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Stand Dynamics of Douglas-fir 20 Years After Precommercial Thinning and Nitrogen Fertilization on a Poor-Quality Site

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Cover photo: Researchers apply nitrogen fertilizer in spring 1969 to a 30-year-old thinned stand of Douglas-fir near Brinnon, Washington. In this Rocky Brook study, stand dynamics of thinned and nonthinned stands of Douglas-fir were compared for 20 years after application of three rates of nitrogen fertilizer. Photo by Richard E. Miller.

Abstract

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Amendment of soil nutrients through fertilization is used to increase wood production of forest stands. Subsequent allocation of growth to individual trees and the resulting increase in stand volume and value, however, depend on stand density at the time of treatment. Our primary research question was: To what extent can volume growth per acre in precommercially thinned or nonthinned portions of a poor-site, 30-year-old coast Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) plantation be increased by a single application of 200 or 400 lb nitrogen (N)/acre as urea? Each fertilizer treatment was replicated on three 0.2-acre plots in thinned and nonthinned stands located in Rocky Brook drainage on the Olympic Peninsula in Washington. All trees in the interior 0.1-acre plots with a diameter at breast height (d.b.h.) of 1.6 inches and larger were measured for stem diameter, and a subset of trees was measured for total height and height to live crown. We anticipated that poor site quality, prolonged overstocking, and a subsequent severe thinning would influence the responses we observed. In the 20 years after fertilization, net growth in total stem volume on fertilized plots averaged 50 percent greater than on nonfertilized plots in the previously thinned stand and 31 percent greater in the nonthinned stand. In both stands, mortality losses were relatively small, averaging 1 to 15 percent of gross annual growth. Diameter growth of the 100 largest trees per acre was improved by both thinning and fertilization. Present net value (PNV) (in 2014 dollars) at the hypothetical final harvest of the thinned stand was increased by delaying the harvest from 10 years (age 40) until 20 years after fertilization (age 50), and by fertilization, although differences between the 200 and 400 lb N/acre treatments were not significant. Present net value of the nonthinned stand also was increased by delaying final harvest until 20 years after fertilization; however, PNV did not differ significantly among the 0, 200, and 400 lb N/acre treatments, indicating no financial benefit from fertilizing this nonthinned stand. The 90-percent confidence interval for PNV of nonfertilized plots in the thinned stand ($919 ± $278 per acre) did not overlap with that of nonfertilized plots in the nonthinned stand ($2,639 ± $498 per acre), suggesting that the thinning prescription reduced the economic value of this overstocked stand at Rocky Brook. Clearly, the severe thinning at age 30 reduced stocking to the point at which the stand was slow to reoccupy this poor quality site.

Keywords: Douglas-fir plantation, precommercial thinning, forest fertilization, nitrogen, stand growth, economic analysis.

Summary

Amendment of soil nutrients through fertilization is often used to increase wood production and overall vigor of forest stands. However, the allocation of growth to individual trees and the resulting increase in stand volume and value depends on initial density and tree mortality. Our research addressed the following questions:

- To what extent can volume growth per acre in precommercially thinned or nonthinned portions of a 30-year-old poor-site coast Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) plantation be increased by a single application of 200 or 400 lb nitrogen (N)/ac as urea?
- Does inclusion of phosphorus (P), potassium (K), and sulfur (S) amendments with 400 lb N/ac provide additional response?
- How are stem and crown growth of crop trees (i.e., the 100 largest trees per acre by diameter at breast height [d.b.h.]) influenced by fertilization in thinned and nonthinned stands?
- What are the effects of thinning, fertilizer rate, and timing of final harvest (10 vs. 20 years after fertilization) on yield and present net value?

Located in the Rocky Brook drainage on the east side of the Olympic Peninsula in Washington, our plantation originated after clearcut logging to salvage an earlier, storm-toppled stand of Douglas-fir, western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and western redcedar (*Thuja plicata* [Donn ex D. Don]). At about stand age 25, a portion of this plantation was precommercially thinned at high intensity; approximately 75 percent of stand basal area was felled and left on the plots. Five years later, 0.1-ac square plots for measuring tree growth were established within the 0.2-ac treatment areas in the thinned stand. Nine plots were used for our fertilizer trial, and three plots (replications) each were treated in spring of 1969 with either 200 lb N/ac (200N) or 400 lb N/ac (400N) as urea (46 percent N). Three plots remained nonfertilized. Two years later in an adjacent nonthinned portion of the same plantation, six additional and equal-size plots were established and uniformly fertilized. Three additional nonthinned plots of the same size from the nearby levels-of-growing-stock (LOGS) study were used for nonfertilized comparisons.

Urea fertilizer markedly increased live-stand volume of both thinned and nonthinned portions of this 30-year-old plantation in the subsequent 20-year period. Per acre gains in live-stand volume after the 200N application averaged about 1,500 ft^3 in the thinned stand and 1,800 ft^3 in the nonthinned stand. Among fertilized plots in both thinned and nonthinned stands, gains in merchantable volume of trees 5.6 inches and larger to a 4-inch top (CV4) exceeded gains in cubic volume total stem (CVTS). This contrast is important for financial returns to the landowner and for creating wildlife habitat that includes large trees.

In a separate trial, fertilization with 400 lb N/ac plus amendments of phosphorus (P), potassium (K), and sulfur (S) increased diameter growth of individual Douglas-fir relative to nonfertilized trees, but the corresponding 400N-alone treatment provided similar increases in tree growth. The addition of P, K, and S—a costlier treatment than 400N alone—was not justifiable on this poor quality site at Rocky Brook.

In both thinned and nonthinned stands, mean d.b.h. and height of crop trees (i.e., the 100 largest trees per acre by d.b.h.) increased with fertilization. At stand age 50 years, live crown ratio (i.e., crown length/tree height) for crop trees ranged from 0.45 to 0.49 in the thinned stand and from 0.37 to 0.42 in the nonthinned stand.

Our economic analysis compared relative effects of precommercial thinning, N fertilizer rate, and timing of final harvest (i.e., 10 vs. 20 years after fertilization) on present net value (PNV). To remove the effects of inflation, all costs and revenues were adjusted to 2014 dollars using producer price indices from the U.S. Bureau of Labor Statistics. These standardized values were then discounted at an assumed 5 percent interest rate. Real increases in the value of wood products were assumed to be zero. The PNV of thinned stands was greater after fertilization and when timber harvest occurred 20 years after treatment (i.e., at age 50); however, there was no significant difference in PNV between the 200N and 400N treatments. The PNV of nonthinned stands was not affected by fertilization but was greater when final harvest occurred 20 years after treatment. Because formal statistical testing between thinned and nonthinned stands was not appropriate, we instead estimated 90-percent confidence intervals for mean values of PNV that bracketed the range of responses. The 90-percent confidence interval for PNV of nonfertilized plots in the thinned stand ($919 ± $278 per acre) did not overlap with that for nonfertilized plots in the nonthinned stand ($2,639 ± $498 per acre), suggesting that the thinning prescription reduced economic value of this overstocked stand at Rocky Brook. Poor site quality, excessive reduction in stand stocking, and removal of some of the larger trees likely contributed to this negative effect from thinning.

Contents

Introduction

On formerly glaciated sites in the Puget Sound region of Washington, slow growth and chlorotic foliage are typical for young stands of coast Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*). To increase growth and obtain earlier and greater utilizable yield from these slow-growing, generally overstocked stands, foresters of Olympic National Forest initially prescribed precommercial thinning. In the period 1960–1963, the former Hoodsport Ranger District thinned several hundred acres of an extensive plantation that originated in 1940 in the Rocky Brook drainage. Because of dense stocking from volunteer regeneration and steep terrain, thinning costs averaged about $60 per acre at that time.[1] Assuming a 5-percent rate of inflation, current costs would exceed $400 per acre. The removal of excess trees, primarily from lower crown classes, initially resulted in very little increase in diameter growth of residual trees (300–450 trees per acre [TPA]), and their chlorotic appearance and low vigor persisted for at least 3 years after thinning. These early results observed by district personnel generated a desire to determine causes of poor tree growth in this glaciated area and, if possible, apply a corrective treatment that would supplement or possibly substitute for expensive precommercial thinning.

In the Rocky Brook drainage, a short growing season probably limits tree growth. At the nearby levels-of-growing-stock (LOGS) study (located at approximately 2,500 ft elevation on a southerly aspect) (Williamson 1976), height growth started about 1 month later than that observed near sea level at Olympia, Washington.[2] Short, yellowish-green needles on Douglas-fir from this and other local stands indicated nitrogen (N) deficiency, which was confirmed when foliage samples collected in June 1964 near the LOGS study area were chemically analyzed at the University of Washington.[3]

The glacial origin of soils at Rocky Brook also suggested N deficiency. Early research by staff of the University of Washington indicated a general N deficiency in glaciated areas, as repeatedly demonstrated by an increase in growth of Douglas-fir after N fertilization (Gessel et al. 1965). Although magnitude of response differed among their study locations because of differences in site quality, stand condition, treatment year, and amount of N applied, a single application of 200 lb N/ac generally resulted in at least a 20-percent increase in gross volume increment in the first 5-year period after fertilization.

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[1] Grubb, J. 1965. Personal communication. District ranger, Hoodsport Ranger District, Olympic National Forest, Hoodsport, WA 98548.

[2] Williamson, R.L. 1968. Personal communication. Mensurationist (deceased), Forestry Sciences Laboratory, 3625 93rd Avenue SW, Olympia, WA 98512.

[3] Gessel, S. 1960. Personal communication. Professor, College of Forestry, University of Washington, Seattle, WA 98195.

Research Questions

This report presents the 20-year results of a study designed to address the following research questions:

- To what extent can volume growth per acre in precommercially thinned or nonthinned portions of a poor-site, 30-year-old coast Douglas-fir plantation be increased by a single application of 200 or 400 lb N/ac as urea?
- Does inclusion of phosphorus (P), potassium (K), and sulfur (S) amendments with 400 lb N/ac provide additional growth response?
- How are stem and crown growth characteristics of crop trees (i.e., the 100 largest trees per acre by diameter at breast height [d.b.h.]) influenced by fertilization in the thinned and nonthinned stands?
- What are the effects of thinning, fertilizer rate, and timing of final harvest (10 vs. 20 years after fertilization) on yield and present net value?

Can nitrogen fertilization be used on poor quality sites to increase stand growth and value?

Answers to these questions have practical implications. If responses to fertilization are strong and lasting, then application of N fertilizer to similar stands and sites in the general study area would be justified, either: (1) in combination with precommercial thinning to increase growth and hasten recovery of thinning costs, or (2) in lieu of thinning to increase growth and hasten mortality in the lower crown classes.

Methods

Study Area

Our study included three separate areas in a coast Douglas-fir plantation located in Township 26N, Section 18 in Range 2W, and Section 13 in Range 3W, Willamette Meridian (fig. 1) . The study area is located in the upper Rocky Brook drainage on the east side of the Olympic Peninsula near Brinnon, Washington. During the last glaciation (Vashon) approximately 13,000 years ago, water-sorted sediments were deposited in the valley (fig. 2). The uniformly fine texture of these sediments indicates deposition in the deep, still water of a temporary lake. Subsequently, nonsorted materials—gravel through large boulders—were deposited on these indurated (i.e., hardened) sediments mostly by colluvial transport from higher slopes.

Soils of the general study area were mapped as two slope phases of the Hoodcanal-Sawpeak complex (USDA NRCS, n.d.). The Hoodcanal series is mapped in glaciated valleys and formed in glacial residuum and colluvium over dense glacial till. The series consists of medial-skeletal, ferrihydritic, frigid Typic Durudands. This soil drains moderately well to the depth of a cemented horizon above indurated till, which seasonally perches water. Textures range from very gravelly loams to

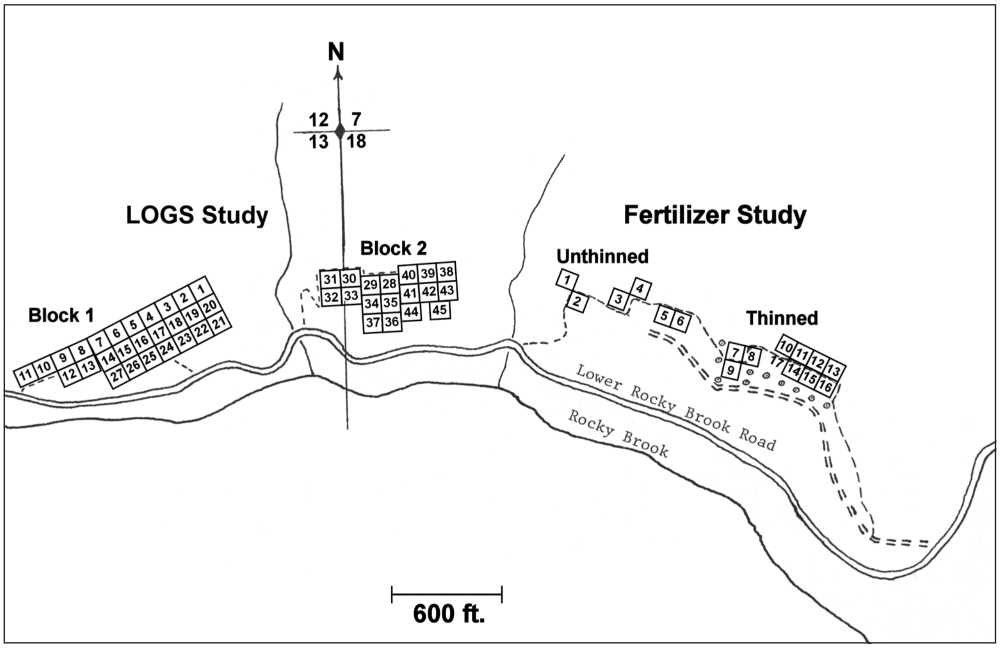

Figure 1—Study area in a Douglas-fir plantation established in 1937–1938 at Rocky Brook, Washington. Treatment plots were located in blocks 1 and 2 of the levels-of-growing-stock (LOGS) study and in both thinned and nonthinned portions of the adjacent plantation.

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Figure 2—Indurated glacial till underlies the Rocky Brook, Washington, study areas.

sandy loams. The Sawpeak series lies on higher slopes and is formed in colluvium from marine basalt. The series consists of medial-skeletal, ferrihydritic, frigid Alic Hapludands (USDA NRCS, n.d.). This soil drains well to basalt bedrock. Typical texture is extremely gravelly sandy loam. The LOGS study area and most of our fertilizer study are situated on the 5- to 30-percent slope phase of this soil complex. A few plots are on the 30- to 60-percent slope phase. Growing season precipitation (April–September) was estimated from rain gauges located on site and at the nearby Quilcene Ranger Station.

Our stand originated from a 1937–1938 planting established after clearcut logging to salvage an earlier, wind- or snow-toppled stand of Douglas-fir, western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and western redcedar (*Thuja plicata* Donn. ex D. Don). Logging slash was broadcast-burned in fall 1937. Two-year-old coast Douglas-fir seedlings were planted at a 10-ft-by-10-ft spacing.

The eastern-most portion of the plantation was precommercially thinned in fall 1963 (figs. 1 and 3). Thinning removed trees primarily from lower crown classes and created a relatively uniform 11-ft-by-11-ft spacing (fig. 3). Based on stump counts and diameters, thinning intensity was severe, removing about 75 percent of basal area and leaving an average of 351 TPA. As enumerated later, numerous volunteer seedlings of local conifers increased stand density and eventually created a two-story stand in the thinned portions. Height and age measurements on individual plots indicated that 50-year site class ranged from IV to V (King 1966).

Plot Installation and Fertilization Treatments

Thinned stand—

Ten 0.2-ac square plots were established in the thinned stand, each with an interior 0.1-ac plot for measuring tree growth. Volume growth was measured on each plot for a 2-year period (1967 and 1968 growing seasons), and based on this calibration growth period, nine plots were selected for the fertilizer study. Treatments were assigned using a completely randomized design, and in spring 1969, urea fertilizer (46 percent N) was uniformly broadcast by hand on the designated 0.2-ac plots. The following treatments were applied to three plots (replications) each: 0, 200, or 400 lb N/ac, designated by the treatment codes 0N, 200N, or 400N, respectively.

To test the effects of other nutritional elements, additional trees were selected to be treated with fertilizer containing N, phosphorus (P), potassium (K), and sulfur (S). Ten dominant trees were systematically chosen outside the cluster of thinned-stand plots by projecting a compass line either diagonally from plot

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Figure 3—The fertilization study at Rocky Brook, Washington, was installed in 1968 in a portion of a 30-year-old Douglas-fir plantation that had been precommercially thinned 5 years earlier by Quilcene District personnel. Portions of the planation remained nonthinned. Thinned plot 12 (top) and nonthinned plot 29 (bottom) of the levels-of-growing-stock study.

corners or perpendicularly from the midpoint of one side. The closest, nondamaged dominant tree located at least 33 ft from any plot was tagged. To provide spacing comparable to that of other fertilized trees, two trees were felled near each of the trees numbered 8, 9, and 10. Fertilizer was concurrently and uniformly broadcast around these 10 exterior trees (within an 18.6 ft radius=0.025 ac). The complete fertilizer treatment provided N at 400 lb/ac as urea (the largest dosage tested on the larger plots), P at 150 lb/ac as single and treble superphosphate, K at 100 lb/ac as potassium chloride, and S at 50 lb/ac contained in the phosphate fertilizer. Because tree spacing was about 11 ft, this fertilized area included the subject tree and its nearest competitors. Consequently, growing conditions for the fertilized, individual subject trees should closely simulate those of d.b.h.-matched trees in the 0.1-ac plots. For comparison, 10 similar-sized dominant trees were selected in plots treated with 400 lb N/ac and from nonfertilized plots.

Does the addition of phosphorus, potassium, and sulfur increase tree response to nitrogen fertilization?

Nonthinned stand—
Six additional, equal-size plots were installed in 1968 in the adjacent, nonthinned portion of the same plantation. The same 200N and 400N treatments were each randomly assigned to three of the six 0.2-ac plots. Three nonthinned plots in the nearby LOGS study located in the same plantation (Williamson 1976) were used for the 0N control plots. We acknowledge that this was not a randomly assigned control treatment.

Application—
All fertilizer treatments were applied on May 9, 1969, to the 12 designated 0.2-ac treatment areas and exterior trees. Weather at application and in the preceding and subsequent 5 days was clear, dry, and warm. We suspect volatilization losses of urea were minimal.

Tree Tagging and Measurements

All trees within the 0.1-ac measurement plots with a stem d.b.h. of 1.6 inches and larger were identified with numbered aluminum tags, and their d.b.h. was measured to the nearest 0.1 inch. Crown class and damage were also recorded. Trees were measured at 1- to 10-year intervals, specifically after the growing seasons of 1968, 1969, 1970, 1972, 1974, 1976, 1978, and 1988. Within each plot, total height and height to live crown to the nearest foot were measured with an Abney level on 20 randomly chosen trees; two-thirds of these height trees had a d.b.h. greater than the quadratic mean d.b.h. of the plot. Concurrently, d.b.h. and height to the nearest foot were measured on the 10 exterior trees selected for the NPKS study.

Stand volumes for 1968 through 1988 were computed from tarif equations (Brackett 1973). Cubic volume total stem (CVTS) was computed for all trees measured for height using the equation derived by Bruce and DeMars (1974) from which tarifs were calculated. Individual tree tarifs were averaged for each plot, and mean tarifs for each plot and measurement year were smoothed over the 20-year period. Total stem volume inside bark of each tree 1.6 inches d.b.h. and larger (CVTS) was computed from d.b.h. and tarifs, summed to give volume per plot, and expanded to give volume per acre. Total stem volumes were converted to merchantable volumes to a 4-inch top (CV4) for trees 5.6 inches d.b.h. and larger using equations from Brackett (1973). Relative density (RD), a measure of stand stocking, was computed from basal area per acre, TPA, and quadratic mean d.b.h. (QMD) using the following equation (Curtis 1982): RD = BA/sqrt(QMD).

Experimental Design and Analysis

We estimated effects of N treatment on gross periodic annual increment (PAI) of live-stand volume (CVTS), merchantable volume (CV4), d.b.h., height, and crown variables for the 100 largest trees per acre (by d.b.h.). We also calculated fertilizer response efficiency as the additive gain in CVTS from fertilization (relative to the 0N control) divided by N dosage (lb/ac).

Lack of randomization among all plots constrained some statistical analyses of this 20-year study. Fertilizer treatments in the thinned stand were randomized, so these data were analyzed separately. Likewise, the fertilizer study in the nonthinned stand was analyzed separately, although randomization of fertilizer treatments was constrained because all nonfertilized plots were restricted to the nearby LOGS study. Because the thinning treatment was not randomized, statistical tests of significance were not appropriate for comparing the main effects of thinning and the thinning-by-fertilizer interaction. Instead, inferences will be made based on contrasting the results of separate statistical analyses of data from the thinned and nonthinned stands.

Data for each level of thinning were subjected to repeated-measures analysis of variance (ANOVA) using PROC MIXED, a mixed-model approach in SAS software (SAS Institute, Inc. 2013), to test for significant fixed effects of decadal period (10 or 20 years after fertilization), N fertilizer rate (0, 200, or 400 lb N/ac), and their interaction. A first-order autoregressive covariance structure was used to adjust each repeated measures ANOVA for serial correlation. When a given model failed to converge, an unstructured covariance structure was assumed. Plots within thinned and especially nonthinned portions had a wide range of initial stand volumes; therefore, our preliminary statistical analyses of fertilizer effects tested the utility of using initial stand volume (CVTS) as a covariate to adjust for such differences. Scatter-grams documented the overall pattern of the relation between growth and initial volume and slopes of individual treatments so we could determine if covariance adjustment of treatment means along a common slope would be appropriate (Quinn and Keough 2002). We found that we were able to analyze the data with the covariate because the individual treatments shared a common slope for each of the growth variables.

Data from the thinned and nonthinned stands were analyzed separately as completely randomized designs

Data from the thinned and nonthinned stands were analyzed separately as completely randomized designs according to the following analysis of variance:

Source of variation	Degrees of freedom
N fertilizer (F)	2
Replication within F (Error 1)	5
Period (P)	1
P × F	2
Error 2	26
Covariate	1
Total (18-1)	17

Statistical significance was assigned at $\alpha = 0.10$; however, probability values are provided so readers can make their own interpretations. If an *F* test in the ANOVA indicated a significant main effect of N fertilizer rate, multiple comparisons of means were conducted with Bonferroni adjusted probabilities to control the Type I error rate (Quinn and Keough 2002). If a significant interaction was detected between period and N fertilizer rate, multiple comparisons were conducted with Bonferroni-adjusted probabilities to identify differences among N fertilizer rates within a given period or between periods within a given N fertilizer rate (i.e., the simple main effects). Potential linear effects of N fertilizer rate were tested for each period using orthogonal contrasts and Bonferroni-adjusted probabilities (Sokal and Rohlf 1981).

The combined effect of P, K, and S additions was evaluated initially by graphically comparing basal area increments of the 10 exterior trees with those of plot trees. Covariance analysis of individual tree growth using initial tree basal area as the covariate was conducted to test for statistical differences using $\alpha = 0.10$ to judge statistical significance.

Similar analyses were conducted for stem and crown size attributes of the 100 largest trees per acre (by d.b.h.) to determine potential effects of thinning and fertilization on crop trees, which constitute the primary component of stand structure and wildlife habitat.

Results

Effects of the Operational Thinning

The belated and severe thinning at stand age 25 years felled about 75 percent of stand volume (table 1). Five years later at fertilization, relative density (Curtis 1982) averaged 19 (range of 18 to 20) in thinned plots compared to 67 (range of 56 to 81) in nonthinned plots. Note that RD 65 equates to a normal, fully stocked stand of Douglas-fir based on the seminal study by McArdle et al. (1961). Among the several species of conifers, Douglas-fir averaged 90 percent by basal area in the thinned stand compared to 76 percent in the nonthinned stand.

Table 1—Stand statistics for trees with a diameter at breast height of 1.6 inches and larger at time of fertilization in 1968 in thinned and nonthinned stands at Rocky Brook, Washington

Treatment[a]	Plot	Trees	QMD	H_{40}	CVTS	Relative density	50-year site index	Douglas-fir BA[b]
		Number/acre	*Inches*	*Feet*	*Ft³/acre*		*Feet*	*Percent*
Thinned stand:								
0N	8	400	4.3	35	501	19	70	100
	9	330	4.8	41	577	19	78	96
	17	280	5.4	41	631	19	81	92
200N	10	410	4.1	34	467	19	70	98
	12	350	4.7	38	598	19	66	59
	13	320	5.1	51	794	20	83	88
400N	11	380	4.6	42	635	20	76	94
	15	360	4.4	33	478	18	66	87
	16	330	4.8	35	534	19	71	100
	Mean	351	4.7	39	579	19	73	90
Nonthinned stand:								
0N	14	1,550	3.8	37	1,520	62	79	73
	27	1,180	4.3	53	2,296	58	91	80
	29	1,250	4.2	45	1,849	58	90	68
200N	1	1,190	4.2	46	1,914	56	88	71
	4	1,700	4.3	48	2,923	81	91	80
	5	1,520	4.3	43	2,689	74	81	78
400N	2	1,650	4.2	52	2,897	78	82	67
	3	1,680	4.2	49	2,808	77	88	87
	6	980	4.8	50	2,333	57	94	80
	Mean	1,411	4.2	47	2,359	67	87	76

QMD = quadratic mean diameter at breast height; H_{40} = average height of 40 largest trees per acre, by diameter; CVTS = cubic volume of the total stem, inside bark; N = nitrogen;

[a] Application of 0, 200, or 400 lb N/ac.

[b] Percentage of stand basal area (BA) in Douglas-fir.

Initial quadratic mean diameter averaged 4.7 and 4.2 inches in the thinned and nonthinned stands, respectively (table 1). Height of the 40 largest trees per acre by d.b.h. (H40) averaged 39 ft in the thinned stand versus 47 ft in the nonthinned stand. Based on estimated H40 and documented age counts from 91 increment cores extracted at plot establishment, estimated site index (King 1966) averaged only 73 ft in the thinned stand compared to 87 ft in the nonthinned stand. This difference may be due to lower site quality in the thinned stand, the likelihood that some potential site-index trees were felled during thinning, or some combination of both effects.

In both thinned and nonthinned stands, species composition among plots at fertilization did not differ in basal area per acre or in percentage of total basal area by species (tables 2 and 3). Total basal area per acre of the nonthinned stand averaged almost three times that of the thinned stand, and the percentage of basal area in Douglas-fir was less in the nonthinned stand.

Effects of Urea-N in the Thinned Stand

Live-stand volume—

Two years before fertilization (1966), mean live-stand volumes (CVTS) were similar among the three pending treatments (fig. 4). In the 20 years after the 2-year calibration period (1966–1968), accumulation of live-stand volume differed markedly among the fertilizer treatments. Live-stand volume more than doubled in period 2 (the second decade after fertilizer treatment), especially on fertilized plots; the ratio of period 2 to period 1 (first decade after fertilizer treatment) values (P2/P1) ranged between 2.0 and 2.2 (table 4). Live-stand volume differed significantly among the N dosages. In each period, stand volume increased linearly with N dosage, indicating a proportionate response to the treatment. Fertilizer response efficiency (gain in CVTS from fertilization/N dosage) did not differ significantly between 200N and 400N for either of periods 1 and 2 (table 5).

In thinned stands, wood volume more than doubled during the second decade after fertilization.

Gross periodic annual increment—

Throughout the 20-year study, PAI in the thinned stand increased gradually over time, and growth was roughly proportional to fertilizer rate (fig. 5). Annual growth or PAI did not appear to be related to growing season precipitation as measured on site and at the local ranger station in Hoodsport. Covariance analysis indicated that mean gross PAI differed significantly among fertilizer treatments and between periods, but the fertilizer-by-period interaction was also significant ($P = 0.001$); therefore, generalizations about main effects are not justified (table 6). In period 1, gross PAI for the 0N control averaged 116 ft^3/ac/yr compared to 168 and 200 ft^3/ac/yr for the 200N and 400N treatments, respectively. Responses to the two N dosages

Table 2a—Analysis of variance of mean basal area per acre by species before fertilization in the thinned stand at Rocky Brook, Washington

		Douglas-fir		Hemlock		Other		All	
Source of variation	D.f.	F-value	P	F-value	P	F-value	P	F-value	P
N fertilizer (F)	2	1.5	0.304	1.6	0.279	1.5	0.296	0.1	0.888
Error	6	—	—						
Total (9-1)	8								

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.

Table 2b—Mean basal area per acre by species (mean ± standard error) before fertilization in the thinned stand at Rocky Brook, Washington

Treatment[a]	Douglas-fir	Hemlock	Other	All	Douglas-fir	Hemlock
	Ft²/acre				*Percentage of all*	
0N	39.8 ± 2.6 a[b]	1.8 ± 2.5 a	0 ± 0 a	41.6 ± 1.4 a	96	4
200N	33.7 ± 2.6 a	7.6 ± 2.5 a	0 ± 0 a	41.4 ± 1.4 a	81	18
400N	38.2 ± 2.6 a	2.5 ± 2.5 a	0 ± 0 a	40.7 ± 1.4 a	94	6

Note: A similar ANOVA of starting trees per acre (TPA) by species demonstrated no statistically significant differences among fertilizer rates for Douglas-fir, other species, and all species. For hemlock, however, TPA of the 200N treatment (73 TPA) greatly exceeded that of the 0N and 400N treatments (13 and 20 TPA, respectively) (P = 0.087).

[a] Application of 0, 200, or 400 lb N/ac.

[b] Means within a column followed by a different letter differ significantly ($P \leq 0.10$).

Table 3a—Analysis of variance of mean basal area per acre by species before fertilization in the nonthinned stand at Rocky Brook, Washington

		Douglas-fir		Hemlock		Other		All	
Source of variation	D.f.	F-value	P	F-value	P	F-value	P	F-value	P
N fertilizer (F)	2	0.5	0.653	0.3	0.772	3.1	0.117	0.6	0.586
Error	6	—	—						
Total (9-1)	8								

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.

Table 3b—Mean basal area per acre by species (mean ± standard error) before fertilization in the nonthinned stand at Rocky Brook, Washington

Treatment[a]	Douglas-fir	Hemlock	Other	All	Douglas-fir	Hemlock
	Ft²/acre				*Percentage of all*	
0N	97.1 ± 9.4 a[b]	24.5 ± 4.9 a	5.4 ± 1.1 a	127.0 ± 9.0 a	76	19
200N	106.6 ± 9.4 a	28.8 ± 4.9 a	2.3 ± 1.1 a	137.7 ± 9.0 a	77	21
400N	109.2 ± 9.4 a	29.0 ± 4.9 a	1.6 ± 1.1 a	139.7 ± 9.0 a	78	21

Note: A similar ANOVA of starting stems per acre by species demonstrated no statistically significant differences among N dosage means for Douglas-fir, hemlock, other, and all species.

[a] Application of 0, 200, or 400 lb N/ac.

[b] Means within a column followed by a different letter differ significantly ($P \leq 0.10$).

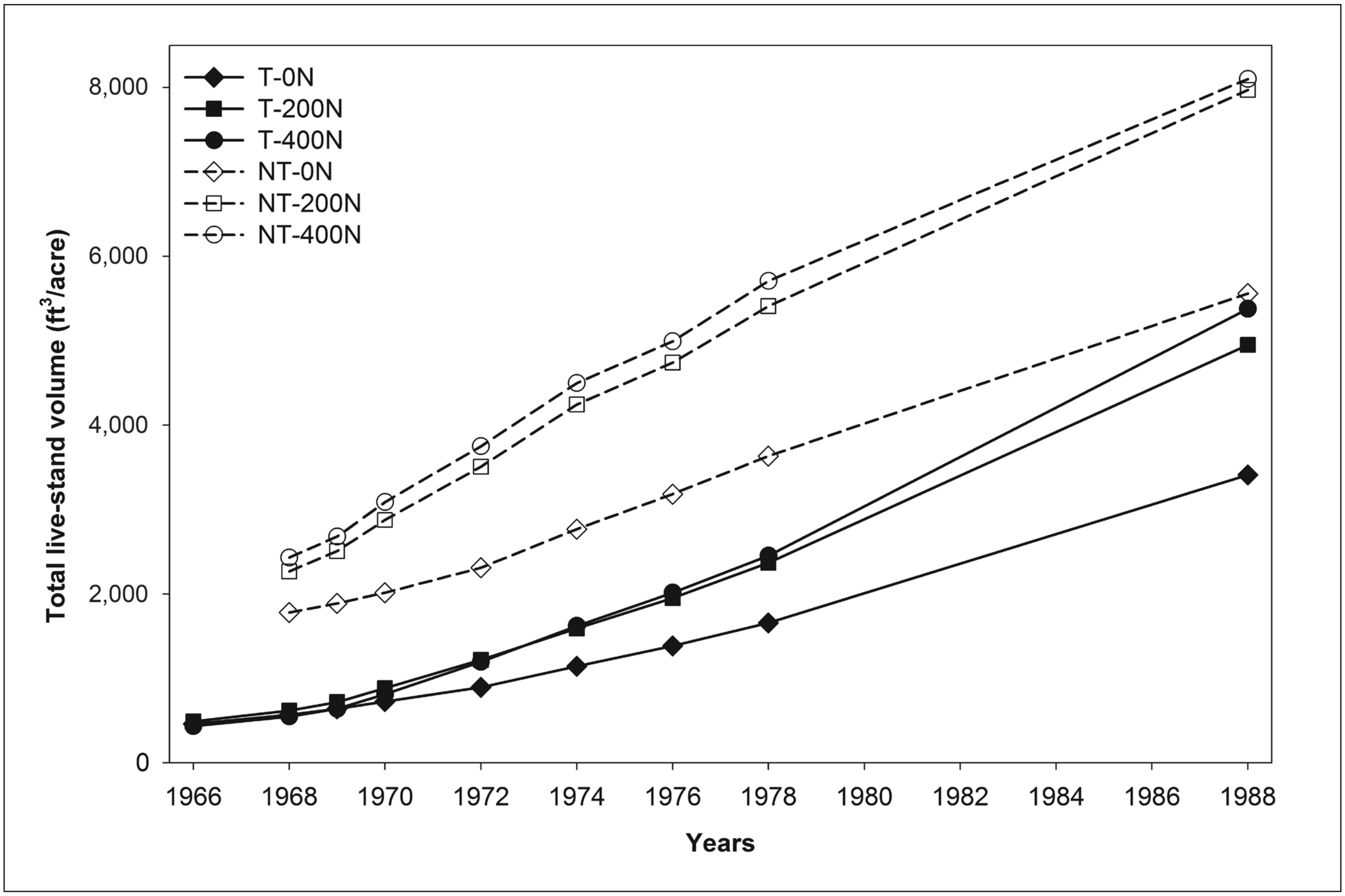

Figure 4—Trends of observed live-stand volume (CVTS, cubic volume-total stem) over time, by thinning and fertilizer treatments (T = thinned and NT = nonthinned; 0N, 200N, and 400N indicate urea fertilizer rates of 0, 200, and 400 lb N/ac, respectively), Rocky Brook, Washington.

Table 4a—Analysis of covariance of mean live-stand volume (CVTS) by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	130.2	<0.001
Rep. within F (Error 1)	5	—	—
Period (P)	1	2,319.2	<0.001
F × P	2	48.1	<0.001
Linear, period 1[a]	1	145.9	<0.001
Linear, period 2	1	214.7	<0.001
Covariate (starting CVTS)	1	98.6	<0.001
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.
[a] Linear contrasts with $P \leq 0.05$ are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 4b—Adjusted mean live-stand volume (mean CVTS ± standard error) by period after fertilization in the thinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	P1	P2	P1	P2	P2/P1
	- - - - - - - *Ft³/acre* - - - - - - -		- - - *Percent* - - -		
0N*[b]	1,690 ± 50 c	3,441 ± 98 c	100	100	2.0
200N*	2,244 ± 52 b	4,825 ± 99 b	133	140	2.2
400N*	2,549 ± 51 a	5,475 ± 99 a	151	159	2.1

CVTS = cubic volume of the total stem, inside bark; N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly ($P \leq 0.10$). Fertilizer means within a given period followed by a different letter differ significantly ($P \leq 0.10$).

Table 5a— Analysis of covariance of fertilizer response efficiency by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	1	2.7	0.197
Rep. within F (Error 1)	3	—	—
Period (P)	1	339.7	<0.001
F × P	1	9.9	0.034
Covariate (starting CVTS)	1	36.6	0.004
Error 2	4	—	—
Total (12-1)	11		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.

Table 5b—Adjusted mean fertilizer response efficiency (mean ± standard error) by period after fertilization in the thinned stand at Rocky Brook, Washington

			Relative to 200N		
Treatment[a]	P1	P2	P1	P2	P2/P1
	- - - - *Ft³/ac ÷ dosage* - - - - -		- - - *Percent* - - -		
200N*[b]	3.0 ± 0.44 a	7.1 ± 0.44 a			2.4
400N*	2.6 ± 0.44 a	5.5 ± 0.44 a	87	77	2.1

Fertilizer response efficiency = CVTS gain ÷ dosage; CVTS = cubic volume of the total stem, inside bark; N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly ($P \leq 0.10$). Fertilizer means within a given period followed by a different letter differ significantly ($P \leq 0.10$).

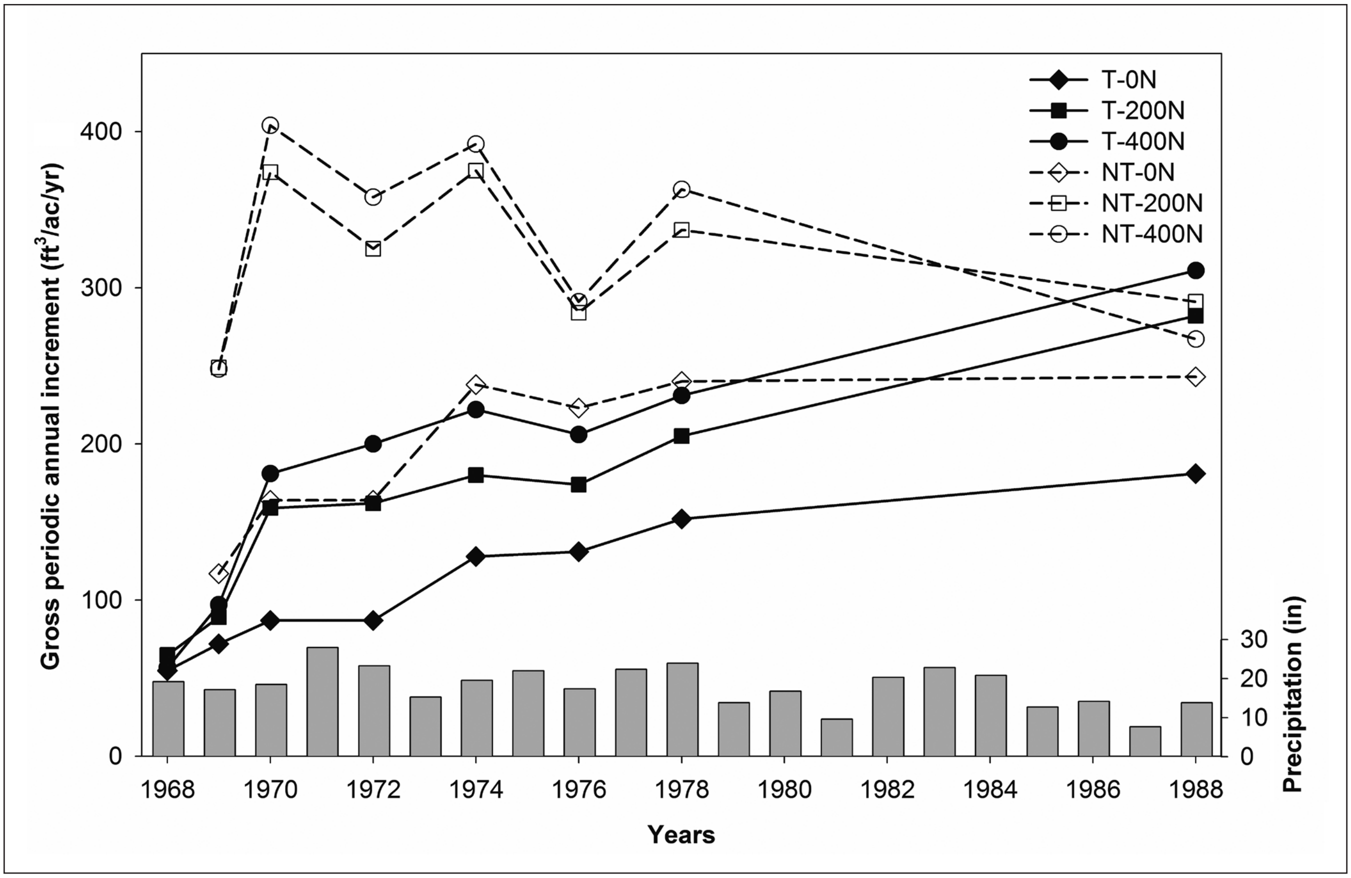

Figure 5—Trends of observed gross periodic annual increment over time, by thinning and fertilizing treatments (T = thinned and NT = nonthinned; 0N, 200N, and 400N indicate urea fertilizer rates of 0, 200, and 400 lb N/ac, respectively) and histograms indicating growing season (April-September) precipitation at Rocky Brook, Washington.

Table 6a—Analysis of covariance of mean annual gross volume growth (PAI) by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	110.6	<0.001
Rep. within F (Error 1)	5	—	—
Period (P)	1	1,260.9	<0.001
F × P	2	31.7	0.001
Linear, period 1[a]	1	171.0	<0.001
Linear, period 2	1	186.4	<0.001
Covariate (starting CVTS)	1	53.2	<0.001
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate; PAI = periodic annual increment.
[a] Linear contrasts with $P \leq 0.05$ are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 6b—Adjusted mean annual gross volume growth (mean ± standard error) by period after fertilization in the thinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	P1	P2	P1	P2	P2/P1
	- - - - - - *Ft³/ac/year* - - - - - -		- - - *Percent* - - -		
0N*[b]	116 ± 4.5 c	182 ± 6.8 b	100	100	1.6
200N*	168 ± 4.7 b	280 ± 6.9 a	145	154	1.7
400N*	200 ± 4.6 a	313 ± 6.8 a	172	172	1.6

N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly ($P \leq 0.10$). Fertilizer means within a given period followed by a different letter differ significantly ($P \leq 0.10$).

differed, indicating 45- and 72-percent gains (52 and 84 ft^3/ac/yr) as a result of N fertilization with 200N and 400N, respectively.

In period 2, mean PAI increased for all three treatments (table 6). For the 0N control, mean PAI (182 ft^3/ac/yr) was 60 percent greater in period 2 than in period 1, whereas PAI for 200N and 400N (280 and 313 ft^3/ac/yr) averaged 70 and 60 percent greater, respectively. Orthogonal contrasts indicated that gross PAI increased linearly with increasing N dosage in each decade. Gross PAI of fertilized plots in period 2 exceeded that of nonfertilized plots by 54 and 72 percent for 200N and 400N, respectively.

Mortality losses—

Cubic volume per acre—Although scant CVTS volume was lost to mortality in period 1 in the thinned stand, volume losses on fertilized plots increased in period 2 (table 7). In period 1, mean mortality losses among the three treatments were small and similar (0.0 to 1.8 ft^3/ac/yr). In period 2, however, mortality volume was significantly greater after fertilization (22 and 12 ft^3/ac/yr for 200N and 400N, respectively) than in the nonfertilized control (2 ft^3/ac/yr). The higher after-thinning density of plot 13 (794 trees per acre) compared to other plots in the thinned stand (467–635 trees per acre) may account for the observed greater mortality in the 200N treatment (table 1). Increased mortality in period 2 along with differences among N dosages explains the fertilizer-by-period interaction. Despite a greater volume loss to mortality in period 2, mortality losses in the thinned stand averaged only about 1 to 8 percent of gross PAI among the three treatments (table 7 vs. table 6).

Fertilization of thinned stands increased mortality volume.

Number and volume of dead trees—In period 1, adjusted mean losses of trees were small, and values were similar among the three treatments, ranging from 0 to 3 TPA per decade (table 8). Significantly more trees died in period 2 (second decade after treatment), averaging 71, 94, and 215 TPA per decade in the 0N, 200N, and

Table 7a—Analysis of covariance of mean annual losses in CVTS per acre by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	1.1	0.416
Rep. within F (Error 1)	5	—	—
Period (P)	1	149.8	<0.001
F × P	2	35.7	<0.001
Linear, period 1[a]	1	2.5	0.165
Linear, period 2	1	18.9	0.005
Covariate (starting CVTS)	1	3.8	0.100
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; CVTS = cubic volume of the total stem, inside bark; N = nitrogen; — = not appropriate.
[a] Linear contrasts with $P \leq 0.05$ are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 7b—Adjusted mean annual losses in CVTS per acre (mean ± standard error) by period after fertilization in the thinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	P1	P2	P1	P2	P2/P1
	- - - - - - *Ft³/ac/year* - - - - - -		- - - *Percent* - - -		
0N	1.8 ± 0.6 a	2.3 ± 6.1 b	100	100	1.3
200N*[b]	0 ± 0.6 a	22.4 ± 6.1 a	0	974	—
400N*	0.5 ± 0.6 a	11.9 ± 6.1 a	28	517	23.8

CVTS = cubic volume total stem, inside bark; — = not appropriate; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly ($P \leq 0.10$). Fertilizer means within a given period followed by a different letter differ significantly ($P \leq 0.10$).

400N treatments, respectively. Despite these apparent differences in tree losses in period 2, the three N dosages did not differ statistically. Moreover, tree losses did not increase linearly with N dosage.

We wondered whether the large losses in mortality volume in period 2 were related to the loss of more trees or to the loss of more volume per tree. Note that prior to fertilizer treatments, the starting density among all plots averaged 351 TPA (table 1). Over time, trees were added through ingrowth, and some of these died and were counted as mortality. We compared average volume of both dead and live trees from observed (unadjusted by covariance analysis) metrics of CVTS and TPA

Table 8—Analysis of covariance of mean 10-year losses in trees per acre (TPA) by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	2.0	0.234
Rep. within F (Error 1)	5	—	—
Period (P)	1	162.6	<0.001
F × P	2	3.4	0.103
Linear, period 1[a]	1	1.2	0.313
Linear, period 2	1	3.7	0.102
Covariate (starting TPA)	1	2.8	0.147
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.
[a] Linear contrasts with $P \leq 0.05$ are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 8b— Adjusted mean 10-year losses in trees per acre (mean TPA ± standard error) by period after fertilization in the thinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	**P1**	**P2**	**P1**	**P2**	**P2/P1**
	- - Trees/acre/decade - -		*- - - Percent - - -*		
0N[b]	3 ± 2.0	71 ± 32	100	100	24
200N	0 ± 2.0	94 ± 32	0	132	—
400N	1 ± 2.0	215 ± 32	33	303	215

N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/acre.
[b] Fertilizer-by-period means shown for information only. Main effect differences are described in the text.

(table 9). In both periods after fertilization, and in nearly all plots, average dead-tree volume was much less than the average volume of surviving trees. On average, smaller trees died. Both number and total volume of dead trees increased markedly in period 2, especially on fertilized plots. Average total volume of mortality was greatest on 200N plots (297 ft^3/ac/decade and 103 TPA) and was notably high in plots 12 and 13 where the death of some large trees was attributed to storm damage. We doubt that these losses were caused by fertilization at the 200N dosage. Also in period 2, losses on control plots averaged 93 TPA and 0.27 ft^3 per tree compared to 213 TPA and 0.56 ft^3 per tree after 400 lb N/ac was applied. We infer that application of 400 lb N/ac in the thinned stand increased both number and average volume of trees lost to mortality.

Table 9— Observed mean ending volume (CVTS) of live and dead trees by period after fertilization in the thinned stand at Rocky Brook, Washington

		Ending live CVTS				Dead tree count		Ending dead tree CVTS				CVTS dead/live ratio	
		Per acre		Per tree		Trees		Per acre		Per tree		Per tree	
Treatment[a]	Plot	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
		Cubicfeet				*Number/acre*		*Cubicfeet*					
0N	8	1,454	2,912	2.64	5.29	0	60	0	10	—	0.17	—	0.03
	9	1,635	3,400	2.60	5.40	10	170	37	54	3.70	0.32	1.42	0.06
	17	1,888	3,919	3.85	8.00	10	50	34	16	3.40	0.32	0.88	0.04
	Mean	1,660	3,410	3.03	6.23	7	93	24	27	3.55	0.27	1.15	0.04
200N	10	1,785	4,190	2.55	5.98	0	170	0	125	—	0.74	—	0.12
	12	2,400	5,032	5.45	11.44	0	40	0	227	—	5.68	—	0.50
	13	2,925	5,631	6.80	13.09	0	100	0	539	—	5.39	—	0.41
	Mean	2,370	4,951	5.78	10.17	0	103	0	297	—	3.94	—	0.34
400N	11	2,579	5,520	4.23	9.05	0	130	0	78	—	0.60	—	0.07
	15	2,321	5,151	3.36	7.46	0	270	0	97	—	0.36	—	0.05
	16	2,461	5,468	4.64	10.32	10	240	16	170	1.60	0.71	0.34	0.07
	Mean	2,450	5,380	4.08	8.94	3	213	5	115	1.60	0.56	0.34	0.06

CVTS = cubic volume of the total stem, inside bark; P1 = years 1 to 10; P2 = years 11 to 20; N = nitrogen.
[a]Application of 0, 200, or 400 lb N/acre.

Effects of additional nutrient elements in the thinned portion—
Prior to fertilization, average arithmetic mean d.b.h. was greatest for the 10 trees that were systematically selected for fertilization with NPKS (5.2 inches) and least for the trees selected in 400N plots (4.6 inches). This initial ranking of treatment means gradually reversed after fertilization. Basal area growth per tree was clearly enhanced after fertilization, and the 400N dosage as a single fertilizer was as stimulating as that same amount of N combined with PKS.

Addition of phosphorus, potassium, and sulfur did not increase stand response to nitrogen fertilization.

Covariance analysis indicated that the 400N application increased mean d.b.h. of subject trees both 10 and 20 years after treatment, but d.b.h. in the NPKS application did not differ significantly from the 0N treatment (table 10). An additional covariance analysis used mean annual growth in cross-sectional area at breast height (i.e., basal area increment) as the response variable. This more sensitive metric of response indicated a decline for the NPKS treatment in both growth and

Table 10a—Analysis of covariance of mean diameter at breast height (d.b.h.) 10 and 20 years after fertilization and basal area increment (BAI) after individual tree fertilization in the thinned stand at Rocky Brook, Washington

	D.b.h. (inches)			Basal area increment (inch^2)	
Source of variation	**D.f.**	**F-value**	**P**	**F-value**	**P**
N fertilizer (F)	2	7.6	0.003	6.1	0.007
Rep. within F (Error 1)	26	—	—	—	—
Period (P)	1	571.4	<0.001	4.3	0.049
P × F	2	2.8	0.076	11.5	<0.001
Covariate (starting d.b.h.)	1	123.3	<0.001	36.7	<0.001
Error 2	27	—	—		
Total (60-1)	59				

N = nitrogen; — = not appropriate.

Table 10b—Adjusted mean diameter at breast height (mean d.b.h. ± standard error) 10 and 20 years after fertilization and basal area increment (BAI ± standard error) after individual tree fertilization in the thinned stand at Rocky Brook, Washington

	d.b.h.		Relative to 0N			BAI				
Treatment[a]	**P1**	**P2**	**P1**	**P2**	**P2/P1**	**P1**	**P2**	**P1**	**P2**	**P2/P1**
	- - - - Inches - - - -		*- - Percent - -*			*- - Square inches per year - -*		*- - Percent - -*		
0N*[b]	7.4 ± 0.3 b	9.5 ± 0.3 b	100	100	1.28	2.5 ± 0.3 b	3.0 ± 0.3 b	100	100	1.2
400N*	8.5 ± 0.3 a	11.1 ± 0.3 a	115	117	1.31	3.8 ± 0.3 a	4.1 ± 0.3 a	152	137	1.1
400NPKS*	8.1 ± 0.3 b	10.2 ± 0.3 b	109	107	1.26	3.3 ± 0.3 b	2.9 ± 0.3 b	132	97	.9

d.b.h. = diameter at breast height; NPKS = nitrogen plus phosphorus, potassium, and sulfur; P1 = years 1 to 10; P2 = years 11 to 20.
[a]Application of 0 or 400 lb N/ac or 400 lb N/ac plus phosphorus, potassium, and sulfur.
[b]Asterisks (*) indicate period means for a given fertilizer rate that differ significantly ($P \leq 0.10$). Year means for BAI only differ significantly for 0N. Fertilizer means within a given period followed by a different letter differ significantly ($P \leq 0.10$).

response relative to control trees in the second decade when the P2/P1 ratio for the NPKS treatment averaged 0.9 compared to 1.2 for the control and 1.1 for the 400N treatment. We suspect that the smaller fertilized area around our individually fertilized NPKS trees was too limited to provide a treatment effect that was as lasting as that of the N-only trees located within a fertilized area of 0.2 ac.

Effects of Urea-N in the Nonthinned Stand

Live-stand volume—

Note there was no calibration period before fertilization in the nonthinned stand. Starting volume (CVTS) in the three nonthinned, nonfertilized plots located in the nearby LOGS study averaged slightly less than the means of fertilized plots. Average RD was also less (table 1). Live-stand volume of the nonthinned stand increased linearly in the 20 years since study establishment with a strong divergence between fertilized and nonfertilized treatments, but little differentiation between the 200N and 400N dosages (fig. 4). Stand volume in the nonthinned stand increased by about 50 percent in the second decade (P2/P1 = 1.4 to 1.5) (table 11). CVTS was greater in fertilized plots than in the nonfertilized control in each period, but there was no significant difference between N dosages. Both N dosages increased net accumulation of live-stand volume over that of the 0N control by about 30 percent at the end of both period 1 and period 2. In each decade, fertilizer response efficiency (gain in CVTS from fertilization/N dosage [lb/ac]) in the 200N treatment was over twice that observed in the 400N treatment, indicating more gain in live-stand volume per pound of applied N (table 12).

Gross periodic annual increment—

In the nonthinned stand, gross PAI of fertilized plots exhibited some variability and increased considerably in period 1, whereas PAI of nonfertilized plots was similar to that of the thinned stand (fig. 5). Covariance analysis indicated a significant fertilizer-by-period interaction (table 13). The covariate, initial CVTS, was highly significant ($P < 0.001$), and observed mean PAI for the 0N treatment was increased by about 13 percent after mathematical adjustment from the covariance analysis. This adjustment also lowered observed means for the fertilized plots, and thereby reduced estimated response to N.

In period 1 in the nonthinned stand, gross PAI for the 0N control averaged 223 ft^3/ac/yr compared to 320 and 330 ft^3/ac/yr for the 200N and 400N treatments, respectively. The 43 to 48 percent increases in gross growth from these N treatments, relative to the control, were statistically significant but not different from each other (table 13). The gross PAI response to fertilizer rate was linear in period 1 but not in period 2.

Table 11a—Analysis of covariance of mean live-stand volume (CVTS) 10 and 20 years after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	16.7	0.006
Rep. within F (Error 1)	5	—	—
Period (P)	1	897.0	<0.001
F × P	2	6.2	0.035
Linear, period 1[a]	1	19.4	0.004
Linear, period 2	1	26.7	0.002
Covariate (starting CVTS)	1	19.4	0.005
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; CVTS = cubic volume of the total stem, inside bark; N = nitrogen; — = not appropriate.
[a] Linear contrasts with $P \leq 0.05$ are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 11b—Adjusted mean live-stand volume (mean CVTS ± standard error) 10 and 20 years after fertilization in the nonthinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	P1	P2	P1	P2	P2/P1
	- - - - - - *Cubic feet/ac* - - - - - -		- - - - - - - *Percent* - - - - - -		*Ratio*
0N*[b]	4,094 ± 193 b	6,018 ± 229 b	100	100	1.5
200N*	5,280 ± 165 a	7,840 ± 206 a	129	130	1.5
400N*	5,379 ± 179 a	7,771 ± 217 a	131	129	1.4

CVTS = cubic volume of the total stem, inside bark; N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/acre.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly ($P \leq 0.10$). Fertilizer means within a given period followed by a different letter differ significantly ($P \leq 0.10$).

In period 2, gross growth in the nonfertilized plots increased by 10 percent but declined in the 200N and 400N treatments by 10 and 20 percent, respectively (table 13). The 20-percent reduction for the 400N treatment was statistically significant. In contrast, recall that gross PAI in the thinned stand accelerated in period 2 in both nonfertilized and fertilized plots (table 6). In the nonthinned stand, gross PAI in the 400N treatment (265 ft^3/ac/yr) did not differ significantly from either of the 0N or 200N treatments (246 and 290 ft^3/ac/yr, respectively). Gain in gross PAI from fertilization averaged 44 ft^3/ac/yr for 200N compared to 19 ft^3/ac/yr for 400N.

Table 12a—Analysis of covariance of fertilizer response efficiency by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	1	42.3	0.007
Rep. within F (Error 1)	3	—	—
Period (P)	1	21.9	.009
F × P	1	4.7	.096
Covariate (starting CVTS)	1	39.3	.003
Error 2	4	—	—
Total (12-1)	11		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate; CVTS = cubic volume of the total stem, inside bark.

Table 12b— Mean fertilizer response efficiency (mean ± standard error) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

			Relative to 200N		
Treatment[a]	P1	P2	P1	P2	P2/P1
	- - - - - *Ft^3/ac ÷ dosage* - - - - -		- - - *Percent* - - -		*Ratio*
200N*[b]	9.6 ± 0.7 a	12.8 ± 0.7 a			1.3
400N	4.4 ± 0.7 b	5.6 ± 0.7 b	46	44	1.3

Fertilizer response efficiency = CVTS gain ÷ dosage; CVTS = cubic volume of the total stem, inside bark; P1 = years 1 to 10; P2 = years 11 to 20.

[a] Application of 0, 200, or 400 lb N/ac.

[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

Table 13a—Analysis of covariance of mean annual gross volume growth (PAI) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	10.9	0.015
Rep × F (Error 1)	5	—	—
Period (P)	1	6.8	.040
F × P	2	7.5	.023
Linear, period 1[a]	1	16.6	.006
Linear, period 2	1	2.9	.138
Covariate (starting CVTS)	1	49.4	<.001
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate; PAI = periodic annual increment; CVTS = cubic volume of the total stem, inside bark.

[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 13b—Adjusted mean annual gross volume growth (mean PAI ± standard error) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Treatment[a]	P1	P2	Relative to 0N P1	Relative to 0N P2	P2/P1
	- - - - - *Feet³/acre/year* - - - - -		- - - *Percent* - - -		
0	223 ± 18 b	246 ± 7 b	100	100	1.1
200	320 ± 18 a	290 ± 6 a	143	118	0.9
400* [b]	330 ± 18 a	265 ± 7 ab	148	108	0.8

[a] Application of 0, 200, or 400 lb N/ac; P1 = years 1 to 10; P2 = years 11 to 20.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly ($P \leq 0.10$).
Fertilizer means within a given period followed by a different letter differ significantly ($P \leq 0.10$).

Mortality losses—

Cubic volume per acre—Covariance analysis indicated that the difference between the two periods was the only significant response for annual mortality in CVTS (table 14). In period 1, adjusted means of annual mortality in CVTS in the nonthinned stand were small and similar, ranging from about 10 to 17 ft^3/ac/yr among the three treatments, which did not differ significantly. Mortality losses in period 2 increased two- to three-fold for all treatments, but losses did not differ among the three fertilizer treatments. We suspect that high variability among replicate plots of each treatment constrained detection of significant differences among N dosages in either period. As a percentage of gross PAI, mortality losses in the second decade were 12, 13, and 15 percent of gross production of the 0N, 200N and 400N treatments, respectively. These are larger percentages than in the thinned stand, where CVTS mortality averaged only 1 to 8 percent of gross PAI (tables 6 and 7).

Fertilization of the nonthinned stand did not increase mortality volume.

Number and volume of dead trees—Note that mean starting density among these treatments in the nonthinned stand averaged 1,411 TPA in 1968 (table 1), and ingrowth trees—some of which died and were counted as mortality—were later recruited into the starting TPA. As expected, many trees died in the overstocked nonthinned stand in both 10-year periods (table 15). Losses were related linearly to N dosage in the first decade, but unrelated in the second. Covariance analysis indicated a significant fertilizer-by-period interaction ($P = 0.021$). Tree losses in nonfertilized plots more than doubled in the second decade and this increase was statistically significant. Tree losses in 400N plots exceeded those in the 0N control plots in the first decade, but not in the second decade when adjusted losses averaged 260 and 307 TPA, respectively.

Table 14a— Analysis of covariance of mean annual losses in CVTS per acre by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	3.1	0.132
Rep. within F (Error 1)	5	—	—
Period (P)	1	105.2	<0.001
F × P	2	0.6	0.576
Linear, period 1[a]	1	4.1	0.088
Linear, period 2	1	5.6	0.056
Covariate (starting CVTS)	1	10.1	0.019
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; CVTS = cubic volume of the total stem, inside bark; N = nitrogen; — = not appropriate; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 14b—Adjusted mean annual losses in CVTS per acre (mean ± standard error) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	P1	P2	P1	P2	P2/P1
	- - Cubic feet/acre/year - -		*- - - Percent - - -*		
0N[b]	9.8 ± 0.8	29.4 ± 4.2	100	100	3.0
200N	12.8 ± 0.8	38.8 ± 4.2	131	132	3.0
400N	17.2 ± 0.8	40.6 ± 4.2	176	138	2.4

CVTS = cubic volume of the total stem, inside bark; N = nitrogen; — = not appropriate; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Fertilizer-by-period means shown for information only. Main effect differences are described in the text.

We compared the average volume of dead and live trees as derived from CVTS and TPA (table 16). Among all treatments and in both decades, smaller than average-sized trees died. Similar numbers died on fertilized plots, but dead trees had more volume per tree in the second decade, especially on fertilized plots. In the first decade, dead tree volume averaged 0.67, 0.67, and 0.70 ft^3, respectively, for 0N, 200N, and 400N, and in the second decade volume averaged 0.90, 1.38, and 1.76 ft^3. This greater volume per tree, rather than greater numbers of dead trees, probably explains the greater losses in CVTS after fertilization of the nonthinned stand.

Considerably more mortality occurred in the nonthinned stand than in the thinned stand (fig. 6). Volume mortality in the nonthinned stand increased in proportion to

Table 15a—Analysis of covariance of mean 10-year losses in trees per acre by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	3.0	0.142
Rep. within F (Error 1)	5	—	—
Period (P)	1	16.4	0.007
F × P	2	7.9	0.021
Linear, period 1[a]	1	20.2	0.004
Linear, period 2	1	0.9	0.376
Covariate (starting TPA)	1	17.8	0.006
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 15b—Adjusted mean 10-year losses in trees per acre (mean ± standard error) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	P1	P2	P1	P2	P2/P1
	- - - - Trees/acre/decade - - - -		*- - - Percent - - -*		*Ratio*
0N*[b]	128 ± 12 b	307 ± 28 a	100	100	2.4
200N	189 ± 12 ab	277 ± 28 a	148	90	1.5
400N	280 ± 12 a	260 ± 28 a	219	85	0.9

N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/acre.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

the RD present at the start of each decade. This trend was especially apparent in the second decade when RD equaled or exceeded 100 in several of the fertilized plots. Mortality volume of the thinned stand was relatively independent of RD, probably because initial values at the start of each decade never exceeded RD 50.

Net periodic annual increment after mortality losses—

In the two decades after fertilization, volume lost to mortality was generally less than 5 percent of total gross growth in the thinned stand, but it was 8 to 10 percent in the nonthinned stand (fig. 7). Both mortality and net PAI averages were greater on fertilized plots.

Table 16—Observed ending mean volume (CVTS) of live and dead trees by period after fertilization in the nonthinned stand at Rocky Brook, Washington

		Ending live (CVTS)				Ending mortality						Dead/live ratio	
								CVTS				CVTS	
		Per acre		Per tree		Trees		Per acre		Per tree		Per tree	
Treatment[a]	Plot	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
		Cubic feet				*Number/acre*		*Cubic feet*				*Ratio*	
0N	14	3,545	5,189	2.20	3.93	80	310	65	228	0.81	0.74	0.37	0.19
	27	3,888	6,036	3.16	6.35	170	280	96	295	0.56	1.05	0.18	0.17
	29	3,470	5,451	2.99	6.05	270	260	175	236	0.65	.91	0.22	0.15
	Mean	3,630	5,560	2.78	5.44	173	283	112	253	0.67	.90	0.24	0.17
200N	1	4,428	6,583	4.02	8.33	140	310	121	346	0.86	1.12	0.21	0.13
	4	6,098	8,706	4.15	7.57	250	330	158	575	0.63	1.74	0.15	0.23
	5	5,704	8,621	4.32	8.06	240	260	125	333	0.52	1.28	0.12	0.16
	Mean	5,410	7,970	4.16	7.99	210	300	135	418	0.67	1.38	0.16	0.17
400N	2	5,731	8,080	4.55	8.69	410	330	392	503	0.96	1.52	0.21	0.17
	3	6,182	8,771	4.65	8.77	390	340	190	526	0.49	1.55	0.11	0.18
	6	5,213	7,450	6.52	10.49	140	160	93	352	0.66	2.20	0.10	0.21
	Mean	5,710	8,100	5.24	9.32	313	277	225	460	0.70	1.76	0.13	0.19

CVTS = cubic volume of the total stem, inside bark; N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/acre.

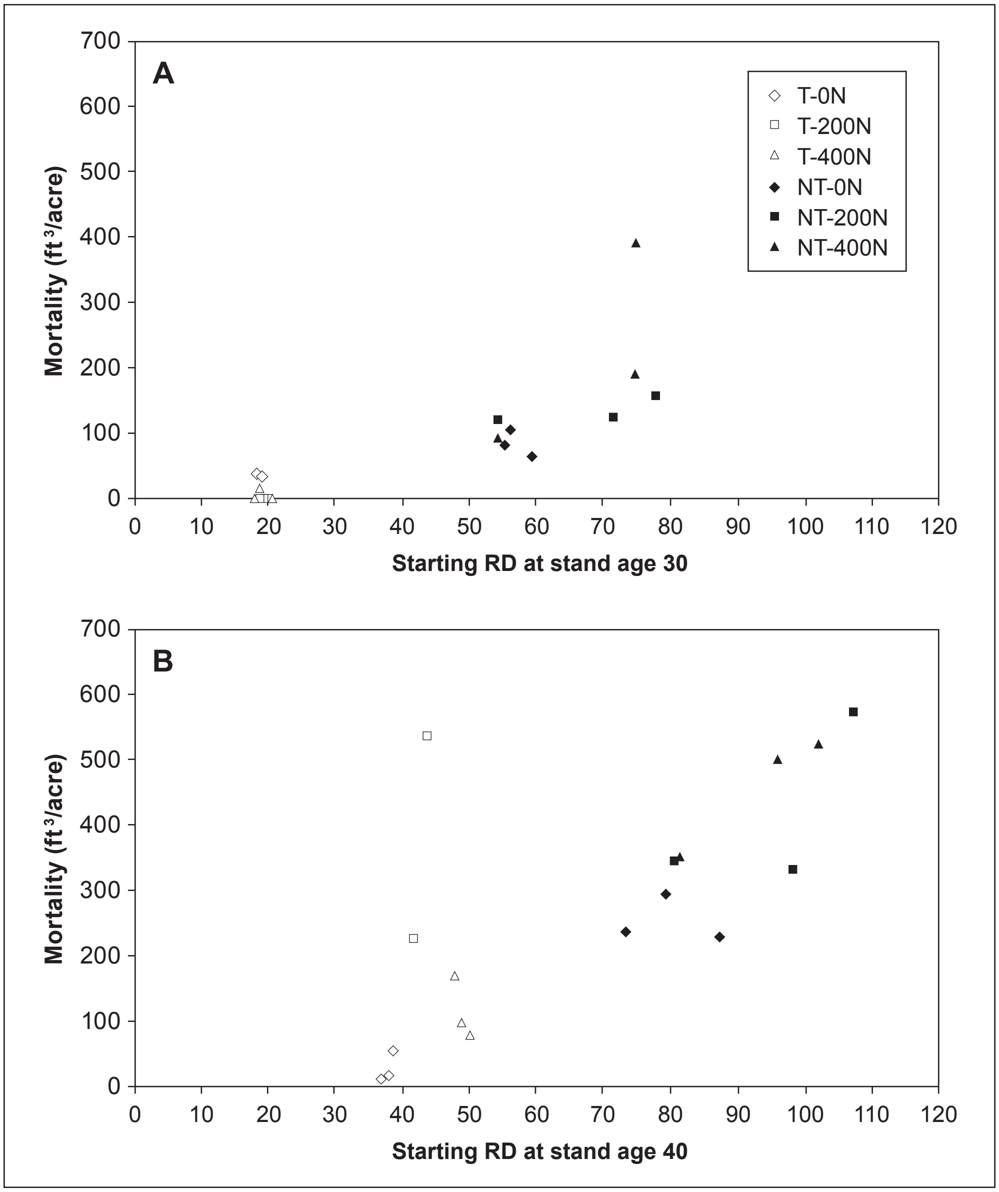

Figure 6—Total volume of dead trees in a 10-year period compared to relative density (RD) at the start of the period (A) the first decade after fertilization and (B) the second decade after fertilization, by thinning and fertilizer treatments (T = thinned and NT = nonthinned; 0N, 200N, and 400N indicate urea fertilizer rates of 0, 200, and 400 lb N/ac, respectively), Rocky Brook, Washington.

Mortality volume per decade was related to initial relative density.

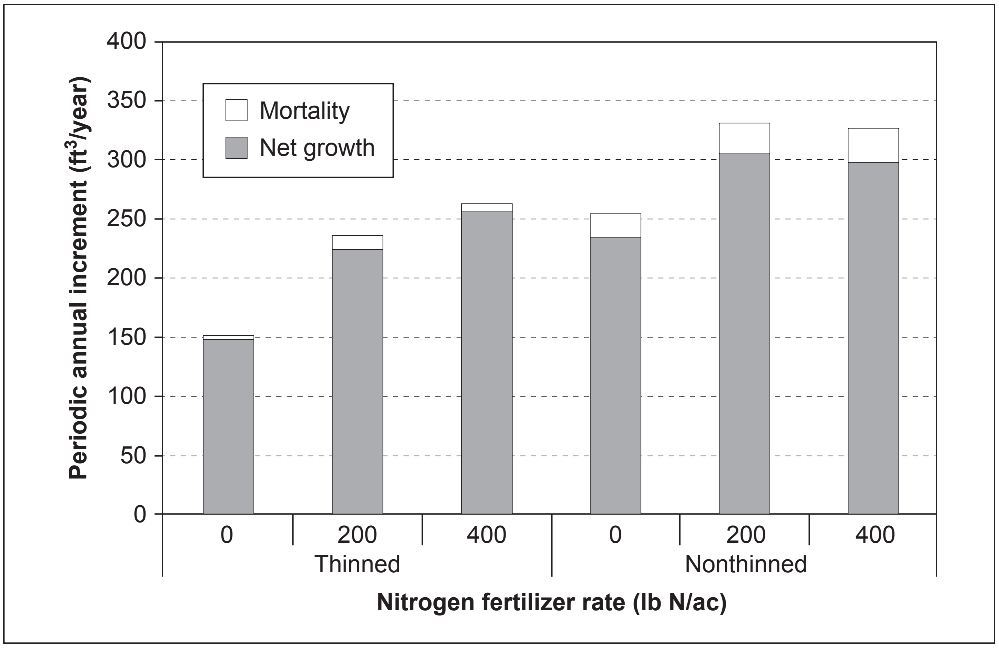

Figure 7—Mean annual mortality and net growth increment in live-stand volume (CVTS) in the two decades after fertilization, by thinning and fertilizing treatments, Rocky Brook, Washington. Note that mortality plus net increment equals gross periodic annual increment (PAI).

Stand Density and Species Composition by Trees per Acre

Thinned stand—

Initial TPA in the thinned stand at fertilization averaged 337, 360, and 357, respectively, for the 0N, 200N, and 400N treatments (table 17). Despite mortality losses, especially in period 2, unadjusted tree density on all plots increased in the 20 years after treatment as volunteers attained the 1.6-inch d.b.h. threshold for measurement. Stem density at the end of the second decade increased by 181 percent in the nonfertilized treatment compared to 128 percent after 200N and 146 percent after 400N. Although TPA in 0N plots increased in both periods, TPA increased in the first decade but decreased in the second decade for 200N and 400N plots, presumably the result of increasing competitive stress among trees. Percentage of Douglas-fir by TPA in 1968 averaged 96, 82, and 94, respectively, for the 0N, 200N, and 400N treatments (table 17). This percentage decreased slightly on most thinned plots over the next 20 years as mostly western hemlock volunteers were recruited to our inventory.

Nonthinned stand—

Before fertilization in the nonthinned stand, live trees per acre averaged 1,327, 1,470, and 1,437, respectively, for the 0N, 200N, and 400N treatments (table 17). In contrast to increasing tree numbers for all treatments in the thinned stand, tree numbers decreased over the next 20 years on all treatments in the

Table 17—Observed means of starting and ending trees per acre (TPA) by period after fertilization in the thinned and nonthinned stands at Rocky Brook, Washington

	All live trees				Douglas-fir/all			
	P1		P2		P1		P2	
Treatment[a]	Start	End	End	20-year change	Start	End	End	20-year change
	Number/acre			*Percent*				
Thinned:								
0N	337	557	610	181	96	92	89	-7
200N	360	523	460	128	82	78	83	1
400N	357	610	523	146	94	91	93	-1
Nonthinned:								
0N	1,327	1,333	1,057	-20	74	72	71	-4
200N	1,470	1,297	1,003	-32	77	77	77	0
400N	1,437	1,150	880	-39	78	79	79	1

N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/acre.

nonthinned stand. Net loss of TPA averaged 20 percent on 0N plots compared to 32- and 39-percent losses on 200N and 400N plots, respectively. Initially, percentage of Douglas-fir by TPA averaged 74, 77, and 78, respectively, for the 0N, 200N, 400N treatments. As in the thinned plots, the percentage of Douglas-fir in trees per acre decreased slightly on most plots over the next 20 years as the percentage of hemlock increased.

Species Composition by Basal Area

Thinned stand—

At stand age 30 years and 5 years after thinning, basal area per acre in the thinned stand averaged less than half that in the nonthinned stand. Of this total, Douglas-fir averaged 90 percent by basal area among the nine plots in the thinned stand and averaged 76 percent in the nonthinned stand, presumably because other species were not felled by thinning (table 1).

Total basal area per acre and Douglas-fir composition by basal area increased in both periods after treatment, especially in period 2 (table 18). Basal area of Douglas-fir increased by 60 to 70 percent in the second decade over the first decade (P2/P1 = 1.6 to 1.7). Increases in the percentage of basal area in western hemlock were smaller in the second decade (P2/P1 = 0.9 to 1.2). As a portion of total basal area for all species, the percentage of Douglas-fir by age 50 averaged 84 percent on control plots, but it was 5 to 7 percent greater on 200N and 400N plots, respectively.

Table 18a—Analysis of covariance of mean basal area per acre (BA) by species and period after fertilization in the thinned stand at Rocky Brook, Washington

		Douglas-fir		Hemlock	
Source of variation	D.f.	F-value	P	F-value	P
N fertilizer (F)	2	213.5	<0.001	0.2	0.789
Rep × F (Error 1)	5	—	—	—	—
Period (P)	1	567.7	<0.001	0.5	0.492
F × P	2	9.0	0.016	0.4	0.669
Linear, period 1[a]	1	81.1	<0.001	0.8	0.401
Linear, period 2	1	246.3	<0.001	0.2	0.676
Covariate (starting BA)	1	222.5	<0.001	604.4	<0.001
Error 2	6	—	—	—	—
Total (18-1)	17				

D.f. = degrees of freedom; N = nitrogen; — = not appropriate; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 18b—Adjusted mean basal area per acre (mean BA ± standard error) by species and period after fertilization in the thinned stand at Rocky Brook, Washington

	All species		Douglas-fir					Hemlock				
Treatment[a]	P1	P2	P1	P2	P1	P2	P2/P1	P1	P2	P1	P2	P2/P1
	Feet²/acre				*Percent*			*Feet²/acre*		*Percent*		
0N*[b]	88 c	141 c	72 ± 2.6 b	118 ± 2.6 c	82	84	1.6	12 ± 2.1	15 ± 2.1	14	11	1.2
200N*	107 b	165 b	93 ± 2.7 a	147 ± 2.7 b	87	89	1.6	12 ± 2.1	15 ± 2.1	11	9	1.2
400N*	122 a	193 a	105 ± 2.6 a	176 ± 2.6 a	86	91	1.7	15 ± 2.0	14 ± 2.0	12	7	0.9

[a] Application of 0, 200, or 400 lb N/ac; P1 = years 1 to 10; P2 = years 11 to 20.
[b] Asterisks (*) indicate all-species and Douglas-fir period means for a given fertilizer rate that differ significantly (P ≤ 0.10). All-species and Douglas-fir fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

After the first decade, average basal area of Douglas-fir on fertilized plots exceeded that on nonfertilized plots, but it did not differ between 200N and 400N (table 18). After the second decade, all three treatments differed statistically, and BA was the greatest in the 400N treatment for Douglas-fir only and for all species combined. In each decade, Douglas-fir basal area increased linearly with fertilizer rate. Basal area of western hemlock averaged less than 15 percent of total basal area per acre in both periods. Variation in hemlock basal area was not related to N application or period.

Nonthinned stand—

In the nonthinned stand, the amount of Douglas-fir and hemlock calculated as a percentage of total basal area for all species changed very little in two decades (table 19). By age 50, Douglas-fir averaged 75 to 79 percent and hemlock averaged 19 to 22 percent of the total basal area in the nonthinned stand. The percentage of Douglas-fir averaged 2 to 4 percent greater on fertilized plots than nonfertilized plots.

As also measured in the thinned stand, total basal area per acre for all species combined increased in both decades, especially in the second decade (table 19). Although the fertilizer-by-period interaction was not significant for Douglas-fir basal area, both fertilizer and period main effects were significant. Averaged across periods, basal area of Douglas-fir was 175, 191, and 191 ft^2/ac for the 0N, 200N, and 400N treatments, respectively, and it was significantly greater in fertilized plots than in the nonfertilized control. Averaged across fertilizer rates, Douglas-fir basal area was significantly greater in period 2 (203 ft^2/ac) than in period 1 (169 ft^2/acre). Only period main effects were significant for hemlock basal area (44 vs. 54 ft^2/ac in periods 1 and 2, respectively).

Table 19a—Analysis of covariance of mean basal area per acre (BA) by species and period after fertilization in the nonthinned stand at Rocky Brook, Washington

		Douglas-fir		Hemlock	
Source of variation	**D.f.**	**F-value**	**P**	**F-value**	**P**
N fertilizer (F)	2	4.1	0.09	1.4	0.339
Rep × F (Error 1)	5	—	—	—	—
Period (P)	1	218.3	<0.001	57.4	<0.001
F × P	2	1.1	0.404	0.8	0.511
Linear, period 1[a]	1	5.3	0.062	0.0	0.982
Linear, period 2	1	5.2	0.064	1.2	0.312
Covariate (starting BA)	1	71.5	0.001	80.1	<0.001
Error 2	6	—	—	—	—
Total (18-1)	17				

D.f. = degrees of freedom; N = nitrogen; — = not appropriate; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 19b—Mean basal area per acre (mean BA ± standard error) by species and period after fertilization in the nonthinned stand at Rocky Brook, Washington

	All species		Douglas-fir					Hemlock				
Treatment[a]	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**	**P2/P1**	**P1**	**P2**	**P1**	**P2**	**P2/P1**
	Square feet per acre				*Percent*			*Square feet per acre*		*Percent*		
0N[b]	208	254	160 ± 4.9	191 ± 4.9	77	75	1.2	43 ± 2.4	55 ± 2.4	21	22	1.3
200N	224	271	172 ± 4.8	210 ± 4.8	77	77	1.2	47 ± 2.4	57 ± 2.4	21	21	1.2
400N	223	263	176 ± 4.9	207 ± 4.9	79	79	1.2	43 ± 2.4	51 ± 2.4	19	19	1.2

[a] Application of 0, 200, or 400 lb N/acre; P1 = years 1 to 10; P2 = years 11 to 20.
[b] Fertilizer-by-period means shown for information only. Main effect differences are described in the text.

Relative Density

Recall that relative density (RD) is computed from basal area per acre, TPA, and quadratic mean d.b.h. (QMD), and that QMD is derived from TPA and basal area per acre (Curtis 1982). Consequently, changes in tree numbers and stand basal area over time result in changes in RD.

Thinned stand—

Relative density in 1968 was similar among thinned plots and averaged 19 for pending 0N, 200N, and 400N treatments (table 1). Although this narrow range of starting RDs before fertilization resulted in a nonsignificant covariate (P = 0.98), we still used covariance to adjust for small differences among plots in prefertilization RD (table 20). In period 1, mean initial RD doubled to 38 on

Table 20a—Analysis of covariance of mean relative density (RD) by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	81.9	<0.001
Rep. within F (Error 1)	5	—	—
Period (P)	1	1,397.1	<0.001
F × P	2	3.7	0.091
Linear, period 1[a]	1	109.0	<0.001
Linear, period 2	1	120.4	<0.001
Covariate (starting RD)	1	0	0.980
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.

[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 20b—Adjusted mean relative density (mean RD ± standard error) by period after fertilization in the thinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	**P1**	**P2**	**P1**	**P2**	**P2/P1**
	- - - - Relative density - - - - -		*- - - Percent - - -*		
0N*[b]	38 ± 0.8c	55 ± 0.8 b	100	100	1.4
200N*	43 ± 0.8b	58 ± 0.8 b	113	105	1.3
400N*	49 ± 0.8a	67 ± 0.8 a	129	122	1.4

N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.

[a] Application of 0, 200, or 400 lb N/ac.

[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

nonfertilized plots. Concurrently, mean RDs averaged 13 and 29 percent greater than that after the 200N and 400N treatments, respectively. Relative density differed significantly among each of the three fertilizer treatments, and there was a linear trend with increasing fertilizer rate. In the second period, RD increased in all treatments (P2/P1= 1.3 to 1.4). By the end of period 2, RD was 67 in the 400N plots, and this exceeded the RD of both the 0N control and the 200N treatment (RD of 55 and 58, respectively). The lower RD at stand age 50 years for the 200N treatment is probably explained by storm-caused mortality losses of some large trees in period 1 in plots previously fertilized with 200N (fig. 6b). The 22 percent greater RD in the 400N treatment was statistically significantly different from the control treatment and notably equaled the starting RD in the nonthinned stand 20 years earlier (table 1).

Twenty years after fertilization, relative density of the thinned stand equaled the starting density of the nonthinned stand.

Nonthinned stand—
In 1968 and before fertilization, nonthinned stand RD averaged 59, 70, and 71, respectively, for the 0N, 200N, and 400N treatments (table 1). Note that RD in nonfertilized plots initially averaged less than in fertilized plots, and the covariance analysis adjusted for this difference. Large starting RDs in the nonthinned stand forecasted subsequent loss of trees and their cumulative volume in subsequent decades (fig. 6).

Covariance analysis indicated that starting RD was a significant covariate and the fertilizer-by-period interaction was nonsignificant (table 21; P = 0.346). Real differences were observed between the two periods but not among fertilizer treatments. Averaged across fertilizer rates, RD was significantly greater in period 2 than in period 1 (RD = 96 and 89, respectively). Adjusted mean RD for fertilized plots were similar to control plots in both 10-year periods. To explain the net effect of fertilization on RD, urea increased growth in basal area (the numerator in RD) (tables 18 and 19), but it also increased QMD (the denominator in RD) through growth and change in tree numbers, especially for trees of below-average d.b.h. (tables 8 and 15).

By stand age 50 years, adjusted RDs on nonfertilized plots averaged 94 in the nonthinned stand, compared to 55 in the thinned stand (tables 20 and 21). For the 200N and 400N treatments, RDs in the nonthinned stand averaged RD 100 and 94, respectively, compared to RD 58 and 67 in the thinned stand.

Table 21a—Analysis of covariance of mean relative density (RD) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	1.1	0.411
Rep × F (Error 1)	5	—	—
Period (P)	1	77.9	<0.001
F × P	2	1.3	0.346
Linear, period 1[a]	1	0.3	0.621
Linear, period 2	1	0.0	0.990
Covariate (starting RD)	1	38.4	<0.001
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; N = nitrogen; — = not appropriate; RD = relative density.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 21b—Adjusted mean relative density (RD ± standard error) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	P1	P2	P1	P1	P2/P1
			- - - Percent - - -		
0N[b]	87 ± 2.7	94 ± 2.7	100	100	1.1
200N	92 ± 2.4	100 ± 2.4	106	106	1.1
400N	89 ± 2.4	94 ± 2.4	102	100	1.1

N = nitrogen; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Fertilizer-by-period means shown for information only. Main effect differences are described in the text.

The 100 Largest Trees Per Acre

Diameter at breast height—

Before fertilization at stand age 30 years, mean d.b.h. of the 100 largest trees per acre in the three treatments in both thinned and nonthinned stands did not differ (tables 22 and 23). Surprisingly, d.b.h. averaged about 1 inch smaller in the thinned stand than in the nonthinned, probably because some large trees were felled in the intensive precommercial thinning about 5 years earlier.

In the thinned stand, fertilization increased average d.b.h. of the 100 largest trees by 11 to 18 percent over the two decades after treatment (table 22). In both decades, the 400N treatment stimulated a greater increase in average d.b.h. than did 200N treatment. The relationship of d.b.h. to fertilizer rate was linear in both decades. Regardless of treatment, d.b.h. increased about 30 percent more in the second decade than in the first decade.

In the nonthinned stand, increases in average d.b.h. of the 100 largest trees after fertilization were less than in the thinned stand (tables 22 and 23). In contrast to the results from the thinned stand, the fertilizer-by-period interaction was not significant in the nonthinned stand. Instead, both period and fertilizer main effects were significant. Regardless of treatment, adjusted mean d.b.h. increased about 20 percent more in the second decade than in the first, which is a lower percentage and absolute increase than in the thinned stand. When averaged across both periods, mean d.b.h. for trees treated with 400 lb N/ac (10.8 inches) was

Table 22a—Analysis of covariance of mean diameter at breast height (d.b.h.) of the 100 largest trees per acre (by d.b.h.) by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	79.5	<0.001
Rep × F (Error 1)	5	—	—
Period (P)	1	2,430.4	<.001
F × P	2	11.3	.009
Linear, period 1[a]	1	88.8	<.001
Linear, period 2	1	178.8	<.001
Covariate (starting d.b.h.)	1	95.8	<.001
Error 2	6	—	—
Total (18-1)	17		

Note: 100 TPA = 10 trees/0.1 ac plot. Of these 10 trees, the size of five to nine was measured, not estimated.

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.

[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 22b—Adjusted mean diameter at breast height (mean d.b.h. ± standard error) of the 100 largest trees per acre (by d.b.h.) prior to treatment and by period after fertilization in the thinned stand at Rocky Brook, Washington

				Relative to 0N		
Treatment[a]	P0	P1	P2	P1	P2	P2/P1
	- - - - - - - - - - Inches - - - - - - - - - -			*- - - Percent - - -*		
0N*[b]	6.0 a	8.1 ± 0.1 c	10.3 ± 0.1 c	100	100	1.3
200N*	5.6 a	9.0 ± 0.1 b	11.5 ± 0.1 b	111	112	1.3
400N*	5.7 a	9.5 ± 0.1 a	12.2 ± 0.1 a	117	118	1.3

N = nitrogen; P0 = prior to treatment; P1 = years 1 to 10; P2 = years 11 to 20.

[a] Application of 0, 200, or 400 lb N/ac.

[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

Table 23a—Analysis of covariance of mean diameter at breast height (d.b.h.) of the 100 largest trees per acre (by d.b.h.) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	5.2	0.061
Rep × F (Error 1)	5	—	—
Period (P)	1	2,061.3	<0.001
F × P	2	0.6	0.576
Linear, period 1[a]	1	8.5	0.027
Linear, period 2	1	11.0	0.016
Covariate (starting d.b.h.)	1	91.4	<0.001
Error 2	6	—	—
Total (18-1)	17		

Note: 100 TPA = 10 trees/0.1 ac plot. Of these 10 trees, the size of five to nine was measured, not estimated.
D.f. = degrees of freedom; N = nitrogen; — = not appropriate.
[a] Linear contrasts with $P \leq 0.05$ are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 23b—Adjusted mean diameter at breast height (mean d.b.h. ± standard error) of the 100 largest trees per acre (by d.b.h.) by period after fertilization in the nonthinned stand at Rocky Brook, Washington

				Relative to 0N		
Treatment[a]	P0	P1	P2	P1	P2	P2/P1
	Inches			*Percent*		
0N[b]	7.3 a	9.3 ± 0.1	11.0 ± 0.1	100	100	1.2
200N	6.5 a	9.6 ± 0.1	11.4 ± 0.1	103	104	1.2
400N	7.0 a	9.8 ± 0.1	11.7 ± 0.1	105	106	1.2

N = nitrogen; P0 = prior to treatment; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Fertilizer-by-period means shown for information only. Main effect differences are described in the text.

Fertilizer increased the d.b.h. of the largest trees by 12 to 18 percent in thinned stands but only 3 to 6 percent in nonthinned stands.

greater than the nonfertilized control trees (10.1 inches) by 7 percent, but did not differ from trees treated with 200 lb N/ac (10.5 inches). As in the thinned stand, the relation between mean d.b.h. of the 100 largest trees and N dosage was linear in both decades.

For the total 20-year period, mean values for these crop trees increased by 4.3 to 6.5 inches in the thinned stand compared to 3.7 to 4.9 inches in the nonthinned stand. Fertilizer increased d.b.h. by 12 to 18 percent in thinned stands compared to 3 to 6 percent in nonthinned stands.

Height—

Before fertilization in both thinned and nonthinned stands, mean height of the 100 largest trees per acre did not differ among the pending fertilizer treatments (tables 24 and 25). Starting height of these 100 largest trees at age 30 years averaged 7 to 13 ft taller in the nonthinned stand than in the thinned stand, probably a consequence of somewhat poorer soil quality in the thinned stand and the removal of some larger trees when the stand was intensively thinned.

Table 24a—Analysis of covariance of mean height of the 100 largest trees per acre by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	9.7	0.019
Rep × F (Error 1)	5	—	—
Period (P)	1	2,866.0	<0.001
F × P	2	35.8	<0.001
Linear, period 1[a]	1	3.6	0.105
Linear, period 2	1	32.4	0.001
Covariate (starting d.b.h.)	1	56.7	<0.001
Error 2	6	—	—
Total (18-1)	17		

Note: 100 TPA = 10 trees/0.1 ac plot. Of these 10 trees, the size of five to nine was measured, not estimated.

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.

[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 24b—Adjusted mean height (mean ± standard error) of the 100 largest trees per acre prior to treatment and by period after fertilization in the thinned stand at Rocky Brook, Washington

				Relative to 0N		
Treatment[a]	P0	P1	P2	P1	P2	P2/P1
	- - - - - - - - - - - *Feet* - - - - - - - - - - -			- - - *Percent* - - -		
0N*[b]	36 a	53 ± 1.1 a	67 ± 1.1 b	100	100	1.3
200N*	38 a	56 ± 1.1 a	75 ± 1.1 a	106	112	1.3
400N*	35 a	56 ± 1.1 a	75 ± 1.1 a	106	112	1.3

N = nitrogen; P0 = prior to treatment; P1 = years 1 to 10; P2 = years 11 to 20.

[a] Application of 0, 200, or 400 lb N/ac.

[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

Table 25a—Analysis of covariance of mean height of the 100 largest trees per acre by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	4.6	0.074
Rep × F (Error 1)	5	—	—
Period (P)	1	307.4	<0.001
F × P	2	0.5	0.636
Linear, period 1[a]	1	9.5	0.022
Linear, period 2	1	4.9	0.069
Covariate (starting d.b.h.)	1	18.1	0.005
Error 2	6	—	—
Total (18-1)	17		

Note: 100 TPA = 10 trees/0.1-ac plot. Of these 10 trees, size of five to nine was measured, not estimated.

D.f. = degrees of freedom; N = nitrogen; — = not appropriate.

[a] Linear contrasts with $P \leq 0.05$ are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 25b—Adjusted mean height (mean ± standard error) of the 100 largest trees per acre prior to treatment and by period after fertilization in the nonthinned stand at Rocky Brook, Washington

				Relative to 0N		
Treatment[a]	P0	P1	P2	P1	P2	P2/P1
	- - - - - - - - *Feet* - - - - - - - -			- - - *Percent* - - -		*Ratio*
0[b]	44	61 ± 1.4	76 ± 1.4	100	100	1.2
200	45	64 ± 1.4	79 ± 1.4	105	104	1.2
400	48	67 ± 1.4	81 ± 1.4	110	107	1.2

N = nitrogen; P0 = prior to treatment; P1 = years 1 to 10; P2 = years 11 to 20.

[a] Application of 0, 200, or 400 lb N/ac.

[b] Fertilizer-by-period means shown for information only. Main effect differences are described in the text.

The fertilizer-by-period interaction was significant for thinned stands because average height of the 100 largest trees did not differ among treatments in period 1 but did differ in period 2 (table 24). Fertilized trees averaged about 12 percent taller than nonfertilized trees after the second decade, but there was no significant difference between the 200N and 400N dosages. Regardless of treatment, mean height in the second decade was about 30 percent greater than in the first decade. Change in mean height of crop trees in 20 years averaged 31, 37, and 40 ft, respectively, for the 0N, 200N and 400N treatments.

In the nonthinned stand, the fertilizer-by-period interaction was not significant; however, main effects of fertilizer and period were significant (table 25).

Averaged across periods, heights of the largest Douglas-fir were 69, 71, and 74 ft for the 0N, 200N, and 400N treatments, respectively, and height differed significantly between 0N and 400N. Averaged across fertilizer rates, height was significantly greater in the second decade (79 ft) than in the first decade (64 ft). The percentage increase in mean heights in the second period was slightly less than in the thinned stand.

At stand age 50 years, mean heights of crop trees in the thinned stand (67, 75, and 75 ft tall for 0N, 200N and 400N, respectively) averaged 4 to 9 ft shorter than those in the nonthinned stand (76, 79, and 81 ft, respectively). In the 20-year period, means of crop tree height increased by 31 to 40 ft in the thinned stand and by 32 to 34 ft in the nonthinned stand. In the two decades after fertilization, mean height of fertilized plots in the thinned stand increased by 24 percent (mean of the 200N and 400N treatments) more than nonfertilized. The gain over initial height from fertilization in the nonthinned stand averaged only 5 percent, in part because starting height was greater.

In both thinned and nonthinned stands, fertilization increased the height of the largest trees.

Height to live crown—

Prior to fertilization in both the thinned and nonthinned stands, the mean height to live crown (HLC) did not differ among the three N fertilizer treatments, and ranged from 8 to 11 ft in the thinned stand (table 26) and 12 to 13 ft in the nonthinned stand (table 27) ($P = 0.281$ and 0.844, respectively; ANOVA output not shown). Thus, crown base averaged 2 to 4 ft higher from the ground in the more densely stocked, nonthinned stand.

In the thinned stand, average HLC of the 100 largest trees elevated nearly three-fold more rapidly in the second decade than in the first (table 26). Specifically, mean crown height elevated 4 to 6 ft among all treatments in period 1 and 23 to 26 ft in period 2. Although the fertilizer-by-period interaction was significant ($P = 0.031$), fertilization had no detectable effect on mean HLC.

Ten years after fertilization of the nonthinned stand, height to live crown base of the 100 largest trees per acre already averaged 10 to 16 ft higher than those in the thinned stand (table 27 vs. table 26). Crowns receded faster in the second decade than the first, but not as rapidly as in the thinned stand. The P2/P1 ratio in the nonthinned stand was 1.6 to 2.0 compared to 2.7 to 2.9 in the thinned stand (table 27 vs. table 26). Covariance analysis for the nonthinned stand indicated a marginally significant fertilizer-by-period interaction ($P = 0.098$), probably because fertilization increased the rate of crown recession in the second decade, particularly in the 200N treatment. However, as was found for the thinned stand, multiple comparisons of HLC in the nonthinned stand failed to detect a significant effect attributable to fertilization.

Table 26a—Analysis of covariance of mean height to live crown (HLC) of the 100 largest trees per acre by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	2.1	0.219
Rep × F (Error 1)	5	—	—
Period (P)	1	2,963.5	<0.001
F × P	2	6.6	0.031
Linear, period 1[a]	1	1.1	0.340
Linear, period 2	1	4.6	0.075
Covariate (starting HLC)	1	7.0	0.038
Error 2	6	—	—
Total (18-1)	17		

Note: 100 TPA = 10 trees/0.1 ac plot. Of these 10 trees, size of five to nine was measured, not estimated.
D.f. = degrees of freedom; N = nitrogen; — = not appropriate.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 26b—Adjusted mean height to live crown (mean HLC ± standard error) of the 100 largest trees per acre prior to treatment and by period after fertilization in the thinned stand at Rocky Brook, Washington

				Relative to 0N		
Treatment[a]	P0	P1	P2	P1	P2	P2/P1
	- - - - - - - - - - *Feet* - - - - - - - - - -			- - - *Percent* - - -		
0N*[b]	8 a	12 ± 1.3 a	35 ± 1.9 a	100	100	2.9
200N*	11 a	15 ± 1.3 a	40 ± 1.9 a	125	114	2.7
400N*	8 a	14 ± 1.3 a	40 ± 1.9 a	117	114	2.9

N = nitrogen; P0 = prior to treatment; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

At stand age 50 years, height to live crown in the nonthinned stand averaged 43 ft for 0N and 49 ft for both the 200N and 400N treatments compared to 35 ft for 0N and 40 ft for both the 200N and 400N treatments in the thinned stand. In the 20-year period after fertilization, means of crop tree HLC increased by 31 to 37 ft in the nonthinned and by 27 to 32 ft in the thinned stand. This faster recession of crowns in the nonthinned stand is expected and consistent with denser stocking of trees and greater RD.

Table 27a—Analysis of covariance of mean height to live crown (HLC) of the 100 largest trees per acre by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	6.6	0.039
Rep × F (Error 1)	5	—	—
Period (P)	1	354.7	<0.001
F × P	2	3.5	0.098
Linear, period 1[a]	1	4.1	0.089
Linear, period 2	1	11.2	0.016
Covariate (starting HLC)	1	1.9	0.221
Error 2	6	—	—
Total (18-1)	17		

Note: 100 TPA = 10 trees/0.1 ac plot. Of these 10 trees, size of five to nine was measured, not estimated.
D.f. = degrees of freedom; N = nitrogen; — = not appropriate.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 27b—Adjusted mean height to live crown (mean HLC ± standard error) of the 100 largest trees per acre prior to treatment and by period after fertilization in the nonthinned stand at Rocky Brook, Washington

				Relative to 0N		
Treatment[a]	P0	P1	P2	P1	P2	P2/P1
	- - - - - - - - - *Feet* - - - - - - - - -			- - - *Percent* - - -		
0N*[b]	12 a	26 ± 1.5 a	43 ± 1.2 a	100	100	1.7
200N*	13 a	25 ± 1.5 a	49 ± 1.2 a	96	114	2.0
400N*	12 a	30 ± 1.5 a	49 ± 1.2 a	115	114	1.6

N = nitrogen; P0 = prior to treatment; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

Live crown ratio—

Change in live crown ratio (LCR) expresses the net result of differential increases in tree height and HLC. Before fertilization in the thinned stand, mean LCR was 0.77, 0.71, and 0.77 for the 0N, 200N, and 400N treatments, respectively (table 28). An ANOVA of pre-fertilization values of LCR suggested that potential differences existed among treatments (P = 0.080; ANOVA output not shown); however, multiple comparisons failed to detect them. After period 1, mean ratios ranged from 0.74 to 0.76 but declined to 0.45 to 0.49 by stand age 50 years (table 28). Only the main effect of period was statistically significant (P < 0.001); LCR declined much more rapidly in the second decade than in the first. Fertilization had no real effect on LCR in either decade.

Table 28a—Analysis of covariance of mean live crown ratio (LCR) of the 100 largest trees per acre by period after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	0.4	0.681
Rep × F (Error 1)	5	—	—
Period (P)	1	1,374.3	<0.001
F × P	2	1.8	0.245
Linear, period 1[a]	1	.6	0.460
Linear, period 2	1	.5	0.507
Covariate (starting LCR)	1	5.1	0.066
Error 2	6	—	—
Total (18-1)	17		

Note: 100 TPA = 10 trees/0.1 ac plot. Of these 10 trees, size of five to nine was measured, not estimated.
D.f. = degrees of freedom; N = nitrogen; — = not appropriate.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 28b—Adjusted mean live crown ratio (mean LCR ± standard error) of the 100 largest trees per acre prior to treatment and by period after fertilization in the thinned stand at Rocky Brook, Washington

				Relative to 0N		
Treatment[a]	P0	P1	P2	P1	P2	P2/P1
	Ratio			*Percent*		
0N[b]	0.77 a	0.76 ± 0.02	0.47 ± 0.02	100	100	0.6
200N	0.71 a	0.75 ± 0.02	0.49 ± 0.02	99	104	0.7
400N	0.76 a	0.74 ± 0.02	0.45 ± 0.02	97	96	0.6

N = nitrogen; P0 = prior to treatment; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Fertilizer-by-period means shown for information only. Main effect differences are described in the text.

Fertilization had no effect on live crown ratio.

In the nonthinned stand before fertilization, mean LCR did not differ among the three treatments, which ranged from 0.71 to 0.74 (P = 0.835; ANOVA output not shown). After period 1, mean LCR ranged for 0.56 to 0.61 but averaged only 0.37 to 0.42 after period 2 (table 29). Again, fertilization had no real effect in either decade. The marginally significant fertilizer-by-period interaction is likely explained by the trend of mean LCR for the 200N treatment, which had the largest LCR in period 1 and the smallest in period 2.

At stand age 50 years, means of LCR ranged from 0.45 to 0.49 in the thinned stand and from 0.37 to 0.42 in the nonthinned stand (fig. 8). The larger LCR in the

Table 29a—Analysis of covariance of mean live crown ratio (LCR) of the 100 largest trees per acre by period after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	0.4	0.699
Rep × F (Error 1)	5	—	—
Period (P)	1	195.1	<.001
F × P	2	3.5	.097
Linear, period 1[a]	1	.4	.558
Linear, period 2	1	.6	.460
Covariate (starting LCR)	1	3.1	.127
Error 2	6	—	—
Total (18-1)	17		

Note: 100 TPA = 10 trees/0.1 ac plot. Of these 10 trees, size of five to nine was measured, not estimated.
D.f. = degrees of freedom; N = nitrogen; — = not appropriate.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant; period 1 = 1 to 10 years and period 2 = 11 to 20 years after fertilization.

Table 29b—Adjusted mean live crown ratio (mean LCR ± standard error) of the 100 largest trees per acre prior to treatment and by period after fertilization in the nonthinned stand at Rocky Brook, Washington

				Relative to 0N		
Treatment[a]	P0	P1	P2	P1	P2	P2/P1
	- - - - - - - *Ratio* - - - - - - -			- - - *Percent* - - -		*Ratio*
0N*[b]	0.72 a	0.58 ± 0.02 a	0.42 ± 0.02 a	100	100	0.7
200N*	0.71 a	0.61 ± 0.02 a	0.37 ± 0.02 a	105	88	0.6
400N*	0.74 a	0.56 ± 0.02 a	0.40 ± 0.02 a	97	95	0.7

N = nitrogen; P0 = prior to treatment; P1 = years 1 to 10; P2 = years 11 to 20.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Asterisks (*) indicate period means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given period followed by a different letter differ significantly (P ≤ 0.10).

thinned stand likely resulted from the combination of greater height growth and slower upward recession of the crown (tables 24 and 26 vs. tables 25 and 27). Larger LCR in the less densely stocked thinned stand is likely to support faster growth of crop trees in the future.

Sample trees used for the 100 largest trees per acre changed somewhat between stand age 30 and 50 years because some of the original trees were damaged and replaced by other trees. Average values for total height, height to live crown, and live crown ratio also changed (fig. 8). Initial variation among means of fertilizer treatments at age 30 is evident, especially in the thinned stand.

Both crown length and live crown ratio declined during the 20-year period of measurement.

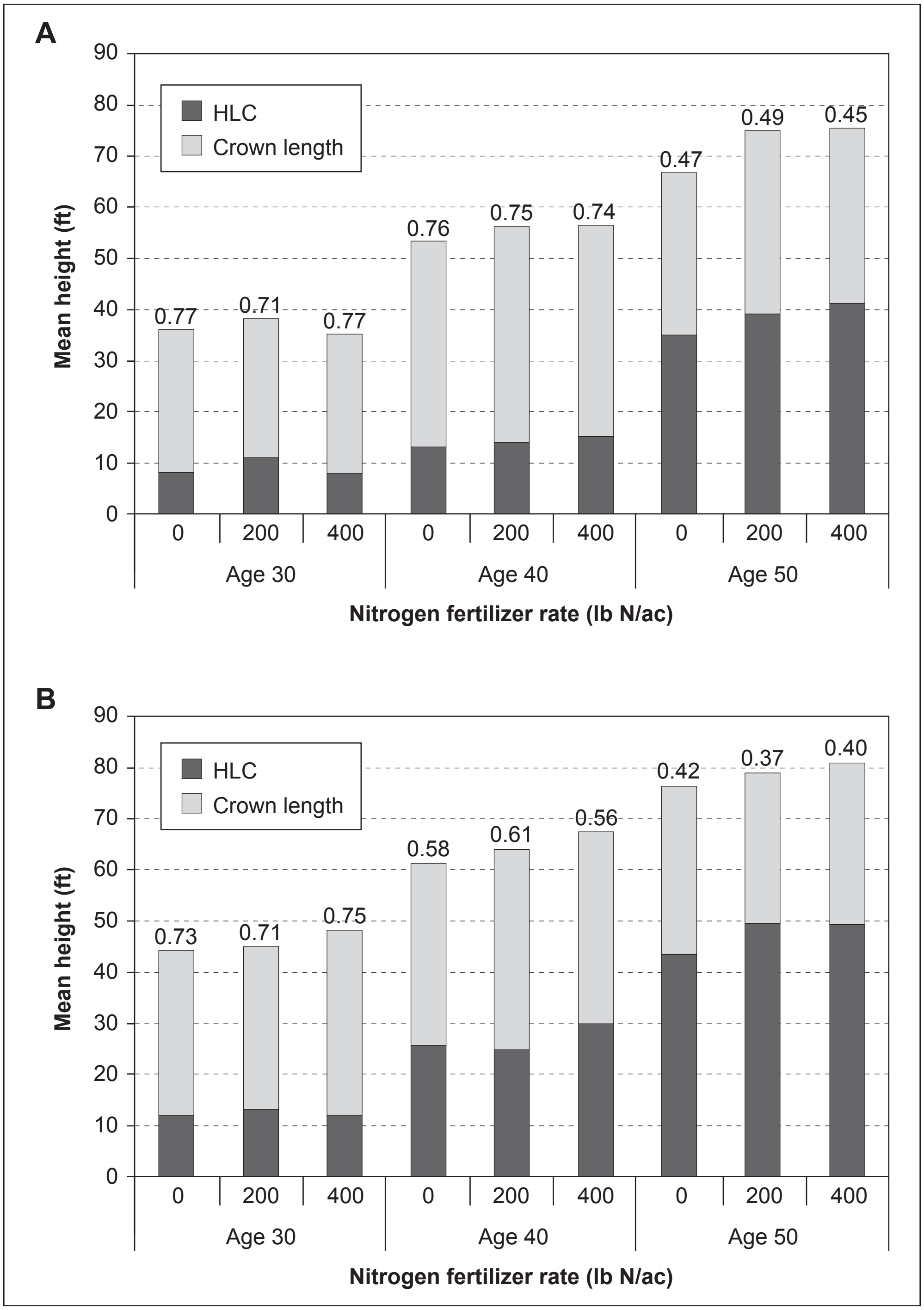

Figure 8—Average total height (top of bars), height to live crown (HLC), and live crown ratio (numbers on top of bars) of the 100 largest trees per acre 20 years after fertilization, by fertilizer treatment in (A) thinned stands and (B) nonthinned stands, Rocky Brook, Washington. Crown length is the difference between total height and HLC.

Discussion

Initial Variability in Stand and Site Characteristics

Our 0.1-acre measurement plots sampled a coast Douglas-fir plantation initially established in 1937-1938. Although originally planted at an average density of about 436 TPA, density in the nine nonthinned plots 30 years later ranged from 980 to 1,700 TPA. Percentage of Douglas-fir by basal area in these nonthinned plots ranged from 67 to 87 percent (table 1). Because of volunteer western hemlock and western redcedar, this Rocky Brook plantation was not a monoculture. Similarly, in the Snow Creek plantation of Douglas-fir that was successfully established in 1927–1928 on the nearby former Quilcene District, natural regeneration of hemlock averaged 28 percent of the total number of trees at age 60 years (Miller and Anderson 1995).

Site quality based on estimated mean 50-year site index (SI) varied greatly (66 to 94 ft; table 1) among the 18 plots. Some differences in site index could be related to a variation in the thickness or depth of soil above an indurated, fine-textured glacial deposit that underlies most of our study area. Tree roots cannot penetrate this hard lake sediment or till, and on-site and upslope sources of groundwater accumulate seasonally on this compact layer. For example, after snow melt in early May 1975, LOGS study plot 26 (located next to one of our 0N control plots) had standing water on the soil surface, and that plot was the only one containing devilsclub (*Oplopanax horridus* [(Sm.] Miq.).[4] In addition to site conditions related to soil depth and topographic positions that accumulate or shed subsurface flow, another source of variation in site quality relates to the proportion and size of gravel- through boulder-sized material. We did not, however, attempt to quantify relations among these soil factors and site index.

Additionally, we suspect that some among-plot variation in mean 50-year SI arises from the selection of trees measured for tree height and breast-height age, and then used to estimate SI. As a substitute for the sample selection specified by King (1966) for estimating SI, we used mean height of the 40 largest trees per acre by d.b.h. (H40). According to Curtis and Clendenen (1994), H40 is commonly used as the basis for site index estimates in the region. For our 0.1-acre measurement plots, H40 corresponded to the average height of the four largest d.b.h. trees per plot. Surprisingly, our random sample of 20 tree heights per plot, of which two-thirds were restricted to being larger than the mean diameter, seldom included all four of the largest trees, nor did our 91-tree sample of breast-height ages. To some extent, these sampling deficiencies for estimating H40 were mitigated by estimating missing

[4] Williamson, R.L. 1975. Field work report. On file with: Forestry Sciences Laboratory, 3625 93rd Avenue SW, Olympia, WA 98512.

heights from height-d.b.h. curves for individual plots and by substituting the overall mean breast-height age of 20 years for missing ages. Nonetheless, we surmise that these sampling deficiencies contributed to the wide range of values estimated for H40 and SI among our study plots.

Initial SI in the thinned stand averaged about 14 ft less than in the nonthinned stand (73 vs. 87 ft) (table 1). Differences in soil attributes and tree sampling may explain some of this variation, although the severe thinning 5 years earlier probably removed some large trees in attempts to create uniform spacing. We estimate that about 75 percent of the original trees were felled in the belated precommercial thinning at plantation age 25 years. The unexpected smaller mean d.b.h. of the 100 largest trees per acre in the thinned stand compared to the nonthinned stand also suggests that some large trees were felled which were potentially suitable for site index estimation. Moreover, reduced height growth by residual trees for several years after intensive thinning was previously reported at this Rocky Brook location (Williamson 1976) and at other low-quality sites (DeBell et al. 2002, Harrington and Reukema 1983).

Growth and Mortality

Individual trees in well-stocked stands compete for light, soil moisture, and nutrients. On N-deficient sites such as our Rocky Brook study site, N fertilizer enhances growth of some trees more than others (Miller et al. 1981). Larger trees, which already have larger crowns and rooting volumes, are more likely to capture and respond to added N. Fertilizer-enhanced growth of these larger trees further increases their competitive advantage over smaller trees. Consequently, loss of smaller trees can be accelerated by N fertilization as occurred in our nonthinned stand, but only in the first decade (table 16). The ultimate effect of fertilization on tree stocking in our thinned or nonthinned stands is uncertain. The net of tree losses and additions to an arbitrary minimum d.b.h. threshold, like our 1.6 inch minimum, will change over time. In this general area of the Olympic Peninsula, numbers and species composition of understory trees shift to shade-tolerant western hemlock and western redcedar, which are more likely to survive under shade than Douglas-fir. In our study area and the neighboring LOGS study area (Curtis and Marshall 2009), thinned stands gradually develop a two-layer structure with a Douglas-fir overstory and an understory of younger, mostly shade-tolerant species. Typically, seed crops of western hemlock are frequent and heavy, which produce recurring pulses of volunteer trees, some of which eventually attain diameters for recruiting as ingrowth. For example, our 20-year inventory of the nonthinned stand documented a decrease in the percentage composition of Douglas-fir as more trees of other species were included in our inventory. This change in species composition in our study area was evident in both tree numbers and as a percentage of total basal area.

We anticipated that applying urea fertilizer to this N-deficient site would enhance native site quality and tree growth. We used rates of gross volume PAI of trees 1.6 inches d.b.h. and larger as our biological measure of response to fertilization. We anticipated that gain in stem volume (CVTS) from fertilizing a recently thinned portion of this plantation could differ from gain in the nonthinned portion. Although fertilization would have enhanced content of soil N in both thinned and nonthinned portions, we expected starting differences in stocking between the thinned and nonthinned stand would affect subsequent volume growth per acre and volume of mortality. Because gross growth per acre is related positively to initial growing stock, we expected and documented less gross growth per acre in the first decade in the thinned stand. Conversely, volume lost to mortality was less in the thinned stand.

Of particular relevance are results from a thinning and fertilizer study at a poor-quality site near Shawnigan Lake, B.C. This study was installed in 1971–1972 as a 3-by-3 factorial design in a 24-year-old Douglas-fir plantation. The most severe thinning treatment tested removed two-thirds of starting basal area, which is similar to the estimated 75 percent removal at our Rocky Brook location. Moreover, urea fertilizer was applied at corresponding dosages of 200 and 400 lb N/ac. Results 24 years after fertilization were reported by McWilliams and Therien (1996). The 32-year results extend trends reported for the 24-year period (Omule et al. 2011). In general, results and conclusions from the Shawnigan Lake study and our Rocky Brook study were similar and will be discussed later.

Because thinning treatments at Rocky Brook had restricted randomization, statistical tests to compare effects of urea-N in thinned and nonthinned portions of this plantation were not justified. Instead, we could only conduct informal contrasts of growth responses in these two stands.

Gross growth—

Application of urea fertilizer increased volume growth in the first year in both thinned and nonthinned stands (fig. 4). We were unable to detect any clear relation between gross PAI and growing season precipitation as estimated from on-site measurements in the first decade and supplemented with measurements at the Quilcene Ranger Station about 10 miles away. In the first decade after fertilization of the under-stocked thinned stand (mean RD = 19), gross volume growth (gross PAI) of nonfertilized plots averaged about half that in the nonthinned stand, and growth increased by 45 and 72 percent compared to the nonfertilized control after the 200N or 400N treatments, respectively (tables 6 and 13). Both control and fertilized plots

Gross volume growth in thinned stands was 60 percent greater in the second decade than in the first.

in the thinned stand accelerated PAI by 60 percent in the second decade compared to their respective PAIs in the first decade, presumably because crown size and photosynthetic efficiency increased in response to available growing space and added N. Relative to the nonfertilized control, response to N in the second decade averaged about the same as in the first decade. Despite accelerated losses in tree numbers and CVTS in the second decade, ending RD in the thinned stand at age 50 years averaged 55, 58, and 67, respectively, for the 0N, 200N, and 400N treatments (table 20). This recovery to nearly full stocking was attained about 25 years after the intense precommercial thinning at stand age 25. In contrast, the nonthinned stand had already attained RD of 67 by age 30 years.

In the first decade after application of 200 and 400 lb N/ac in the nonthinned stand, we estimated 43 and 48 percent increases, respectively, in gross volume growth (table 13). In the second decade, gross volume PAI slowed on fertilized plots but increased by 10 percent on nonfertilized plots. This decline in volume growth was especially noticeable after fertilization with 400 lb N/ac where growth averaged 20 percent less than in the first decade. We ascribe this growth reduction on fertilized plots in the second decade to progressive over-stocking and greater mortality losses.

At the end of the second decade, RD averaged 94, 100, and 94, respectively, for the 0N, 200N, and 400N treatments in the nonthinned stand (table 21). Such large values of RD probably resulted from a mixture of shade-tolerant species and the inclusion of small diameter, ingrowth trees when calculating RD (Curtis 2010). Small trees reduce QMD, the divisor in the RD calculation, because they contribute little to basal area per acre but add fully to TPA in calculation of QMD. Had we calculated RD using the summation method (Curtis 2010), our RD values likely would have been lower.

In the second decade of the study, gross PAI was similar in the thinned and nonthinned stands (fig. 7), but greater volume was lost to mortality in the nonthinned stand. In the 20 years after fertilization in both thinned and nonthinned stands, urea fertilizer clearly increased net volume growth and live-stand volume.

Mortality volume—

In the thinned stand, mortality losses were much less than in the nonthinned stand, probably because starting RDs in the nine plots were only 18 to 20. Consequently, fewer and smaller trees died, total volume of mortality was small, and net gains in live-stand volumes were similar to those in gross PAI. Also the thinned stand, volume lost to mortality was minimal in years 1-10 but increased substantially in years 11-20, especially on fertilized plots (table 7). This can be explained in part by a more rapid increase in RD and the larger size of dead trees.

Starting RDs in the nonthinned stand ranged from 56 to 81 among the nine plots (table 1). Cubic volume of subsequent mortality was weakly related to starting RD (fig. 6). Although mortality losses in stem volume accelerated about three-fold in the second decade, fertilization had no real effect in either decade (table 14). Nonetheless, relationships shown in figure 6 and the consistently larger mean values suggest that fertilization did increase mortality losses in stem volume. For all treatments and both periods, average volume per dead tree was much less than average volume of surviving tress. In general, smaller than average trees died in both nonthinned and thinned stands.

Depending on bole size, dead trees that are physically sound can be salvaged when live trees are harvested. In the second decade after fertilization in the nonthinned stand, volume per dead tree averaged 0.90, 1.38, and 1.76 ft^3 in the 0N, 200N, and 400N treatments, respectively (table 16). For corresponding treatments in the thinned stand, volume per dead tree averaged 0.27, 3.94, and 0.56 ft^3 (table 9). Surprisingly, dead trees in the thinned stand averaged less volume than nonthinned stands, except for a few large trees that were wind-thrown on two 200N plots.

Net yield—
Urea fertilization increased live-stand volume in both thinned and nonthinned stands. In the thinned stand, net increase in live CVTS was greater in period 2 than period 1 (table 4). This is expected because initial stocking at age 30 years was less than a RD of 20 as a result of intensive thinning about 5 years earlier. In contrast, the nonthinned stand at the same age had an average RD of 67, a stocking only attained by the thinned stand after fertilization and two decades of growth. At Shawnigan Lake, stand volume at 24 years after a similarly intensive thinning also remained less than nonthinned plots, but the gap narrowed over time. By 32 years after treatment, live-stand volume in thinned plots that were not fertilized remained less than that in the nonthinned stand, but average stand volume was greater on plots fertilized with 200N (McWilliams and Therien 1996, Omule et al. 2011).

Doubling N dosage from 200 to 400 lb N/ac resulted in about 20 percent more net volume gain in the thinned stand but failed to provide additional gain in the nonthinned stand. In the thinned stand, net gains in live-stand volume 20 years after fertilization averaged about 1,380 ft^3/ac (40-percent gain) after 200 lb

N/ac and about 2,040 ft^3/ac (59-percent gain) after 400 lb N/ac (table 4). Despite a greater loss of volume in mortality in the nonthinned stand, application of 200 lb N/ac resulted in average gains of about 1,870 ft^3/ac (31 percent) versus about 1,820 ft^3/ac (30 percent) after 400 lb N/ac (table 11). In both thinned and non-thinned portions of this plantation, a single application of urea fertilizer greatly increased stand productivity. Similarly at Shawnigan Lake, fertilization increased stand total and merchantable volume in both thinned and nonthinned stands (McWilliams and Therien 1996, Omule et al. 2011). Although the 400N treatment resulted in more volume production than the 200N treatment, the lower dosage was more efficient for the nonthinned stand in terms of gain in CVTS per pound of N (table 12).

Large absolute and especially large percentage increases in stand volume growth have been reported after N fertilization of Douglas-fir on poor-quality sites in western Washington (Miller and Tarrant 1983, Miller et al. 1986) and at Shawnigan Lake in British Columbia (McWilliams and Therien 1996, Omule et al. 2011). Growth-projection models that synthesize results at numerous locations sampling a wide range of site qualities also estimate larger gains in total bole volume after fertilizing lower versus higher quality sites (Hann 2011).

Assuming a harvest of all live trees at age 50, additional yield in CVTS 20 years after application of 200 lb N/ac is about 500 ft^3/ac less in the thinned stand than in the nonthinned stand (tables 4 and 11). Note that percentage gains in yield over nonfertilized growth are similar for the thinned and nonthinned stands, at 30 and 40 percent, respectively. We observe that both nonfertilized growth and response to fertilization were related positively to initial stocking (live-stand volume and RD), which was substantially less in the thinned stand.

Unadjusted net gains in merchantable volume—
Most importantly for wood utilization and for creating habitat with large trees, observed gains in merchantable stand volume (CV4) 20 years after fertilization averaged nearly 70 percent greater for the 200N treatment than for the 0N treatment in both thinned and nonthinned stands (table 30). Gains over nonfertilized plots after the 400N treatment were about 95 percent in both stands. Thus, doubling the dosage did not double the gain in CV4. Larger gains in CV4 than CVTS have at least two explanations: (1) biologically, more rapid diameter growth and ingrowth into the 5.6 in and larger diameter classes, and (2) arithmetically, more net loss of small-diameter trees in fertilized plots in both the thinned (table 9) and nonthinned stand (table 16). Although loss of small trees reduces CVTS volume, such losses have little or no effect on CV4.

Growth and Response to Fertilizer Depend on Stand Stocking

Although we could not statistically compare gains from fertilizing thinned vs. nonthinned portions of the plantation, we review and comment on this important and practical topic. Results from the nearby Rocky Brook installation of the LOGS study are particularly relevant (Curtis and Marshall 2009). Volume production in thinned plots in the LOGS study increased with growing stock, expressed as basal area. Results at this poor-quality site are qualitatively consistent with those from other LOGS study installations, although growth has been much slower than for installations on more productive sites. Timing of the initial calibration thinning in 1964 corresponds to the thinning of our study area in 1963. This calibration thinning was intended to create comparable stand densities among the LOGS study plots. All trees less than one-half the initial stand quadratic mean diameter were cut. This left 400 trees per acre (average spacing 10.4 ft) compared to a mean of 351 trees per acre after thinning in our study. In both studies, all trees 1.6 inches d.b.h. and larger were tagged and measured. Subsequent thinning treatments in the LOGS study differed in the amount of basal area allowed to accumulate in growing stock. Average residual basal area of thinned plots after the calibration thinning was the starting point for calculating future growing-stock accumulation. Thereafter, the basal area retained in any thinning was that retained in the previous thinning plus a predetermined percentage of the gross increase found in the nonthinned plots since the previous thinning. Retained growth was 10, 30, 50, and 70 percent of nonthinned growth. Gross growth of nonthinned plots was assumed to represent the productive potential of the site at full stocking.

Trends in live-stand basal area over time for both studies illustrate the consequences severe thinning at about age 30 years has on subsequent growth (fig. 9). Nonthinned stands in both studies had very similar basal area development, with a gradually decreasing rate of growth over time. Plots in our study lagged somewhat behind those of the LOGS study, in part due to lower initial stocking. Thinned stands in both studies had a similar starting point. Repeated thinnings in the LOGS study resulted in somewhat linear development of basal area, with the steepness of slopes increasing with the amount of retained growth. Without any additional thinnings, basal area development in our study demonstrated a gradually increasing rate of growth. Despite the growth acceleration, final trends suggested that thinned plots in our study would need an additional 10 to 20 years to achieve the basal area found in nonthinned plots.

Overall, the various LOGS study installations have clearly demonstrated that in these relatively young stands, volume increment is strongly related to growing-stock level. High volume increment requires at least moderately high

In these relatively young stands, volume increment is strongly related to growing-stock level.

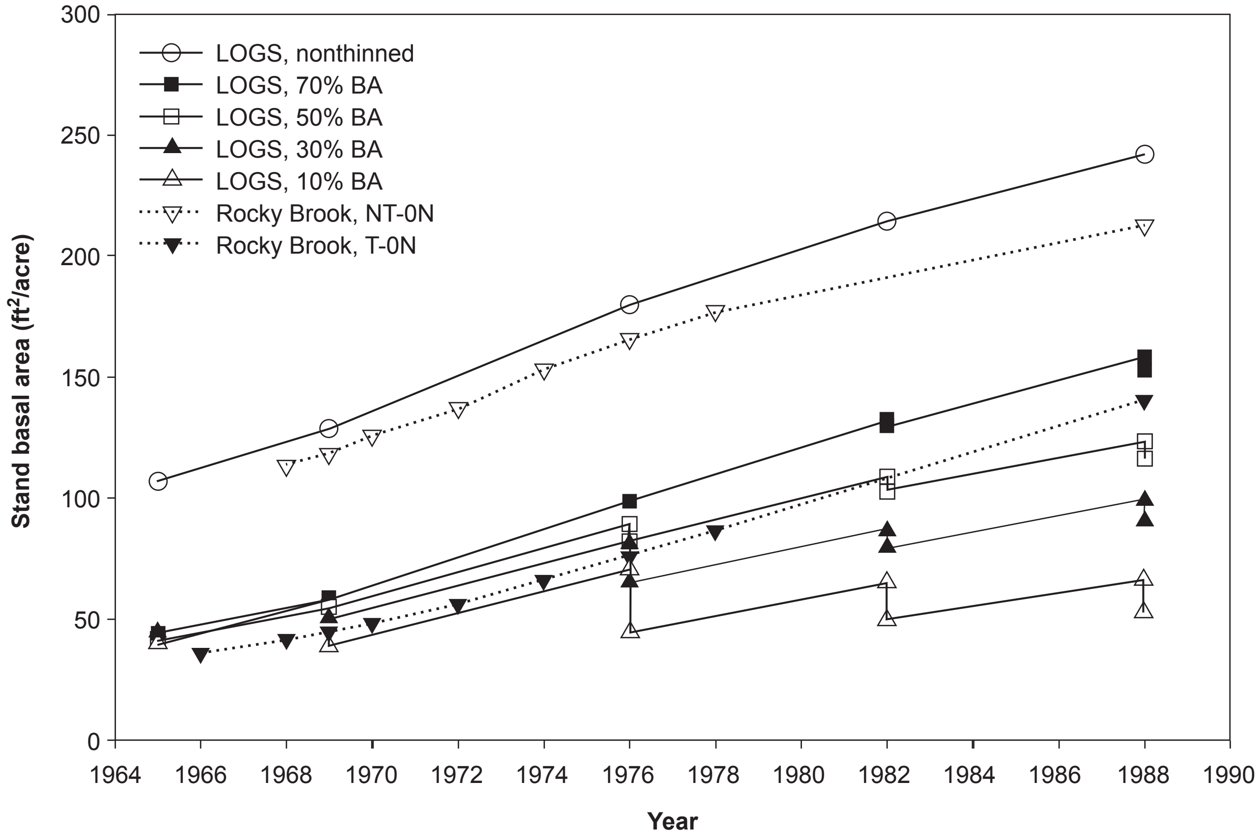

Figure 9—Comparison of stand basal area development in the LOGS study and in unfertilized treatments of the current study in Rocky Brook, Washington. Legend indicates the percentage of gross basal area (BA) growth retained after each thinning treatment of the LOGS study relative to the nonthinned treatment (NT = nonthinned, T = thinned, and 0N = nonfertilized).

growing stock. Results are similar at the two other LOGS study installations located on poor-quality sites (Beddows 2002).

For younger plantations and on higher quality sites than Rocky Brook, Li et al. (2007) reported effects of stand density management and fertilization on subsequent growth of 6- to 13-year-old Douglas-fir plantations at nine locations in western Washington and Oregon. Site quality at eight of these locations was Site Class II or better; only one was Site Class IV. Before precommercial thinning average density, calculated as the initial stems per acre (ISPA), among the nine plantations ranged from 289 to 690 TPA. Three density treatments were imposed at each location: (1) retain all trees (ISPA); (2) retain 50 percent of ISPA (ISPA/2); and (3) retain 25 percent of ISPA (ISPA/4). The RD of these three initial density treatments averaged 14, 7, and 4, respectively; therefore they were clearly under-stocked compared to a RD of 65 to 70, the density at which full stocking occurs and density-related mortality begins to occur for Douglas-fir. In the subsequent 12 years, two plots at each location in the ISPA density treatments were repeatedly thinned to a RD of 35 to 40 whenever RD reached 55 to 60. Plots in ISPA/2 were thinned once when a RD of 55 was attained. Plots in ISPA/4 required no thinning in the first 12 years because average RD did not exceed 30 and plots remained understocked. At each location and for each of the three density levels, one of the two 0.5-acre measurement plots (each within 1 acre treatment areas) was initially fertilized with 200 lb N/ac as urea and was fertilized again after years 4 and 8 for a cumulative total of 600 lb N/ac in 12 years.

As reported by Li et al. (2007), volume growth per acre was more strongly affected by stand density treatments than by fertilization. Thinning reduced per-acre growth for 4 or more years. Averaged across the three densities, fertilization increased volume growth by about 12, 14, and 7 percent, respectively, in the first, second, and third 4-year growth periods. Although statistical significance of the interaction between density and fertilization was not reported, trends of volume PAI are similar to those in our study: less response from fertilizer in understocked stands (Li et al. 2007) (fig. 5). Denser stands (lightly thinned) responded more quickly to the first fertilization than did the less dense stands. However, response in the denser stands decreased over time, while the response in the initially less dense stands increased.

Li et al. (2007) suggest that reducing initial spacing to 50 percent or 25 percent of starting TPA is relatively intense, and growth in such spaced stands had not recovered from the spacing treatment during the first 12 years. Our results were similar at Rocky Brook, where delayed thinning at age 25 probably retained about 25 percent of starting TPA, and where 5 years after thinning RD averaged only 19. Our conclusions are similar: sufficient TPA or RD must be present to occupy a site to exploit fully its native and amended nutrients and water. Moreover, both before and after a site is fully occupied by trees, nutrient shortages can develop and become apparent when the site demonstrates a positive response to fertilization.

Moderate levels of growing stock are required if stands are to respond robustly to fertilization.

Changes in Basal Area and Species Composition

The operational, precommercial thinning of our stands left about 25 percent of the original basal area per acre and favored the retention of the originally planted Douglas-fir. At stand age 30 years and 5 years after thinning, basal area per acre in the thinned stand averaged less than half that in the nonthinned stand. Of this total, Douglas-fir averaged 90 percent by basal area among the nine plots in the thinned stand and averaged 76 percent in the nonthinned stand, presumably because other species were not removed (table 1).

Thinned stand—

Basal area of Douglas-fir and of all species combined increased in both periods, especially in the second decade and after the 400N treatment (table 18). At stand age 50 years, the percentage Douglas-fir averaged 84, 89, and 91 percent, respectively, for the 0N, 200N, and 400N treatments. Basal area of hemlock averaged less than 15 percent of total basal area and showed no relation to N treatments.

Nonthinned stand—

Basal area of Douglas-fir and of all species combined accelerated less rapidly in the nonthinned stand (table 19). Unlike results in the thinned stand, the 400N treatment was not more effective than the 200N for increasing basal area growth. Moreover, percentage of total basal area in Douglas-fir in the second decade decreased by 2 percent in 0N plots and stayed unchanged for both fertilization treatments. At stand age 50 years, the percentage of Douglas-fir by basal area averaged 75, 77, and 79, respectively, for the 0N, 200N, and 400N treatments. Hemlock basal area averaged 20 to 22 percent of total basal area and showed no relation to N treatment.

Relative Density

Relative density (Curtis 1982) is an index of stand density that is commonly used to schedule and prescribe intensity of thinning to manage density in Douglas-fir stands. Changes in RD over time reflect changes in stand basal area, TPA, and their integration to QMD. Therefore, our fertilizer treatments that accelerated basal area growth arithmetically increased RD. However, this potential increase in RD could be offset by a greater net loss of smaller than average d.b.h. trees that occurred in our thinned stand and especially in the nonthinned stand with 400N application. Such losses of small trees would arithmetically increase QMD and lower RD. Recall that we documented greater losses of small trees in the first decade after fertilization in the nonthinned stand and in the second decade in the thinned stand. In short, large increases in RD in the second decade in both thinned and nonthinned stands resulted from a combination of accelerated basal area growth and loss of small trees as influenced by thinning and N fertilizer.

Changes in the 100 Largest Trees per Acre

Our assessment was based on changes in adjusted mean values, by decade. Mean values represented the 100 largest d.b.h. trees per acre at stand ages 30, 40, and 50 years, but these means seldom represented the same trees in each decade. In short, changes in these means over time integrated both tree growth and some changes in sample trees.

In the thinned stand, changes in both mean d.b.h. and height of the 100 largest TPA (i.e., crop trees) were accelerated by N additions, especially in the second decade after fertilization. After the application of 200 lb N/ac, mean d.b.h. was about 12 percent greater than that for the 0N treatment in both decades; after the application of 400 lb N/ac means averaged about 18 percent more than that for the 0N treatment (table 22). Fertilizer affected diameter growth more than height growth in both decades after fertilization, with both dosages causing a similar gain in height over nonfertilized plots of 6 percent in the first decade and 12 percent in the second decade (table 24). Increases in tree height were concurrent with increases in height to live crown, as lower branches died and live crown receded upward. Fertilizer had no detectable effect on HLC or LCR. At stand age 50 years and two decades after fertilization, means of LCR in the thinned stand were 0.47, 0.49, and 0.45 for 0N, 200N, and 400N, respectively (table 28). We infer that N fertilization had no real effect on LCR and that adequate crown was present for sustained growth in the next decade.

In the nonthinned stand, absolute and percentage changes in mean d.b.h. and mean height of crop trees were clearly less than in the thinned stand (tables 23 vs. 22 and 25 vs. 24). As in the thinned stand, both diameter and height growth accelerated in the second decade. Mean d.b.h. increased by only 4 to 6 percent after fertilization; both dosages had similar effects. Fertilizer effects on height growth mirrored those of diameter growth; both dosages had a similar effect of less than a 10-percent gain over nonfertilized means.

Increases in mean tree height (32 to 34 ft) of crop trees in the 20-year period were similar to increases in height to live crown (31 to 37 ft), suggesting a similar length of live crown in the two decades. At stand age 50 years and two decades after fertilization, mean LCR in the nonthinned stand were 0.42, 0.37, and 0.40 for 0N, 200N, and 400N, respectively (table 29). We infer that N fertilization had no real effect on LCR and that a slightly less favorable LCR was present in the nonthinned stand for sustained growth in the next decade (fig. 8b).

An Economic Analysis

The extra volume of wood gained from fertilization and how soon this wood can be harvested strongly affects gross financial return from this investment. Profit is attained when revenue from selling the wood at the mill exceeds the total cost of precommercial thinning, fertilizing, and harvesting discounted at an assumed interest rate. The following economic analysis compares the effects of precommercial thinning, fertilization, and timing of final harvest (i.e., 10 or 20 years after fertilization) on present net value (PNV).

Methods for Economic Analysis

To estimate financial return from precommercial thinning, fertilization, and timing of harvest at Rocky Brook, we first estimated live-stand merchantable volume and tonnage yields for each of the 18 study plots (i.e., nine each in the thinned and nonthinned stands) at 10 and 20 years after fertilization (our assumed years of harvest). These metrics were based on tree numbers and sizes for each plot. Further, we assumed that volume in dead trees was not usable at harvest. Merchantable volume and dollar value paid at a mill were estimated from our tree records that documented species, d.b.h., height, and live/dead status of each tree by plot and measurement date.[5]

Our first step for estimating financial value per acre was to subdivide total bole volume into merchantable volume in logs. For all live trees, diameter inside bark (DIB) at the small end of each log was calculated from the known tree d.b.h. and the estimated average tarif number of each plot at years 10 and 20 after fertilization. Using a tarif taper equation, an iterative process assigned upper stem DIB of each 32-ft log. The last log was 12 to 32 ft long with a minimum DIB of 5 inches. This procedure included any tree that had a full log or partial log to a 5 inch top, but estimates of volume of potential pulpwood less than 5 in DIB were not made. Normally, trees less than 7 inches d.b.h. would not contain any merchantable volume and would be left on the harvested site.

The following procedure estimated total harvested volume and green weight in three categories: saw logs, smaller chip-and-saw, and pulp. The selection of the three grades was based on what mills in western Washington were purchasing in 2008. All logs 8 inches and larger at top end were considered number 3 saw logs. All logs with a DIB of 6 to 7 inches at the small end were considered chip-and-saw grade logs. Logs with a DIB of 5 inches and a length less than 24 ft (top log) were classified as pulp logs. Note that a more accurate estimate of grade and value likely would have resulted if trees had been graded in the field. All estimated product values were current as of 2008. Log prices were based on a moving average of 6-month periods covering 5 years (from July 2003 through January 1, 2008) published in "The Washington Oregon Log Market Report."[6]

We developed the following practical approach for comparing our experimental treatments using PNV.[7] Precommercial thinning costs at Rocky Brook in 1963 were $60 per acre. Based on a survey of commercial forest land owners in 2005, cost of fertilization with 200 lb N/ac averaged $97 per acre with a standard error of $8 per

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[5] Chambers, C.J. 2008. Personal communication. Biometrician (rertired), West Mason Consulting, SE 101 Binns-Swigert Loop Rd, Shelton, WA 98584.

[6] Report available from John Lindberg, logmkt@comcast.net.

[7] Hotvedt, J.E. 2014. Personal communication. Forest economist (retired), Washington State Department of Natural Resources, 1111 Washington St. SE, Olympia, WA 98504.

acre (Briggs 2007). Note that costs of fertilization per acre generally decline as the size of the contract increases. Therefore, we assumed fertilization costs of $100 and $190 per acre for the 200N and 400N treatments, respectively.

To remove the effects of inflation from our analysis, we adjusted all costs and revenues to 2014 dollars using annual values of the producer price index (USDOL BLS, n.d.). To simplify our economic analysis, we assumed no real change in the price of wood products over time. In addition, we did not account for logging and hauling costs, which typically consume about half of the revenue generated from sale at the mill, thus leaving the remaining revenue as stumpage to the landowner. In addition, we did not consider potential financial consequences of alternative investments of revenue generated from timber harvest. In our calculations of PNV we assumed a 5 percent discount rate because such a conservative value was considered appropriate for public lands and small acreages owned by nonindustrial private landowners. The equation for calculating PNV for a given level of precommercial thinning, fertilization, and timing of final harvest is:

$$PNV = R/(1+i)^{t1} - C_{PCT}/(1+i)^{t2} - C_{FERT}/(1+i)^{t3} (1)$$

where R is the revenue generated from the sale of logs at the mill, i is the discount rate (5 percent), *t1-t3* are the number of years in which revenues or costs are discounted, C_{PCT} is the cost of precommercial thinning, and C_{FERT} is the cost of nitrogen fertilization.

For each thinned and nonthinned stand, we subjected our estimates of PNV to covariance analysis as described previously for the growth and mortality variables. To account for differences in initial stocking that existed prior to fertilization, we adjusted the analysis for total cubic volume of live trees (CVTS) immediately before fertilization in 1968. The same analytical approach as described previously for the growth variables was used to assess potential treatment effects and interactions on PNV.

Results and Discussion of Economic Analysis

Estimated mill values clearly accelerated in the second decade because more live-stand volume accumulated and more higher-valued saw logs and chip-and-saw logs were harvested (table 30). Overall, estimated mill value at harvest was greater for nonthinned stands compared to thinned stands, and fertilizer increased estimated values in both thinned and nonthinned stands (fig. 10a).

Present net value of the thinned stand varied as a result of the interaction of fertilization and timing of final harvest (table 31; fig. 10b). For each fertilizer treatment, greater PNV resulted when the stand was harvested 20 years versus 10 years after fertilization. PNV increased with nitrogen fertilization for each timing of final harvest, but there were no significant differences between the 200N and 400N treatments within each timing.

Table 30—Observed mean net increase in live-stand and merchantable volumes and apparent gain from fertilization in the total 20-year period after fertilization at Rocky Brook, Washington

	CVTS					CV4				
Treatment[a]	Start	End	Increase	Gain		Start	End	Increase	Gain	
	- - - - - - - *Cubic feet per acre* - - - - - - -				*Percent*	- - - - - - - *Cubic feet per acre* - - - - - - -				*Percent*
Thinned stand:										
0N	570	3,410	2,840	—	—	0	2,430	2,430	—	—
200N	620	4,950	4,330	1,490	52	0	4,100	4,100	1,670	69
400N	549	5,380	4,830	1,990	70	0	4,720	4,720	2,290	94
Nonthinned stand:										
0N	1,890	5,560	3,670	—	—	344	3,080	2,740	—	—
200N	2,510	7,970	5,460	1,790	49	82	4,700	4,620	1,880	69
400N	2,680	8,100	5,420	1,750	48	170	5,520	5,350	2,610	95

N = nitrogen; — = not appropriate; CVTS is cubic volume of the total stem, inside bark; CV4 is cubic volume of the stem to a 4 inch top, inside bark.
[a] Application of 0, 200, or 400 lb N/ac.

Fertilization increased present net value of thinned stands, but not for nonthinned stands.

In the nonthinned stand, PNV only differed significantly between the two timings of final harvest (table 32; fig. 10b). Averaged across nitrogen fertilizer rates, PNV was 60 percent greater when the stand was harvested 20 years ($2,795 per acre) versus 10 years ($1,743 per acre) after fertilization. Fertilization had no detectable effect on PNV of the nonthinned stand.

To estimate the financial benefit of precommercial thinning, we calculated 90-percent confidence intervals for PNV of nonfertilized plots in both the thinned and nonthinned stands harvested 20 years after fertilization. The confidence interval for the thinned stand ($919 ± $278 per acre) did not overlap with that for the nonthinned stand ($2,639 ± $498 per acre), suggesting that thinning reduced the economic value of this overstocked stand at Rocky Brook. We suspect the delayed and intensive thinning at this location reduced growing stock too severely to allow the stand to fully benefit from thinning. Note also that differences in apparent site index between thinned (73 ft) and nonthinned stands (87 ft) probably had a substantial impact on the estimated volumes at final harvest, which likely also affected the results of our economic analysis (table 1).

Of the factors studied, timing of final harvest (i.e., 10 vs. 20 years after fertilization) had the greatest impact on PNV of both thinned and nonthinned stands, probably because accumulation of merchantable volume was delayed by the poor quality of the site, the prolonged understocked condition of thinned stands, and the overstocked condition of nonthinned stands. Surprisingly, fertilization increased PNV of thinned stands but had no detectable effect on nonthinned stands. Clearly, overstocking of the nonthinned stand limited the benefits of fertilization.

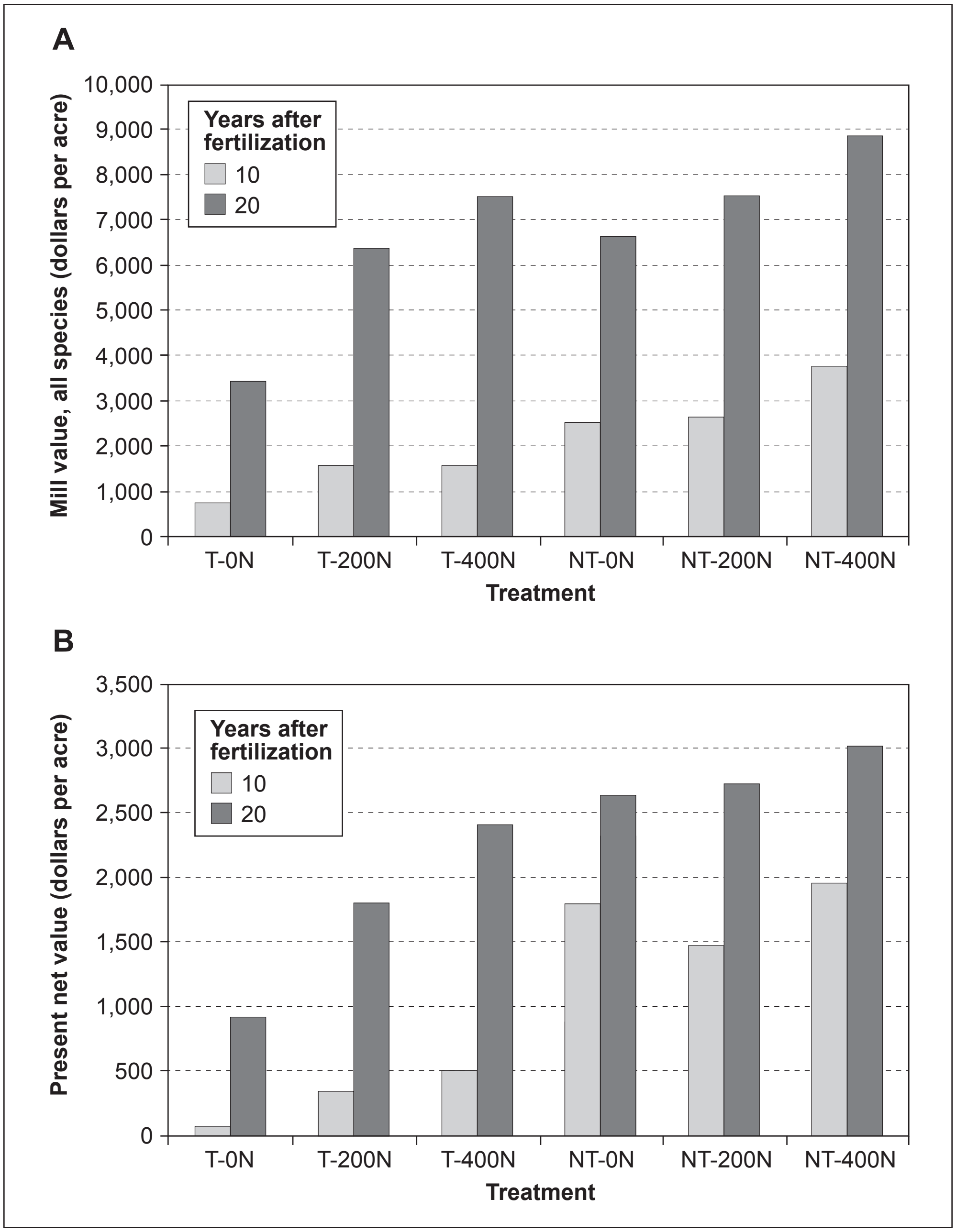

Figure 10—Estimated mean dollar value of (A) bole tonnage as delivered to a mill (2008 dollars) and (B) present net value (2014 dollars) to a landowner at final harvest 10 or 20 years after fertilization, by thinning and fertilizing treatment (T = thinned and NT = nonthinned; 0N, 200N, and 400N indicate urea fertilizer rates of 0, 200, and 400 lb N/ac, respectively), Rocky Brook, Washington.

Table 31a—Analysis of covariance of present net value (PNV) by harvest time after fertilization in the thinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	35.4	0.001
Rep × F (Error 1)	5	—	—
Harvest time (H)	1	322.1	<0.001
F × H	2	15.1	0.004
Linear, harvest at 10 years[a]	1	46.8	<0.001
Linear, harvest at 20 years	1	54.0	<0.001
Covariate (starting CVTS)	1	141.6	<0.001
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; PNV = present net value (dollars per acre) at final timber harvest in 2014 dollars; N = nitrogen; — = not appropriate.
[a] Linear contrasts with P ≤ 0.05 are considered statistically significant.

Table 31b—Adjusted mean present net value (mean PNV ± standard error) by harvest time after fertilization in the thinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	H1	H2	H1	H2	H2/H1
	Dollars/acre		*Percent*		
0N*[b]	67 ± 45 b	919 ± 143 b	100	100	13.7
200N*	335 ± 46 a	1,804 ± 143 a	500	196	5.4
400N*	502 ± 46 a	2,406 ± 143 a	749	262	4.8

PNV = present net value (dollars per acre) at final timber harvest in 2014 dollars; H1 = harvest at 10 years after fertilization; H2 = harvest at 20 years after fertilization; N = nitrogen.
[a] Application of 0, 200, or 400 lb N/acre.
[b] Asterisks (*) indicate harvest time means for a given fertilizer rate that differ significantly (P ≤ 0.10). Fertilizer means within a given harvest time followed by a different letter differ significantly (P ≤ 0.10).

Table 32a—Analysis of covariance of present net value (PNV) by harvest time after fertilization in the nonthinned stand at Rocky Brook, Washington

Source of variation	D.f.	F-value	P
N fertilizer (F)	2	0.8	0.507
Rep × F (Error 1)	5	—	—
Harvet time (H)	1	156.0	<0.001
F × H	2	2.0	0.212
Linear, harvest at 10 years[a]	1	0.1	0.720
Linear, harvest at 20 years	1	1.0	0.365
Covariate (starting CVTS)	1	6.7	0.042
Error 2	6	—	—
Total (18-1)	17		

D.f. = degrees of freedom; PNV = present net value (dollars per acre) at final timber harvest in 2014 dollars; N = nitrogen; — = not appropriate.
[a] Linear contrasts with $P \leq 0.05$ are considered statistically significant.

Table 32b—Adjusted mean present net value (PNV ± standard error) by harvest time after fertilization in the nonthinned stand at Rocky Brook, Washington

			Relative to 0N		
Treatment[a]	H1	H2	H1	H2	H2/H1
	- - - Dollars/acre - - -		*- - - Percent - - -*		
0N[b]	1,801 ± 273	2,639 ± 256	100	100	1.5
200N	1,473 ± 240	2,727 ± 220	82	103	1.9
400N	1,955 ± 256	3,018 ± 238	109	114	1.5

PNV = present net value (dollar per acre) at final timber harvest in 2014 dollars; H1 = harvest at 10 years after fertilization; H2 = harvest at 20 years after fertilization; N = nitrogen.
[a] Application of 0, 200, or 400 lb N/ac.
[b] Fertilizer-by-period means shown for information only. Main effect differences are described in the text.

Conclusions

Thirty-year-old Douglas-fir and other coniferous species at this Site Class IV-V location responded strongly to urea fertilizer. Adding 200 lb N/ac as urea increased cumulative live-stand volume 20 years later by about 1,900 ft^3/ac in the nonthinned portion and by about 1,400 ft^3/ac in the understocked portion that had been belatedly and intensively thinned about 5 years before fertilization. Doubling fertilizer rate to 400 lb N/ac resulted in lesser marginal gain (gain per lb N applied) in nonthinned stands.

Growth in stand basal area and volume in the thinned stand accelerated greatly in the second decade, especially after N fertilization. Change in RD also accelerated so that by stand age 50 years, mean RD in the thinned stand ranged from 55 to 67 after a mean starting RD of 19. In the nonthinned stand at age 50 years, RD ranged from 94 to 99 after a mean starting RD of 67. As basal area and RD stocking increased, live crown ratios of the 100 largest trees per acre narrowed to about 0.47 in the thinned stand and to about 0.40 in the nonthinned stand.

Volume lost to mortality was generally less than 4 percent of total gross growth in the thinned stand, but it was 4 to 15 percent in the nonthinned stand. The d.b.h. of dead trees averaged much smaller than average d.b.h. of live trees in both thinned and nonthinned stands. Mortality losses in both volume and tree numbers accelerated markedly in the second decade. Fertilization increased mortality volume in both the 200N and 400N treatments in the thinned stand but not in the nonthinned stand. Addition of P, K, and S to the 400 lb N/ac treatment provided no additional increase in d.b.h. or basal area growth of crop trees compared to the sole application of 400 lb N/ac.

Both thinning and fertilization accelerated diameter growth of the 100 largest d.b.h. trees. Height to live crown increased rapidly in the second decade, especially in the nonthinned stand; concurrently, live crown ratio decreased to about 0.40. However, fertilization had no measureable effect on HLC or LCR.

Overstocking in nonthinned stands reduced financial benefits from fertilization.

For both thinned and nonthinned stands, delaying a hypothetical final harvest until 20 years after fertilization (age 50) substantially increased PNV over that resulting when harvest was assumed to occur after only 10 years. On these juvenile, N-deficient soils, both merchantable volume and PNV of the stand were clearly increased by fertilization, but the increases were statistically significant only in thinned stands where adequate growing space was available to allow trees to grow into the larger, more valuable size classes. Overstocking in the nonthinned stand prevented realization of any financial benefits from fertilization. However, the lowest PNV was detected for stands receiving a precommercial thinning because felling about 75 percent of the original basal area—including removal of some of the larger trees—severely reduced growing stock and subsequent growth. Results of our study confirm that improved growth and financial benefits are attainable when silvicultural investments such as precommercial thinning and nitrogen fertilization are applied to a poor quality site. On poor quality sites like Rocky Brook, growth potential (capacity) is much less then on higher quality sites. Slower rates of growth extend the time of harvest after thinning or fertilization, which then reduces the financial return from these treatments.

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Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	.305	Meters
Acres	.405	Hectares
Square feet per acre (ft^2/ac)	.229	Square meter per hectare
Cubic feet (ft^3)	.0283	Cubic meters
Cubic ft per acre (ft^3/ac)	.07	Cubic meters per hectare
Trees per acre (TPA)	2.47	Trees per hectare
Pounds (lb)	.454	Kilograms
Pounds per acre (lb/ac)	1.12	Kilograms per hectare

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