percent in both thinned and nonthinned plots.

“Effect size” (ES) relates effect (difference between the treatment means) and the common variance in the treatment and control distributions (expressed as standard deviation or $variance^{1/2}$). In these plantations, ES in observed basal area response to fertilization ranged from -0.32 to 7.88. Effect sizes of 3.28 or larger in basal area response were statistically significant ($P \leq 0.10$). This usually corresponded to 9 percent or greater increases in basal area growth. Effect sizes were much larger at the Bone Mountain plantations than at the two Toledo locations because (1) both observed and adjusted responses were larger and (2) variation in response (residual mean squares) were consistently smaller. When ES is large, fewer replications are required to detect significant differences among treatments (reject a “no effect” [or null] hypothesis from statistical testing).

We demonstrated the potential consequences of assigning only two replications of each treatment in these stands with minimal variation in tree numbers and stand basal area. When the two best-stocked plots of the fertilized were arbitrarily matched to the two poorest stocked control plots (match 1), measured response was inflated. Conversely, response was deflated or negative when the two best stocked control plots were matched to the two poorest stocked fertilized plots. Among the five plantations, basal area responses computed from matches 1 and 2 differed by 30 percent to 32-fold from those observed from using all replicate plots.

To improve detection of response to fertilizers, the following should be attempted:

- Install trials in uniformly stocked and structured stands or, alternatively, group plots in blocks of similar within-block stocking and structure.
- Install at least three replications to enable covariance analysis and adjustment of observed means.
- Recognize that a large number of replications of each treatment is necessary to detect the small response to N fertilization that is characteristic of above-average site quality stands of coast Douglas-fir.

We concluded the following from our fertilization trial in five plantations:

1. Coefficients of variation in tree and stand attributes in these plantations before fertilization were about 5 percent in trees per acre, 15 percent in basal area, and 20 percent in cubic volume, despite the fact that all trees in each plantation (1) originated from the same half-sib families, (2) were planted at precise tree-to-tree spacing, and (3) received intensive protection from large animals and weed competition.
2. Random assignment of three to six plots per treatment did not assure balanced or comparable plots for fertilized and nonfertilized treatments.
3. Covariance analysis did not consistently reduce experimental error (residual mean square) or increase effect size.
4. Detection of stand response to fertilization of Douglas-fir on above-average site quality requires careful planning and execution. Expected response to 200 lb N/acre is small and experimental error (unaccounted sources of variation) is usually large.

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Introduction

Fertilizer trials in Douglas-fir stands (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) in the Oregon Coast Range usually indicate small and statistically nonsignificant response to urea or ammonium nitrate fertilizers.[1] Small response to nitrogen (N) in this area could be explained by N sufficiency as suggested by above-average site quality. The inherently weak experimental design of past trials, however, could make them too insensitive to detect differences that actually existed among treatments. For example, most existing trials have only two replicate plots for each treatment, and stand volume or basal area among plots before fertilization can differ by 20 percent or more. This creates a risk that control and fertilized treatments may not equally sample initial differences in site quality and growing stock. Moreover, large differences among plots in site quality, starting volume, or basal area contribute to large among-plot variation in subsequent tree growth. This variation in growth among replicates inflates the experimental error term in statistical analyses; consequently, response to fertilization is less likely to be judged statistically significant or real.

Numerous factors determine statistical "power" or the sensitivity of trials to detect real differences among treatments (Lipsey 1990). These include (1) the statistical tests used for analyzing data, (2) choice of alpha level for statistical significance testing, (3) sample size (the number of replicates or experimental units per treatment), and (4) "effect size" (the response to treatment relative to its variance). In this report, we examine these factors by using data from five plantations in the Oregon Coast Range.

Our objectives were to detect tree response to N fertilization at these locations and to demonstrate practical benefits of improved experimental design and of covariance analysis. We estimated tree and stand response to 200 lb N/acre applied as urea in four nonthinned plantations. Additionally at the fifth plantation, we compared response to N in nonthinned plots to response in concurrently thinned plots. The five plantations had three to six replicate plots per treatment and calibration periods of 6 or 7 years before fertilization.

Methods

Several plantations of half-sib families (from 30 open-pollinated mother trees) were established in 1972 or 1973 after clearcutting and intensive site preparation at each of five progeny-test locations on Georgia-Pacific Corporation land. Five plantations at three of these locations were selected. These three study areas (Toledo North, Toledo South, and Bone Mountain) provided maximum numbers of trees available from (1) original planting and (2) replacement plantings in years 1, 2, 3, and later (table 1).

Uniformly planted and intensively managed, these plantations provided an opportunity to estimate response to N fertilizer in uniform stand conditions. Each plantation contained 6 to 12 plots with the same 30 half-sib families. Families differed among the five plantations, however. Each plot contained four to five randomly located trees for each family as noncontiguous (single tree) family subplots. After planting at a 9- by 9- or 9- by 10-foot spacing within 5- to 10-acre areas surrounded by an 8-foot tall fence, the 1-year-old, container-grown seedlings at each location were subsequently safeguarded from weeds, disease, and animal damage. These actions and some replacement planting resulted in uniformly spaced, well-stocked stands at age 16 or 17 years from seed (figs. 1, 2, 3, and 4).

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[1] Miller, R.E.; Hazard, J.W.; Bruce, D. 1991. Response of western Oregon stands to nitrogen fertilizer. Interagency Agreement PNW 88-557. Portland, OR. On file with: Forestry Sciences Laboratory, 3625 93rd Ave. SW, Olympia, WA 98512.

Table 1—Description of three study locations installed by Georgia-Pacific Corporation in the Oregon Coast Range

Area	Sets	Soil series [a]	Site index [a] (50 yr)	Plots per plantation	Plot size: Fertilized[b]	Plot size: Measured
			Ft	*No.*	*– – – – – Acres*	*– – – – –*
Toledo:						
North	E, F	Blachy silty clay loam	126	12	0.314	0.225
South	A	Elsie silt loam	143	10	.243	.169
Coquille:						
Bone Mountain	A, B	Preacher loam	127	6	.212	.147

[a] According to soil survey maps and reports.

[b] 200 lb N/acre ÷ 0.46 = 435 lb urea/acre.

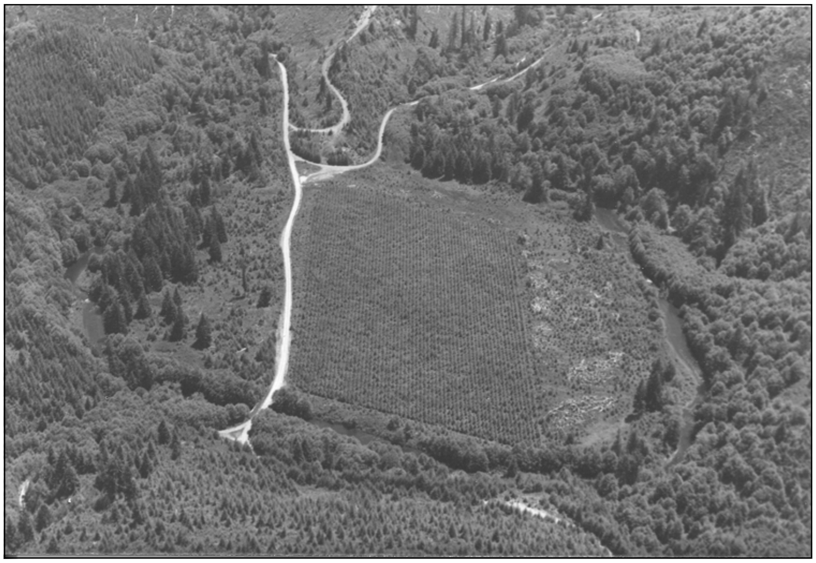

Figure 1—Aerial view of the Toledo North (**A**) and Toledo South (**B**) study areas when trees were about 6 years old.

Figure 2—Portions of the Toledo North plantations after 1989 growing season; tree age 17 years from seed.

Figure 3—Portions of the Toledo South plantation after 1989 growing season; tree age 17 years from seed.

Figure 4—Aerial view of the Bone Mountain plantations after 1980 growing season; tree age 7 years from seed. Sets A and B are in the left half of the more uniform, lower block of trees.

The three study areas, each with one or two study plantations, are located on level to gently sloping topography with well-drained soil series weathered from sedimentary (Preacher), alluvium (Elsie), or basic igneous and sedimentary rock (Blachly). Effective rooting depth of modal (characteristic) profiles is 60 inches or more. Mean site index (50-year base age) ranged between 126 and 143 feet (table 1).

Fertilization and Thinning

A fertilization treatment was assigned randomly to half the plots in each plantation. Urea fertilizer providing 200 lb N/acre was uniformly spread over assigned plots in spring 1990 (table 1). To ensure uniformity of applications, the gross plot area was quartered with string, then the total fertilizer for each plot was weighed and volumetrically allocated to four large containers, each containing the fertilizer for a quarter-plot. Fertilizer in each large container was transferred to four smaller buckets for application. Contents of two buckets were spread uniformly over each quarter-plot; then the fertilizer in the remaining two buckets was spread over the same quarter-plot, but at right angles to the direction of the first spread. Cool weather and showers in the 2 weeks after fertilization probably minimized potential losses from urea volatilization.

Only portions of the set E plantation at Toledo North were thinned. Six of the 12 plots were thinned before the 1990-growing season. About 60 percent of the trees were retained after thinning. Hence, effects of concurrent thinning and fertilization, alone and in combination, could be analyzed as a 2 x 2 factorial design (three replications per treatment).

Tree Measurement

Diameter at breast height (d.b.h.) of all trees in interior subplots (0.169 to 0.225 acres) was measured with a steel tape. Trees for measurement were identified with numbered aluminum tags at breast height (4.5 ft) and were pruned to 6-foot height to provide safe access and more reliable measurement of d.b.h. to nearest 0.1 inch. Total height of 100 or more trees per plot was measured initially at age 16 or 17 years by either height-measuring poles or clinometers (to the nearest foot). Four years later (7 years later at set E, Toledo North), about 60 trees per plot were measured with clinometers. Buffer areas around interior plots contained only one row of trees. Although wider buffers were desirable, interior subplots would have been smaller so that fewer trees would have been available for evaluating effects of fertilization.

Data Summary

Stand basal area growth before and after fertilization was calculated from d.b.h. measurements. Total bole volume (total stem volume above a 6-in stump) was estimated for each tree using a general volume equation (Bruce and DeMars 1974) accessed by measured d.b.h. and either measured height or estimated height from a height-diameter equation specific to each plot and year. The height equation was of the form, H = a - b (1/d.b.h.). Periodic mean annual growth and mortality in basal area and cubic volume were computed by summing individual tree data.

Statistical Analyses

Effects of fertilization on height and diameter growth of surviving trees, and on change in tree numbers, basal area, and volume per acre were estimated and compared by analysis of variance (ANOVA) and by covariance analyses (SAS 1988). Growth before fertilization, and tree and stand statistics at fertilization were used separately as covariates. Thereby, we computed adjusted means of growth and response.

Results

Stand Statistics Before Fertilization

With few exceptions, means of tree and stand attributes before fertilization were similar for fertilized and control groups at the five plantations (table 2). Coefficients of variation (CV) expressing variation among replicate plots in treated and control groups seldom exceeded 10 percent. The five fertilized plots at the Toledo South plantation varied most in before-fertilization statistics.

Tree size—Although trees in all plantations were either 16 or 17 years from seed, quadratic mean d.b.h. (QMD) was markedly larger at Toledo locations in central Oregon than in the 1-year younger plantations at Bone Mountain in southern Oregon (table 2). Height of the 40 largest diameter trees per acre (H_{40}) clearly favored the Toledo plantations, especially at Toledo South, where the modal 50-year site index for the soil series was estimated at 143 feet compared to 126 feet and 127 feet at the two other locations (table 1). H_{40} is similar to the sample height required by King (1966) to estimate site index (Curtis 1983).

Tree numbers, basal area, and volume—All plantations were well stocked before fertilization. Basal area showed less plot-to-plot variation within treatment groups than did volume (table 2). This was expected, because basal area is derived from d.b.h. measurement of all trees, whereas volume is further derived from a sample of tree heights. The height sample in this study was unusually large, consisting of nearly all trees at the prefertilization inventory, but reduced at remeasurement because a commercial thinning 4 years after fertilization removed every third row. Tree d.b.h., however, was measured before thinning occurred.

Thinning Intensity

Only set E at Toledo North was concurrently thinned and fertilized. About 60 percent of trees were retained, and this included at least two trees of each half-sib family on each plot. Relative density (RD) averaged about 46 before thinning and 28 after thinning (table 2). The difference in QMD immediately after thinning (0.2 and 0.1 in for the two thinned treatments) indicates that thinning removed slightly smaller-than-average trees.

Table 2—Mean live-stand statistics before fertilization, by location and treatment, per acre basis when pertinent

			Before fertilization or thinning[b]												After thinning				
			QMD		H^{40}		Stems		BA		Vol.		RD		QMD	Stems	BA	Vol.	RD
Location	Set	Tmt.[a]		CV		CV		CV		CV		CV		CV					
			In	*%*	*Ft*	*%*	*No.*	*%*	*Ft²*	*%*	*Ft³*	*%*	—	*%*	*In*	*No.*	*Ft²*	*Ft³*	—
Toledo North	E	C	6.3	5	43.6	4	521	4	114	6	1,709	9	45.2	5	—	—	—	—	—
		F	6.7	3	44.2	1	529	1	127	5	1,978	5	49.2	4	—	—	—	—	—
		T	6.4	2	42.1	4	531	3	116	2	1,637	6	46.1	1	6.6	308	76	1,095	29.2
		FT	6.3	1	44.4	1	533	2	115	1	1,749	1	45.8	1	6.4	298	68	1,051	26.6
	F	C	6.4	4	43.1	6	539	3	121	6	1,757	16	47.7	5	—	—	—	—	—
		F	6.5	3	43.3	6	529	2	121	6	1,810	11	47.6	5	—	—	—	—	—
Toledo South	A	C	6.7	4	51.3	3	614	4	149	8	2,786	10	57.6	6	—	—	—	—	—
		F	6.5	6	50.6	6	596	3	138	14	2,566	19	54.0	11	—	—	—	—	—
Bone Mountain	A	C	5.1	4	38.0	2	671	4	94	6	1,300	9	41.8	5	—	—	—	—	—
		F	4.9	2	38.0	2	682	2	89	4	1,224	4	40.0	3	—	—	—	—	—
	B	C	5.4	2	39.2	4	676	2	108	7	1,548	9	44.7	12	—	—	—	—	—
		F	5.0	4	37.0	6	673	1	93	10	1,245	13	41.3	8	—	—	—	—	—

[a] C = control, F = fertilized, T = thinned, FT = fertilized and thinned concurrently.

[b] QMD = quadratic mean diameter; CV = (standard deviation ÷ mean) 100; H40 = mean height of largest 40 trees per acre (by d.b.h.); BA = basal area; Vol. = cubic volume of total stem; RD (Curtis 1982) = BA/SQRT(QMD) ½.

Change in Tree QMD and Height After Fertilization

Net change in QMD and mean height resulted from two components: arithmetic changes resulting from tree losses and actual tree growth. Because mortality was relatively slight between age 17 and 21 years in the plantations, change in QMD was only slightly affected by the arithmetic effect of tree losses. Increase in QMD was accelerated by fertilization at most plantations (table 3). Analysis of mean height growth was restricted to trees measured at both starting and ending measurement. Mean height growth of these survivors on fertilized plots was similar to that on nonfertilized plots (table 3).

Tree Mortality After Fertilization

Tree losses between age 17 and 21 years were similar on fertilized and nonfertilized plots (table 3). No trees died on any plots at Bone Mountain, the area of lower site quality.

Stand Basal Area Growth and Response to N Fertilization

Among the five plantations, unadjusted gross basal area growth on fertilized plots ranged from 1.7 percent less to 13.1 percent greater than on nonfertilized plots (table 4). Without covariance adjustment, mean responses of 10 percent or more were statistically significant ($P \leq 0.10$). With covariance adjustment, both absolute and percentage response were decreased at four of five plantations (table 4). This indicates that prefertilization stocking on fertilized plots at these four locations averaged more favorable than those on control plots. After covariance analysis, mean adjusted responses of about 9 percent or more were statistically significant. Basal area growth was more frequently related to growth in the 3- to 6-year period before fertilization than to basal area per acre at fertilization (table 4).

Stand Volume Growth and Response After Fertilization

Observed (unadjusted) net volume growth on fertilized plots averaged statistically significantly greater than that on nonfertilized plots only at two of the five plantations (table 5). With covariance adjustment for differences in starting volume among fertilized and nonfertilized plots, response was decreased at two of five plantations (table 5). Covariance adjustment was especially strong at Bone Mountain, set B, where starting volume averaged 24 percent greater on control plots than on fertilized plots (table 2). Consequently, adjusted 4-year response was 50.9 cubic feet per year (14.9 percent) compared to observed response of -6.8 cubic feet per year (-1.8 percent).

Effect of Concurrent Thinning

Although the number of residual trees in thinned plots at Toledo North (set E) averaged about 60 percent of those in the nonthinned plots (table 2), observed net basal area growth per acre on thinned plots was similar to that on nonthinned plots (table 3). Observed volume growth per acre, however, averaged less on thinned plots than on nonthinned. Reanalyses of the data as a 2 x 2 factorial instead of as separate thinned and unthinned groups permitted statistical testing of these two groups. These tests showed the following: (1) the thinning by fertilizing interaction was nonsignificant (table 6), so that one could generalize separately about the general effects of thinning and of fertilizing; (2) mean height growth for all measured trees that survived the 7-year period was similar for thinned and nonthinned trees; (3) mean basal area growth per acre in thinned plots was similar to that in nonthinned plots; but (4) annual volume growth of thinned plots averaged 286 cubic feet per acre compared to 355 cubic feet per acre for nonthinned plots (This shortfall of 68 ft^3/year [19 percent] is the expected consequence of reduced basal area growing stock [40 percent] after thinning [Evert 1964: 813; Curtis and Marshall 1986: 80]); and (5) N fertilization increased basal area growth by 9 percent in both thinned and nonthinned plots.

Table 3—Observed mean annual change in the first 4 years (set E = 7 years) after fertilization, by location and treatment, per acre basis when pertinent

				Periodic net annual change[b c]												
				QMD		HT		Live stems		BA		Vol.		Periodic annual mortality		
Location	Set	Tmt[a]	Yr		CV		CV		CV		CV		CV	Live stems	BA	Vol.
				In	*%*	*Ft*	*%*	*No.*	*%*	*Ft²*	*%*	*Ft³*	*%*	*No.*	*Ft²*	*Ft³*
Toledo North	E-UT	C	7	0.24	6	2.5	3	-2.1	72	9.2a	3	333b	5	1.6	0	0.10
		F		.24	6	2.6	5	-2.1	45	10.0a	6	376a	3	0	0.02	0
	E-T	T	7	.35	5	2.5	6	0	0	9.4b	3	282a	7	0	0	0
		TxF		.40	4	2.5	12	0	0	10.0a	4	291a	12	0	0	0
	F	C	4	.27	5	2.2	7	-0.4	156	11.1a	5	314a	11	.3	.02	.2
		F		.27	0	2.2	12	-0.9	196	10.9a	5	320a	11	.4	.03	.8
Toledo South	A	C	4	.24	12	2.9	10	-2.1	122	10.2b	6	441a	5	2.1	.30	6.0
		F		.27	12	2.9	4	-3.2	36	11.3a	8	439a	4	2.6	.40	7.4
Bone Mountain	A	C	4	.34	4	2.8	4	0	0	14.5b	2	381b	2	0	0	0
		F		.38	0	3.1	2	0	0	16.4a	1	418a	3	0	0	0
	B	C	4	.30	0	2.5	2	0	0	13.7b	2	371a	5	0	0	0
		F		.36	4	2.6	14	0	0	15.1a	2	365a	10	0	0	0

[a] C = control, F = fertilized, T = thinned, FT = fertilized and thinned concurrently.

[b] HT = mean height of surviving, measured trees.

[c] For each set, treatment means with differing letters are significantly different (P ≤ 0.10).

Table 4–Observed and adjusted, mean gross annual response in basal area growth after fertilization, nonthinned stands, per acre basis[a]

			Observed[b]			Adjusted[c]				Adjusted[d]			
Location	**Set**	**Reps**	**Response**			**Response**			**Regress.**	**Response**			**Regress.**
			Ft^2	%	*P*	*Ft*^{2}	%	*P*	*P*	*Ft*^{2}	%	*P*	*P*
Toledo North	E	3	0.80	8.7	0.11	1.31	14.6	0.11	0.33	0.96	10.5	0.20	0.71
	F	6	-.19	-1.7	.59	-.21	-1.9	.53	.34	-.21	-1.9	.49	.07
Toledo South	A	5	1.19	11.3	.07	[e]	[e]	[e]	[e]	.67	6.3	.25	.08
Bone Mountain	A	3	1.90	13.1	.01	1.77	12.2	.01	.42	1.83	12.6	.01	.63
	B	3	1.42	10.4	.01	1.20	8.7	.08	.58	1.26	9.2	.07	.68

[a] Response = PAI fertilized - PAI control; 7 years at set E, 4 years at other sets.
[b] Analysis of variance; P = probability value.
[c] Covariance analysis using prefertilization basal area as covariate.
[d] Covariance analysis using prefertilization basal area growth as covariate (1982-89 or 7 years at Toledo North and South; 1983-89 or 6 years at Bone Mountain).
[e] Covariance is inappropriate because the relation of growth-starting basal area differed between control and fertilized plots.

Table 5–Observed and adjusted, mean gross annual response in volume growth after fertilization, nonthinned stands, per acre basis [a]

Location	Set	Reps	Observed[b]			Adjusted[c]			
			Response			Response			Regress.
			Ft^3	*%*	*P*	*Ft^3*	*%*	*P*	*P*
Toledo North	E	3	42.9	12.9	0.02	31.0	9.1	.22	0.51
	F	6	5.7	1.8	.79	-0.5	-0.2	.97	.01
Toledo South	A	5	-1.1	-0.2	.92	4.2	.9	.7	.12
Bone Mountain	A	3	37.2	9.8	.01	41.1	10.8	.03	.47
	B	3	-6.8	-1.8	.79	50.9	14.9	.04	.01

[a] Response = PAI fertilized - PAI control; 7 years at set E, 4 years at other sets.
[b] Analysis of variance; P = probability value.
[c] Covariance analysis using prefertilization volume as covariate.

Table 6—Statistical significance of thinning, fertilizing, and their interaction at Toledo North, set E

Factor	d.f.	Mean annual growth[a]					
		Height	%[b]	Basal area	%	Volume	%
		Ft		*Ft^2/acre*		*Ft^3/acre*	
				P – value			
Fertilizing (F)	1	1.000	—	0.018	—	0.075	—
Thinning (T):	1	1.000	—	.695	—	.001	—
F × T	1	.529	—	.793	—	.219	—
Error	8	—	—	—	—	—	—
Residual mean square		.031	—	.182	—	482.100	—
Treatment means							
Control		2.47	100	9.2	100	333	100
Fertilizing		2.53	102	10.0	109	376	113
Thinning		2.53	102	9.4	102	282	85
F + T		2.47	100	10.0	109	291	87

[a] For all trees 1.6 inch d.b.h. and larger.
[b] Percent relative to control = 100.

Discussion

Statistical Tests

Except for thinned set E at Toledo North, a single-factor ANOVA in completely random design is appropriate for testing effects of fertilization in these five plantations. According to ANOVA, observed mean basal area growth on fertilized plots differed significantly from that on nonfertilized plots in three of the five plantations (table 4). Observed responses ranged from 10.4 to 13.1 percent at those plantations.

We also used covariance analysis in an attempt to reduce or account for measurable extraneous factors that contribute to variability in the dependent measures of interest, for example, basal area or volume growth. In most field trials, either pretreatment (starting) stand basal area or volume are readily available covariates to adjust for initial difference between treated and nontreated plots. In our data sets, pretreatment basal area growth also was available. We compared potential benefits of these two covariates for isolating N fertilization effects on gross basal area growth (table 4). We had three to six replicate plots per treatment in each set of half-sib families. Thus, we could use covariance to compute treatment means adjusted for the effects of any random assignment of plots that favored one treatment over another.

Covariance analysis should not be used without preliminary plotting of observations. For example, initial basal area stocking among the five fertilized plots at Toledo South was most variable and averaged 7 percent less than nonfertilized plots (table 2). Although this difference suggested benefits of covariance adjustment of observed treatment means, a plotting of growth related to basal-area stocking of the 10 plots suggested a different relation for the fertilized and control plots (fig. 5). Data from the five nonfertilized plots fail to show a strong underlying relation between growth and initial basal area. The apparent slope is horizontal or slightly positive. In contrast, corresponding data from fertilized plots suggest a strong negative slope either because (1) response to fertilization at this site is extremely variable or (2) response depends on the amount of starting basal area; that is, strong response at relatively low stocking levels and weak or no response at greater basal area stocking. Although one cannot infer which of the two explanations is likely, we concluded from this scattergram that covariance adjustment of observed means of control and fertilized growth would be invalid. Statistical testing supported this concern by showing that slopes of fertilized and control regressions differed ($P = 0.08$). This real difference in regression slopes invalidated use of covariance to fit a common linear regression to quantify the 10 observations (fig. 5), and then to adjust the two treatment means along this regression line to a common starting basal area. The inherent assumption of parallel slopes was more readily assumed at Toledo North, set F (fig. 6), and Bone Mountain, sets A and B (fig. 7).

One- vs. two-tail testing—If one assumed that conventional dosages of N, as applied in this study, could only increase growth, and not decrease it, then one-tailed testing is warranted. One-tailed testing increases the likelihood of statistical significance because critical t- and F-values are lower. Although we observed a small, so-called “negative response” in basal area growth to 200 lb N/acre at Toledo North, set F (based on six replications of each treatment), this negative response was statistically nonsignificant in both ANOVA and covariance tests ($P = 0.49$ to 0.59; table 4). Hence, this “negative response” likely was due to chance and was interpreted as “no effect” of fertilization. Although this interpretation warranted our using one-tail testing, we remained with conventional two-tail tests.

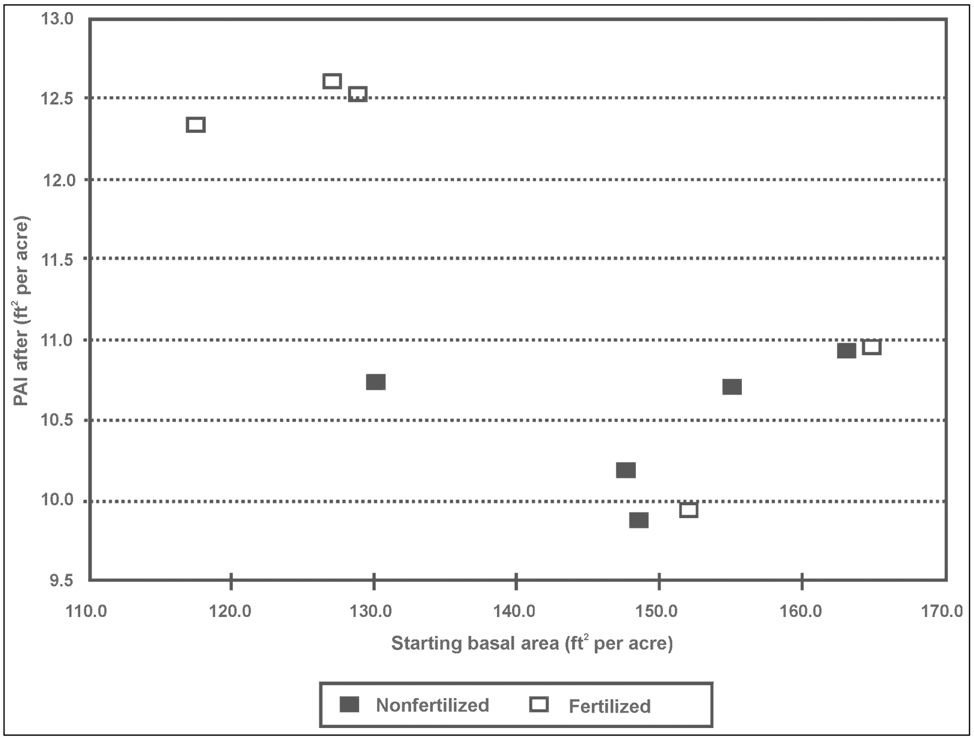

Figure 5—Toledo South, set A: mean periodic annual basal area growth and prefertilization basal area, by treatment, per acre basis.

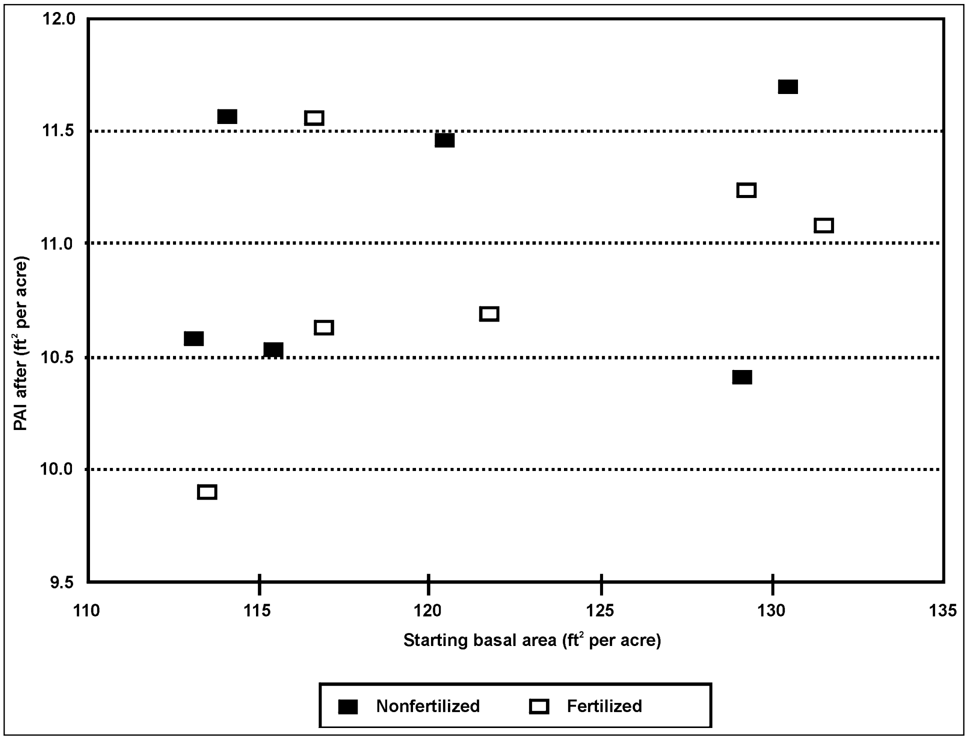

Figure 6—Toledo North, set F: mean periodic annual basal area growth and prefertilization basal area, by treatment, per acre basis.

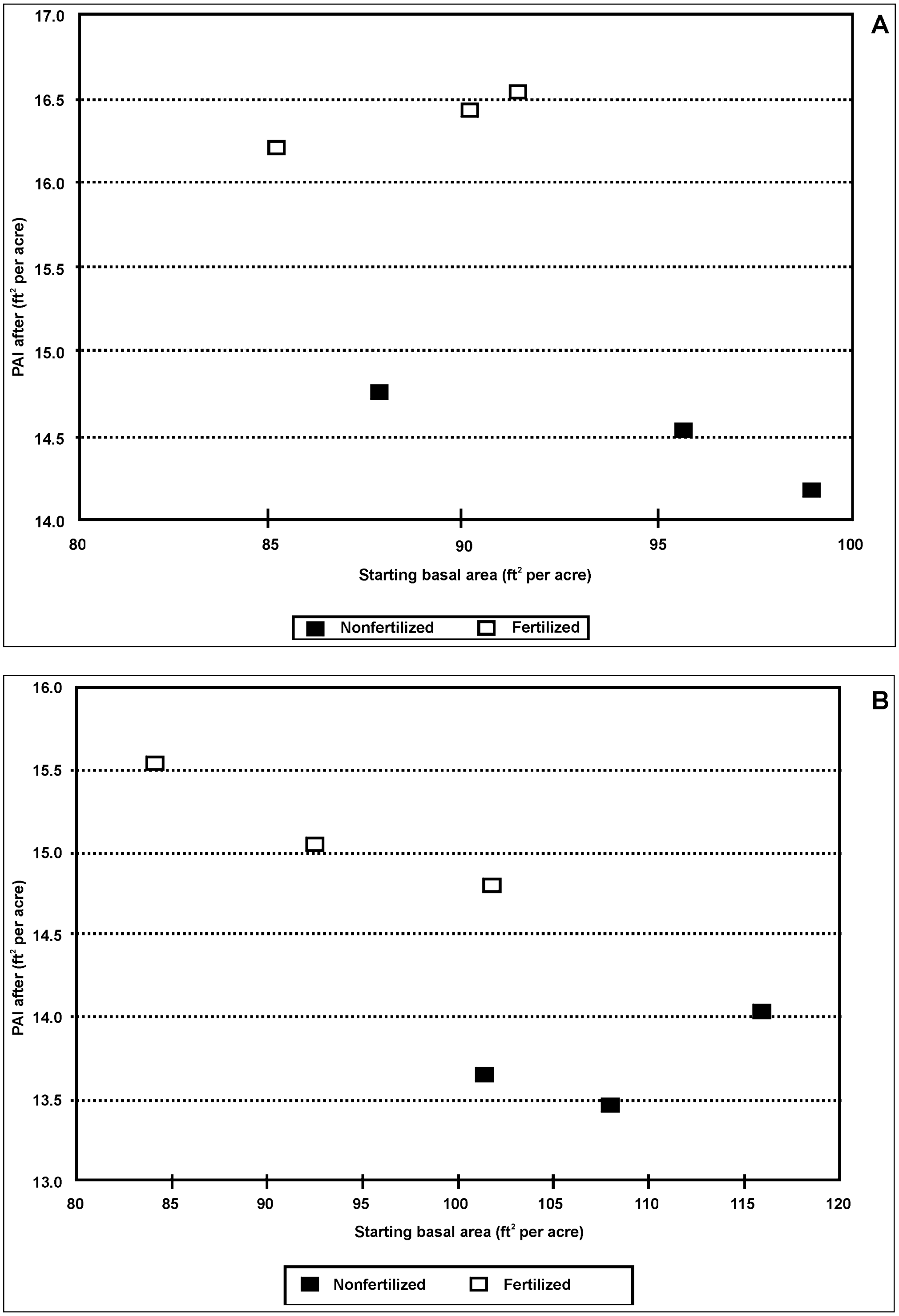

Figure 7—Bone Mountain, sets A and B: mean periodic annual basal area growth and prefertilization basal area, by treatment, per acre basis.

Alpha level—We assigned statistical significance to differences among treatments, when $P \leq 0.10$. In most scientific journals, however, alpha is conventionally set at ≤ 0.05 for statistical significance testing. An alpha of 0.05 corresponds to a 0.95 probability of a correct statistical conclusion when the null hypothesis (no effect) is true. This conservative alpha provides high protection against committing a type 1 error (inferring a difference among treatment means when in fact there is none), but has tradeoffs that should be understood and reconsidered by those conducting field trials. As expressed by Lipsey (1990: 39):

> For example, a promising treatment might be investigated to determine if it has beneficial effects in some problem area. In such applied research the implications of errors of inference may be quite different from those in basic research. To "discover" that an applied treatment is effective when, in fact, it is not, does indeed mislead practitioners just as the analogous case misleads theoreticians. Practitioners, however, are often in situations where they must act as effectively as they can irrespective of the state of their formal knowledge, and it is not unusual for them to use treatments and techniques of plausible but unproven efficacy. Moreover, demonstrably effective treatments for many practical problems are not easy to come by and candidates should not be too easily dismissed. Accepting a relatively high probability of Type 1 error in applied treatment effectiveness research amounts to giving a treatment the benefit of the doubt about whether statistically modest effects represent treatment efficacy or merely sampling error.
>
> A high probability of Type II error [inferring no difference among treatments means when in fact there is], however, presents a rather different circumstance. In that case the research is likely to yield null results for a genuinely effective treatment. Not surprisingly, such results are often taken to indicate that the treatment does not work. In a context where effective treatment is needed and not readily available, a Type II error can represent a great practical loss–an effective treatment is falsely discredited. In applied treatment effectiveness research it may often be desirable to keep the likelihood of such error low even at the expense of accepting an increased probability of Type I error.

Effect Size (ES)

The larger the effect produced by treatment on a dependent variable, the more likely that statistical significance will be attained and the greater the statistical power (Lipsey 1990). The "effect size" relates effect (difference between the treatment means) and the common variance in the treatment and control distributions. This common variance is the "residual mean square" (RMS) of the error term in ANOVA or covariance tests. For computing ES, this RMS is expressed as standard deviation (variance$^{1/2}$). Symbolically, ES = (mean of treatment 1 – mean of treatment 2) /$\sqrt{\mathrm{RMS}}$.

Factors that affect either the numerator (effect) or the denominator (variance) can alter "effect size." In theory, covariance analyses can affect both "effect" (by generating adjusted means of growth, hence adjusted mean response by difference) and "variance" (by reducing the RMS or unaccounted variation).

In these plantations, ES in observed basal area response to fertilization ranged from -0.32 to 7.88 (table 7). Effect sizes of 3.28 or larger in adjusted basal area response were statistically significant ($P \leq 0.10$; table 7). This usually corresponded to 9 percent or greater increases in basal area growth (table 5). Effect sizes were much larger at the Bone Mountain plantations than at the two Toledo locations because both observed and adjusted responses were larger and the variation in response (residual mean square) was consistently smaller (table 7). With larger ES, fewer replications are required to detect significant differences among treatments (reject a "no effect" hypothesis) from statistical testing (table 8).

Table 7—Effect size of observed and adjusted response in gross 4-year mean annual basal area growth (PAI) after fertilization, nonthinned stands, per acre basis [a] [b]

				Observed [c]			Adjusted [d]			Adjusted [e]		
Location	**Set**	**Reps**	**Yr**	**Response**	**RMS**	**ES**	**Response**	**RMS**	**ES**	**Response**	**RMS**	**ES**
							Ft²					
Toledo North	E	3	7	0.80	0.230	1.67	1.31	0.212	2.85	0.96	0.291	1.78
	F	6	4	-.19	.344	-.32	-.21	.343	-.36	-.21	.261	-.41
Toledo South	A	5	4	1.19*	.789	1.34	[f]	[f]	[f]	.67	.569	.89
Bone Mountain	A	3	4	1.90*	.058	7.88	1.77*	.060	7.22	1.83*	.070	6.91
	B	3	4	1.42*	.113	4.23	1.20*	.134	3.28	1.27*	.142	3.37

[a] Effect size (ES) = response/square root of the residual mean square (RMS).

[b] Response = PAI fertilized - PAI control; 7 years at set E, 4 years at other sets; * = significant at $P \leq 0.10$.

[c] Analysis of variance; P = probability value.

[d] Covariance analysis using prefertilization basal area as covariate; this equaled postthinning basal area/acre at set E.

[e] Covariance analysis using prefertilization basal area growth as covariate (1982-89 or 7 years at Toledo North and South; 1983-89 or 6 years at Bone Mountain).

[f] Covariance inappropriate because the relation of growth-starting basal area differed between control and fertilized plots.

Table 8—Table for determining sample size for analysis of variance (fixed-effects model) when alpha = 0.10

	Power (1 - beta)			
	0.70		**0.90**	
Treatments tested	**ES = 1.0**	**ES = 3.0**	**ES = 1.0**	**ES = 3.0**
Number	*Sample size (no.)*			
2	11	3	18	3
4	15	3	25	4

Sources: Adopted from Bratcher and others (1970) and Lipsey (1990).

Ways to Increase Sensitivity of Field Trials

Install adequate replication—Increased replication is a common recommendation for improving experimental design. Estimating adequate sample size, however, requires several decisions (table 8): (1) What risk of type 1 error (alpha) and type 2 error (beta) is acceptable? Lowering risk of either error type increases the required sample size. (2) What is the expected magnitude of response to treatment and of the experimental error that reflects variation among the replicates of each treatment? Large response and small experimental error result in large ES, which markedly reduces the estimated number of needed replications (table 8). (3) What magnitude of effect (that is, response) has practical meaning? There is no point in increasing replication to enable detection of differences that are trivial in magnitude.

With only two replications per treatment, as is common in many field trials, it is less likely that randomization will provide a balanced or comparable mix of above- and below-average plots for each treatment. As demonstrated at Toledo South, even five replications did not provide balanced allocation. To demonstrate the potential effects of only two replications on direction and possible magnitude of observed responses, we deliberately mismatched two fertilized and two control plots in each set. This matching was based on initial basal area (BA) stocking at fertilization. In match 1, we compared periodic annual increment (PAI) of the two best stocked, fertilized plots and the two poorest stocked, nonfertilized plots. In theory, this matching should maximize response (the average difference in PAI between fertilized and control). Conversely in match 2, we computed response as the difference in PAI of the two most poorly stocked fertilized plots and of the two best stocked control plots. In theory, match 2 should minimize response.

Results of our purposeful mismatching of fertilized and nonfertilized plots were as expected (table 9). When best stocked plots are assigned arbitrarily or randomly to fertilized treatments (match 1), measured response is inflated. Conversely, response is deflated or negative when best stocked plots are assigned to control treatments. Responses computed from matches 1 and 2 clearly differed from those observed from all replicate plots by 30 percent to 32-fold (table 9).

Select uniform conditions—Locating field trials in uniform stand and site conditions is an effective way to reduce experimental error. We initially assumed that plots in these genetic-test plantations would be especially uniform because each plot was planted with the same 30 half-sib families, and the planting area was nearly level and smooth. Moreover, the entire plantation was fenced to exclude large animals, and was sprayed or mowed to control vegetative competition. Despite this intensive culture, the three to

Table 9—Observed and theoretical responses in mean annual gross growth after fertilization in nonthinned plantations, per acre basis

Location	Set	Reps	Mean annual response			
			Basal area		Volume	
			Ft^2	*Relative*	*Ft*^{3}	*Relative*
Toledo North	E	3	0.80	100	42.9*	100
		2[a]	1.15	144	55.7	130
		2[b]	.30	38	28.2	66
	F	6	-.19	100	5.7	100
		2[a]	.93	489	74.7	1,334
		2[b]	-1.32	-695	-68.8	-1,228
Toledo South	A	5	1.19*	100	-1.1	100
		2[a]	2.53	213	27.0	2,454
		2[b]	-.38	-32	-35.7	-3,245
Bone Mountain	A	3	1.90*	100	37.2*	100
		2[a]	2.12	112	47.3	127
		2[b]	1.67	88	27.2	73
	B	3	1.42*	100	-6.8	100
		2[a]	1.74	122	19.3	280
		2[b]	1.18	83	-35.6	516

* Statistically significant ($P \leq 0.10$); see table 4.

[a] Best (by starting basal area) two fertilized plots matched to worst two control plots.

[b] Worst (by starting basal area) two fertilized plots matched to best two control plots.

six replications of each imposed treatment (fertilized or control) differed in growing stock (basal area per acre) at age 16 or 17 years from seed. Within the two treatment groups at each plantation, coefficients of variation ranged from 1 to 14 percent (table 2), which is similar to that for 31 nonthinned fertilizer trials in mostly naturally regenerated stands in the Oregon Coast Range (fig. 8). Each of these 31 trials had six to eight plots that were subsequently allocated to three or four treatments. Two comments about figure 8 are pertinent: (1) among-plot variation in stand basal area appears to decline with stand age, and (2) the two trials with unusually large CV of about 28 percent are the only trials with eight plots. This could illustrate the difficulty of locating sufficient area of uniform stand and site conditions to accommodate more than a few plots.

Use blocking or covariance—When faced with heterogeneity among experimental plots or subjects, one can use two other techniques to improve sensitivity of field trials. These are “blocking” and covariance. “Blocking” clusters or stratifies plots of similar stocking into subgroups, then assigns treatment within each subgroup or block. This also ensures that all treatments sample the range of stocking within the test site. We did not block our available plots because these plantations initially appeared to be exceptionally uniform.

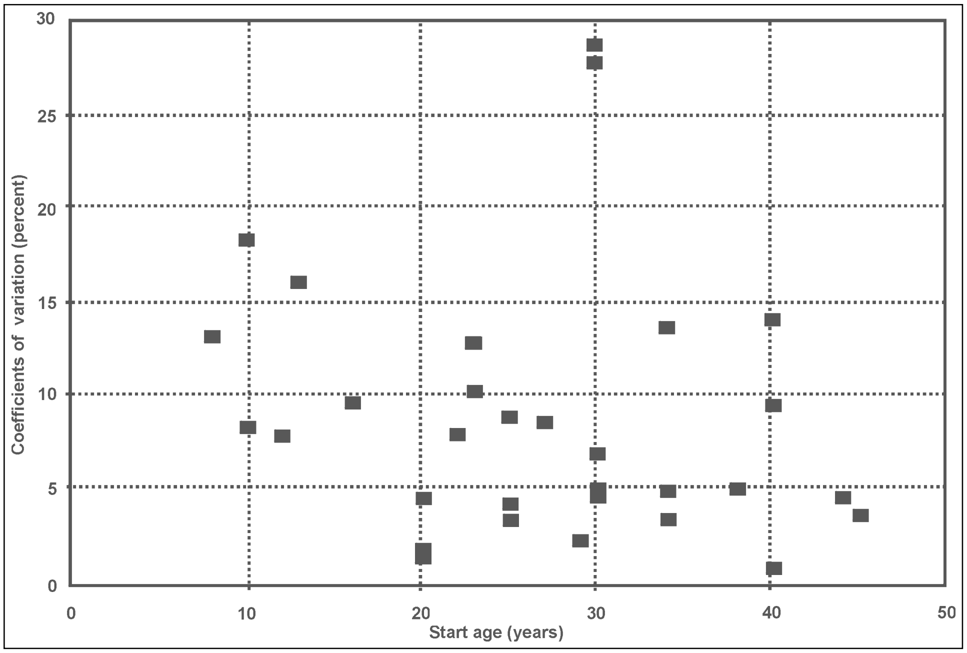

Figure 8—Coefficients of variation in stand basal area within 31 fertilizer trials sampled by six or eight plots each. Adapted from Miller and others (1991, see footnote 1).

Covariance uses the linear correlation between the dependent variable (growth) and the covariate (for example, starting basal area or calibration growth) to compute an adjusted mean growth for each treatment, then a mean response. We demonstrated effects of that technique (table 4). Covariance did not consistently reduce experimental error (RMS) or increase ES in this data set (table 7). We would expect covariance to be more effective where among-plot variations were greater than in these test plantations.

To improve detection of response to fertilizers, the following should be attempted:

- Install trials in uniformly stocked and structured stands, or group plots in blocks of similar within-block stocking and structure.
- Install at least three replications to enable covariance analysis and adjustment of observed means.
- Recognize that a large number of replications of each treatment is necessary to detect the small response to N fertilization that is characteristic of above-average site quality stands of coast Douglas-fir. This characteristically small response (<10 percent) may or may not have practical meaning. There is no point in increasing replication or sensitivity to enable detection of differences that are trivial in a practical sense.

Conclusions

1. Coefficients of variation in tree and stand attributes before fertilization were about 5 percent in trees per acre, 15 percent in basal area, and 20 percent in cubic volume, despite the fact that all trees in each plantation (1) originated from the same half-sib families, (2) were planted at precise tree-to-tree spacing, and (3) received intensive protection from large animals and weed competition.

2. Random assignment of three to six plots per treatment did not assure balanced or comparable plots for fertilized and nonfertilized treatments. Covariance adjustment of observed growth (for initial differences in basal area or volume stocking between fertilized and control plots) changed magnitude and, in some plantations, direction of observed (unadjusted) response.
3. Covariance analysis did not consistently reduce experimental error (residual mean square) or increase effect size.
4. Without covariance adjustments, effect sizes ranged from -0.32 to 7.88 for responses in gross basal area growth per acre. Effect sizes of 1.34 and larger were statistically significant.
5. Detection of response to fertilization of Douglas-fir stands on above-average site quality requires careful planning and execution. Expected response to 200 lb N/acre is small and experimental error (unaccounted sources of variation) is usually large.

Acknowledgments

We thank the following cooperators: Georgia-Pacific Corporation (tree data and professional assistance); University of Washington, Regional Forest Nutrition Research Project (professional and technical assistance); Olympic National Forest and Siskiyou National Forest (partial funding); Unocal Chemical Company (urea fertilizer); U.S. Department of the Interior, Bureau of Land Management (field assistance); and Eunice Ham, formerly at the Forestry Sciences Laboratory, Olympia, WA (data management).

Metric Equivalents

1 inch (in) = 2.54 centimeters

1 foot (ft) = 0.3048 meter

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

1 cubic foot (ft^3) = 0.028 cubic meter

1 acre = 0.4047 hectare

1 square foot per acre = 0.2296 square meter per hectare

1 cubic foot per acre = 0.06993 cubic meter per hectare

1 pound (lb) = 453.592 grams

1 gallon (gal) = 3.785 liters

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