RESPONSE TO FERTILIZATION IN THINNED AND UNTHINNED DOUGLAS-FIR STANDS

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ABSTRACT

Growth data from thinning and fertilizing trials in 27 Douglas-fir stands in western Oregon, Washington, and British Columbia are summarized. These stands ranged from 15 to 68 years and from sites II to V. As expected, the initial effects of heavy thinning were to reduce gross growth per acre during the first 5 to 10 years after thinning. Fertilization with 150 to 600 pounds nitrogen per acre generally increased gross growth in both thinned and unthinned stands. The apparent gain in gross growth after fertilization was consistently greater in lightly to moderately thinned stands than in unthinned stands, however the T×F (thinning/fertilizing) interaction was seldom statistically significant. Thus far at these locations, fertilization increased site productivity and thinning concentrated productivity onto selected crop trees. Our sample of existing trials indicates that improved experimental designs are needed in future trials to answer practical questions.

INTRODUCTION

Fertilizing and thinning are accepted methods for increasing yields of Douglas-fir forests. The basic purpose of fertilization is to temporarily increase site quality or productivity by adding needed nutrients. In Douglas-fir forests of the Pacific Northwest, as with most other commercial species and locations, broadcast applications of N have generally increased tree growth and merchantable yields. Thinning can also increase yields by improving growing conditions for selected trees—those that are likely to attain merchantable size and maximum value in the future. By eliminating some competitors, thinning provides more light, moisture, and nutrients to these crop trees.

Important questions exist about the results of combining these two treatments in the same stand. For example, are the benefits from combining the two treatments less than, equal to, or more than one would anticipate from the addition of their separate effects? Is the gain from fertilization different in thinned than in unthinned stands?

In this paper, we will provide information about fertilizing and thinning in Douglas-fir stands. (1) Describing some bases for anticipating a more-than-additive interaction, (2) presenting direct evidence from field trials that compare fertilization and thinning as separate and combined treatments, (3) comparing the effects of the single and combined treatments on growth of initially small and large trees, and (4) discussing the implications of interaction to forest land managers and researchers.

METHODS

We summarized growth data from 287 plots in fertilizing-thinning trials in 26 Douglas-fir stands in western Washington and Oregon and from one stand in British Columbia. These stands ranged from 15 to 68 yr in age and from II to V in site quality. We will present these trials in order of increasing stand age and compare growth of individual sample trees or gross growth per acre; i.e., growth added to trees that were alive at the start of the measurement period. Where statistical tests were made on the growth data by other authors or by us, We judged differences as statistically significant or true when $P \leq 0.10$. Where no statistical tests of differences were available or when we believed the experimental design lacked sufficient replications or levels of experimental factors to provide a sensitive or valid test of significance, we stated the difference as "apparent."

The simplest experimental design for examining interactions of two factors is a 2×2 factorial. Many of the trials that we examined had such design with the four treatments: control, thinned, fertilized, and thinned and fertilized. Other trials had limitations such as the absence of fertilized-only treatment or a more complex design such as a 3×2 or a 3×3 factorial.

RESULTS AND DISCUSSIONS

Before presenting the results of these trials we should consider some likely results. First, we anticipate that thinning as a separate treatment will usually increase the growth of the remaining trees. If, however, thinning is too severe, the initial effects of thinning could be to temporarily reduce growth of some residual trees. This has been termed a thinning "shock effect" (Staebler 1956). Moreover, per acre growth will be reduced because too few residual trees remain to fully occupy the site. Second, we anticipate that application of N to unthinned stands will temporarily increase growth, if a short supply of available N is limiting growth at that location. Once this growth-limiting factor is supplied by fertilization, however, it is likely that another factor such as light will limit growth. Therefore, application of fertilizer to a thinned stand is likely to be especially effective, because light or moisture is less likely to limit response. With these anticipations in mind let's consider the results from these trials.

FOREST SERVICE—WIND RIVER EXPERIMENTAL FOREST TRIAL

The Trial—USDA Forest Service personnel installed an incomplete 2 × 2 factorial in a 20-yr-old, site IV, Douglas-fir plantation in southwest Washington (Miller and Reukema 1977). Thinning removed 20% of the initial basal area and left 300 trees per acre. Fertilization consisted of 300 lb N/acre as urea applied to 1/40-acre areas centered on six individual dominant trees in the thinned area. Thinning-fertilizing interaction could not be assessed because there was no treatment with fertilizer alone. Although the authors compared growth of these fertilized trees with that of six matched trees within the thinned and six in an adjacent unthinned area, tests are compromised because this is not a cleanly replicated experiment.

Volume Growth of Dominant Trees—During the 5 yr after thinning, released trees grew about the same as control trees in diameter, but about 25% less in height. Fertilized dominants within the thinned stand averaged about 85% more in diameter and height growth than their unfertilized counterparts. The authors concluded that thinning initially failed to increase diameter growth and did reduce height growth, and fertilization clearly improved diameter and height growth of concurrently released dominant trees. They recommended that managers of N-deficient sites consider fertilizing shortly before or after thinning to offset effects of possible "thinning shock" and to accelerate response to release.

CANADIAN FORESTRY SERVICE—SHAWNIGAN LAKE TRIAL

The Trial—Researchers of The Canadian Forestry Service installed a completely randomized, 3 × 3 factorial experiment with four replications in a 24-yr-old, site V, Douglas-fir stand on Vancouver Island (Crown et al. 1977). Size of measurement plots was 0.1 acre. This experiment tested thinning and fertilizing at three levels each, including no thinning and no fertilizing. Moderate thinning removed about 32% of the initial volume and heavy thinning removed about 63%. The researchers applied 200 and 400 lb N/acre as urea in the spring of 2 successive yr and combined results of both years in their data analysis. Crown et al. (1977) did not include statistical analyses.

Volume Growth, All Trees—During the 3 yr after treatment, average annual growth per acre was less on both moderately and heavily thinned plots than the control (Table 1). These growth reductions were a little less than reductions in growing stock. In unthinned plots, growth after fertilization with 200 lb N/acre exceeded control growth by 82 ft³/acre/yr, or 35% (Table 1). The 400-N dosage apparently further increased growth, but not in proportion to the additional amount of fertilizer applied.

Gains from N apparently increased when fertilizer was applied with moderate thinning; this was particularly true with the 400-N dosage. Thus, the 800-N dosage resulted in an annual gain of 0.41 ft³/lb N when applied in the moderately thinned stand compared to 0.26 ft³/lb N applied in the unthinned stand.

Although volume growth after heavy thinning was less than one-half that of the unthinned control, volume growth after 400 lb N/acre were applied in the heavily thinned stand was the same as that in the control stand (234 ft³/acre/yr). Because this growth was distributed exclusively to crop trees, the economic return from this fertilization will be enhanced. As in the moderately thinned stand, the gain from the second 200-lb increment of N was evidently greater in the thinned than in the unthinned stands.

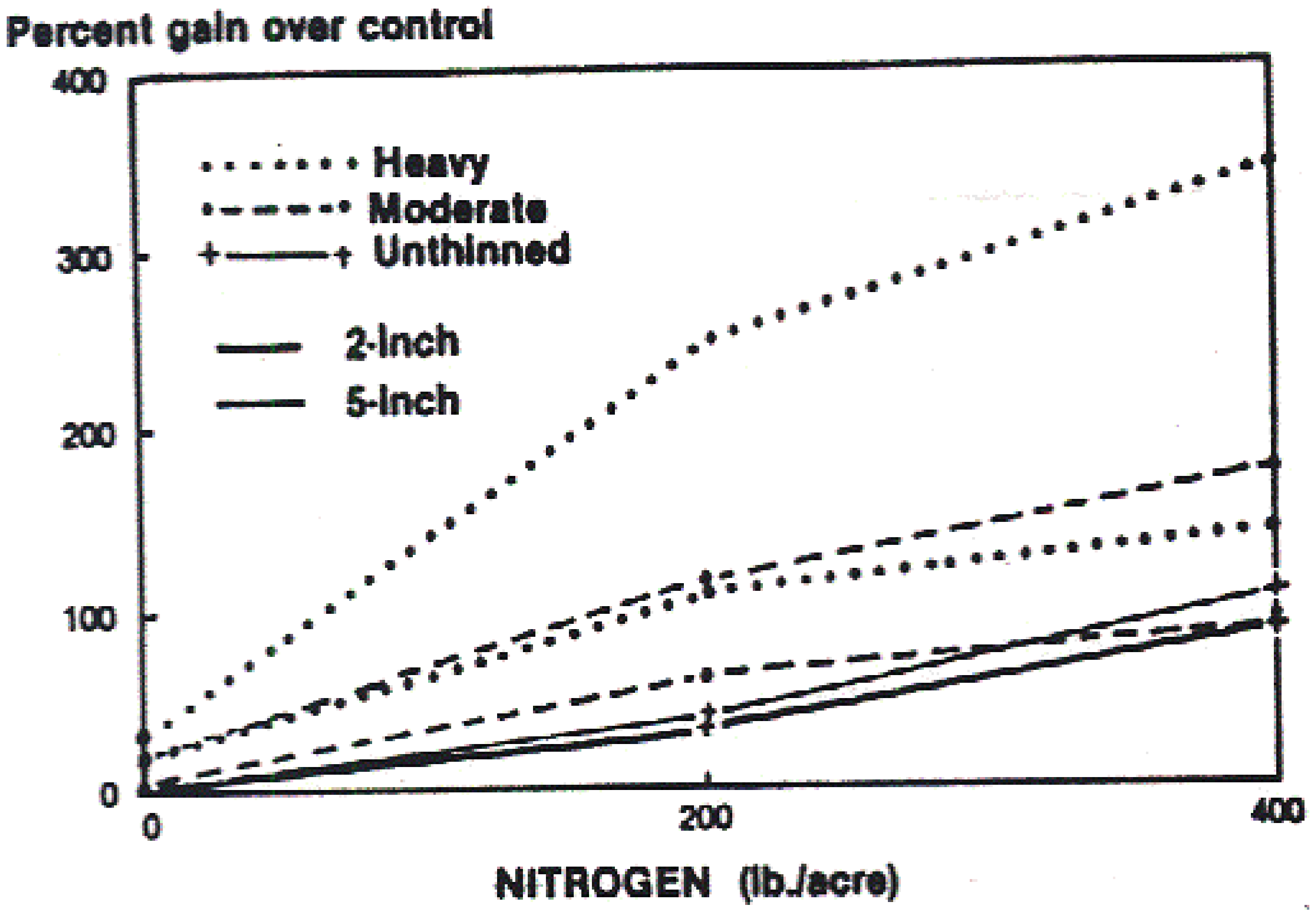
Volume Growth by Tree Size—Crown et al. (1977) provide information about the relative response of 2- to 5-in. dbh trees after various treatments. Relative to untreated trees of the same size, growth of both 2-in. (intermediate?) and 5-in. (dominant) trees apparently increased with increased spacing; i.e., thinning intensity. Likewise, growth of both size classes increased with increasing dosages of fertilizer (Figure 1). As thinning intensity increased, however, 2-in. trees showed increasingly greater relative response than did 5-in. trees. Thus, the smaller trees showed greater percentage gains (relative to untreated

Table 1. Average annual total volume growth by treatment, 3-yr period, Shawnigan Lake British Columbia, per acre basis.

Treatment: Thinned volume %	Treatment: Applied N lb	Annual growth ft³	Annual growth %[a]	Annual gain relative to unfertilized ft³	Annual gain relative to unfertilized per lb N
0	0	234	100		
	200	316	135	82	0.41
	400	337	144	103	0.26
32	0	167	71		
	200	274	117	107	0.54
	400	331	141	164	0.41
63	0	106	45		
	200	188	80	82	0.41
	400	233	100	127	0.32

[a]Percent of control.

Figure 1. Volume response by small and large trees at Shawnigan Lake, B.C.



trees of the same initial dbh) than did the larger trees at each treatment; this indicates only that the smaller trees had the capacity to respond and does not indicate that their contribution to the total volume production of the stand exceeded that of large trees.

ROCKY BROOK

The Trial—Forest Service personnel tested two levels of thinning and three levels of fertilizing in a 30-yr-old, site IV, Douglas-fir stand on the east side of the Olympic Peninsula. Urea was applied at rates of 0, 200, and 400 lb N/acre in the spring of 1968 to each of three 1/5-acre plots in an unthinned stand and in a stand which had been heavily thinned 5 yr earlier. The thinning removed about 74% of the volume and left about 340 trees per acre. Because some treatments were not randomized, statistical tests of significance were not appropriate when comparing effects of thinning and the T × F interaction; however, such tests were used to judge the effects of fertilization in both the thinned and unthinned stands.

Volume Growth, All Trees—During a 10-yr measurement period, annual growth on the thinned-only plots averaged 55% of control growth (Table 2). In the unthinned stand, growth after N fertilization (200- and 400-N dosage) averaged 46%, or 101 ft^3/acre/yr more than the control growth ($P < 0.001$). The additional gain from an additional 200 lb of N was not significantly greater than that from the 200-N dosage ($P < 0.400$).

In the thinned stand, the average annual gain from fertilization was 59% or 72 ft^3/acre ($P < 0.002$). Although the periodic annual increment (p.a.i.) in the 400-N plots was significantly greater than that in the 200-N plots ($P < 0.033$), doubling the N dosage did not double the response from the first 200 lb dosage. Although the gain from fertilization appeared less in the heavily thinned stand, this difference could not be tested statistically because allocation of the thinning was nonrandom. Clearly, however, the additional growth per tree after fertilization did not compensate for the reduced number of trees in the thinned stand.

Volume Growth by Tree Size—The relative contribution to stand growth and to growing stock by trees of varying size can be expressed by comparing the growth percent of individual trees to the average growth percent of the stand. If, for example, the overall stand volume increased at a rate of 6% per yr and volume of an individual tree increased at a rate of 3% per yr, then the relative contribution of that tree to stand growth is 0.5, or one-half the average.

For the Rocky Brook study, we calculated the relative contribution to stand growth of 60 trees in each of the six treatments tested. These trees were our height sample, two-thirds of which were initially larger than the tree of average basal area. By knowing which trees respond most and least to treatment, one has a basis for predicting future stand development and for prescribing marking guides.

In the unthinned control plots, the initial dbh of these trees ranged from about 2 to 9 in. (Figure 2) and larger trees contrib-

Figure 2. Volume response by tree size at Rocky Brook.

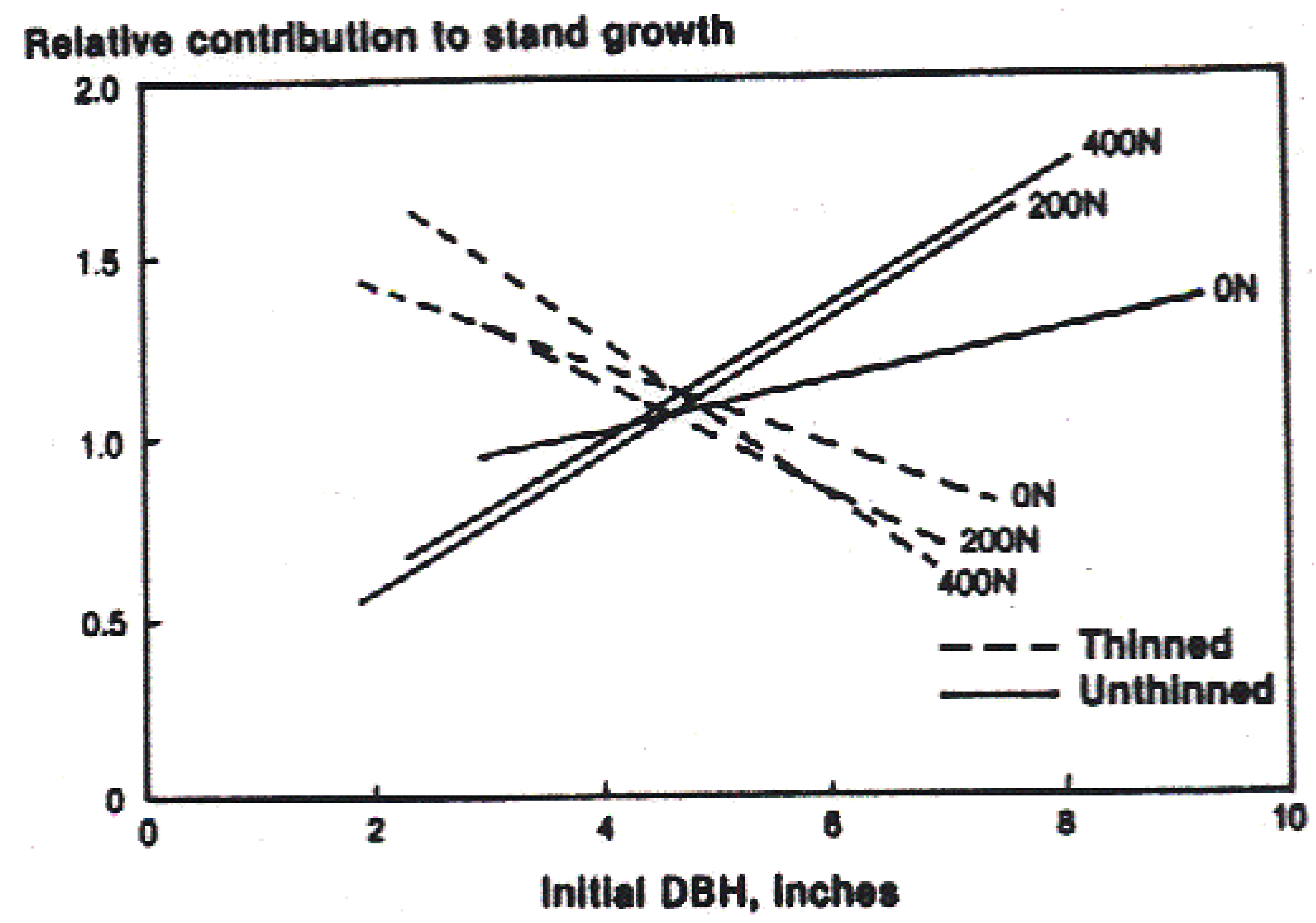


Table 2. Average annual volume growth during 10-yr period after treatment at Rocky Brook, per acre basis.

Treatment: Thinned volume %	Treatment: Applied N lb	Annual growth[a] ft³	Annual growth[a] %[b]	Annual gain relative to unfertilized ft³	Annual gain relative to unfertilized per lb N
0	0	224	100		
	200	317	142	93	0.46
	400	333	149	109	0.27
74	0	123	55		
	200	180	80	57	0.28
	400	210	94	87	0.22

[a]Growth adjusted by covariance for initial differences in height of dominant trees in 1964.
[b]Percent of control.

uted relatively more to stand growth than did smaller trees. Thinning apparently increased the relative contribution of small (mostly codominant) trees. The additions of 200 and 400 lb N/acre in the unthinned stand increased the relative contribution of large trees compared to small trees. Conversely, the same fertilizer additions to the thinned stands tended to increase the relative contribution of smaller trees. Thus, the apparent effect of fertilization at this location was to especially enhance growth of large trees in unthinned stands and smaller trees in the heavily thinned stand. As a result of fertilization, tree size can be expected to become more variable in the unthinned stand and less variable in the thinned stand.

ROSEBURG LUMBER COMPANY TRIALS

The Trials—Harry Spencer, former forester with Roseburg Lumber Company, initiated a completely random, 2×2 factorial test of thinning and fertilizing on unreplicated plots at five locations near Roseburg, Oregon. Size of measurement plots was 0.1 acre. These treatments were applied to 20- to 30-yr-old stands of Douglas-fir growing on sites III to IV quality land. Thinning removed about 40% of the initial volume and left approximately 300 Douglas-fir per acre. Concurrently, 200 lb N/acre as urea were applied to both thinned and unthinned plots. Data were analyzed by covariance using pretreatment volume as the covariate; adjusted means were separated by orthogonal comparisons.

Volume Growth, All Trees—Orthogonal comparisons indicated that the main effects of both thinning ($P < 0.003$) and fertilizing ($P < 0.003$) were statistically significant, but the interaction was not ($P < 0.814$). Removal of about 40% of the initial volume reduced volume growth on thinned plots during the following 6- to 8-yr period by an average of 20% (Table 3). Averaged over the thinning treatments, addition of 200 lb N/acre increased production by 23%. Gross annual growth was increased by 54 and 69 ft^3/acre in the unthinned and thinned stand, respectively. These results—reduced growth following thinning and the trend of greater gains from fertilizing thinned stands—are consistent with other trials reported earlier in this paper.

Volume Growth, 200 Largest Trees Per Acre—Again, the main effect of thinning ($P < 0.010$) and fertilizing ($P < 0.009$) were significant, but the interaction was not ($P < 0.386$). Averaged for fertilized and unfertilized plots, thinning increased volume growth of these largest crop trees by an average of 39% (Table 3). Fertilization increased average annual growth of these crop trees more in the thinned than the unthinned stands (51 vs. 9 ft^3/acre, respectively), yet the nonsignificant T×F interaction indicates this may not be a true difference.

The volume growth of the 200 largest trees per acre averaged 44% of the total volume growth of the unthinned stands compared to 75% in the thinned stands. In the unthinned stand, these 200 largest trees apparently produced 9 of the 54 extra ft^3/acre/yr produced after fertilization. In contrast, the same component in the thinned stand produced 51 of 69 ft^3. These results indicate the benefits of fertilizing in thinned stands so that a large proportion of the increased growth is concentrated on crop trees.

FOREST SERVICE—STAMPEDE CREEK TRIAL

The Trial—Forest Service researchers used a 2×2 completely random factorial with seven replications to test thinning and fertilizing on growth of dominant trees in a 30-yr-old, site IV, Douglas-fir stand near Tiller, Oregon (Miller and Williamson 1974). The thinning removed approximately one-half the initial volume; fertilization combined 300 lb N with 150, 100, and 50 lb of elemental P, K, and S per acre, respectively. The fertilizers were applied within 1/20-acre circular plots centered on dominant trees. The effect of treatments on basal area and height growth of these dominant Douglas-firs was examined 4 yr after treatment using covariance and orthogonal comparisons. These same procedures were used to compare volume growth during a 10-yr period after treatment.

Growth of Dominant Trees—The main effects of both thinning and fertilizing were to increase 4-yr basal area growth ($P < 0.01$); however, the interaction was statistically nonsignificant. Neither the single or combined treatments had a significant effect on 4-yr height growth (Miller and Williamson 1974).

During the 10-yr period after treatment, the main effects of thinning and of fertilizing on volume growth were significant ($P < 0.001$ and $P < 0.01$, respectively). Dominant trees released by thinning grew 27% more volume than control

Table 3. Average annual volume growth by treatment, 6- to 8-yr period, averaged five locations near Roseburg, Oregon, per acre basis.

Treatment: Thinned volume %	Treatment: Applied N lb	Annual growth[a] ft^3	Annual growth[a] %[b]	Annual gain relative to unfertilized ft^3	Annual gain relative to unfertilized per lb N
Total stand, trees 1.6-in. dbh and larger					
0	0	287	100		
	200	341	119	54	0.27
40	0	219	76		
	200	288	100	69	0.34
200 largest per acre					
0	0	133	100		
	200	142	107	9	0.04
40	0	166	125		
	200	217	163	51	0.25

[a]Growth of total stand and the 200 largest per acre was adjusted by covariance for initial differences in volume of the stand component.
[b]Percent of control.

trees, while fertilized, unthinned trees grew 19% more (Table 4). Trees that were both thinned and fertilized outgrew control trees by 49%. Although this apparent gain from the combined treatment was slightly more than that derived by adding the gains from the two individual treatments, the absence of a statistically significant interaction ($P < 0.890$) indicated that the effects of the combined treatments were simply additive.

BOISE CASCADE CORPORATION—PROSPECT, OREGON, TRIAL

The Trial—Boise Cascade Corporation personnel installed a 2×2 factorial with two replications in the western Cascade Range of Oregon, near Prospect. They applied treatments to a 30-yr-old, site IV, Douglas-fir stand that originated after partial overstory removal or selective logging in the forties. Most remaining residuals were removed after the 1970 growing season and before plot installation and treatment; however, scattered residual trees probably reduced growth on three plots (all fertilized). Thinning removed about 50% of the initial volume of the younger stand and left about 400 stems per acre. Concurrently, 200 lb N/acre as urea were applied to some plots.

Volume Growth, All Trees—Volume growth during a 5-yr period after thinning was reduced in proportion to the thinning intensity. Orthogonal contrasts showed the main effect of thinning ($P < 0.02$) was significant, but effects of fertilizing ($P < 0.640$) and the interaction of the two treatments ($P < 0.31$) were not. The heavy thinning apparently reduced growth in proportion to the growing stock reduction (Table 5). Although 200 lb N/acre applied to unthinned plots apparently reduced growth by 16%, the presence of a residual old-growth tree near each of these plots may explain this result. The same N dosage in the thinned stands apparently increased growth by approximately 12% (Table 5), yet the nonsignificant thinning × fertilization interaction indicated that the apparent greater response in the thinned plots might be due to chance.

Table 4. Average annual volume growth of dominant Douglas-fir during a 4-yr period, near Tiller, Oregon.

Treatment: Thinned volume %	Treatment: Applied N[a] lb	Annual growth[b] ft^3	Annual growth[b] %[c]	Annual gain relative to unfertilized ft^3	Annual gain relative to unfertilized per lb N
0	0	1.24	100		
	300	1.48	119	0.24	19
50	0	1.58	127		
	300	1.84	149	0.26	16

[a]Fertilizers containing N, P, K, and S. provided 300, 150, 100, and 50 lb of element per acre, respectively. [b]Growth adjusted by covariance for initial differences in average tree volume among treatments. [c]Percent of control.

Volume Growth, 200 Largest Trees—Orthogonal comparisons showed that neither the main effects of thinning and fertilizing nor their interactions were significant. Therefore, differences among the treatments might be due to chance.

Surprisingly, the 200 largest trees per acre evidently failed to respond to release; in fact, reduced growth was indicated (Table 5), perhaps because some of the original large trees had been cut in the heavy thinning. Fertilization also appeared ineffective in stimulating growth of these large crop trees in the unthinned stands; again, the confounding effect of an overstory tree near both fertilized plots may be responsible. In the thinned stand, however, growth of fertilized crop trees exceeded that of unfertilized.

FOREST SERVICE—DEADFALL CREEK TRIAL

The Trial—Forest Service researchers tested three dosages of N, with and without thinning, in a 40-yr-old, site V, overstocked Douglas-fir and hemlock stand on the east side of the Olympic Peninsula. The design was a completely random 3×2 factorial with six replications. They applied N dosages of 0, 300, and 600 lb/acre as urea. Thinning removed about 60% of the initial basal area and left about 250 trees per acre. Each treatment was applied on six 1/20-acre areas each centered on a dominant Douglas-fir. After adjustment for initial differences in tree volume, the treatment means of 10-yr volume growth were separated by orthogonal comparisons.

Volume Growth of Dominant Trees—The "main effects" of thinning ($P < 0.082$) and fertilizing ($P < 0.001$) were statistically significant; so was the thinning × fertilizing interaction ($P < 0.002$). Therefore, the effects of treatment in this stand

Table 5. Average annual growth of a 30-yr-old stand near Prospect, Oregon, 5-yr period, per acre basis.

Treatment: Thinned volume %	Treatment: Applied N lb	Annual growth ft^3	Annual growth %[a]	Annual gain relative to unfertilized ft^3	Annual gain relative to unfertilized per lb N
Total stand, trees 1.6-in. dbh and larger					
0	0	300	100		
	200	252	84	-48	0
50	0	153	51		
	200	172	57	17	0.10
200 largest per acre[b]					
0	0	133	100		
	200	102	77	-31	0
50	0	112	84		
	200	128	96	16	0.10

[a]Percent of control. [b]Growth adjusted by covariance for initial differences in the total volume of the 200 largest trees per acre.

depended on the specific combination of these treatments that was used (Table 6). Clearly, N fertilization enhanced growth more when applied with thinning than without. For example, the 600-N dosage resulted in a 129% increase when combined with thinning, and only a 20% gain when applied to unthinned trees. In both thinned and unthinned stands, the 600-N dosage was more effective than the 300-N dosage ($P < 0.001$); the effect of doubling the N dosage more than doubled the response of these dominant Douglas-fir.

The reduced growth of dominant trees released by thinning may be another example of thinning shock; more puzzling, however, is the reduced growth following fertilization with 300 lb N/acre without thinning (Table 6). The fact that the 600-N treatment was effective in both thinned and unthinned conditions suggests N deficiency. Perhaps the addition of 300 lb N/acre in unthinned plots was sufficient to stimulate microorganisms and competing smaller trees, but concurrently reduced N available to the dominant Douglas-fir. Conversely, part of the effectiveness of the 600-N dosage was likely due to the increased mortality we measured among smaller trees.

SOME COOPERATIVE REGIONAL FOREST SERVICE NUTRITION TRIALS

The Trials—Personnel of the Regional Forest Nutrition Research Project (University of Washington) installed thinning-fertilizing trials at 12 locations on Forest Service land. These stands ranged in age from 20 to 55 yr and in sites from II to IV. Because unthinned plots differed in size from thinned plots in these trials (0.025 vs. 0.10 acres) and were so small as to include only 10 trees per plot in the older stands, we were unable to validly examine the factorial effects of the two treatments. Instead, we compared the effectiveness of increasing amounts of urea N in the thinned plots after adjusting growth for initial differences in residual volume after thinning.

Table 6. Average annual volume growth of dominant Douglas-fir trees during a 10-yr period at Deadfall Creek.[a]

Treatment: Thinned volume %	Treatment: Applied N lb	Annual growth ft^3	Annual growth %[b]	Annual gain relative to unfertilized ft^3	Annual gain relative to unfertilized per lb N
0	0	1.0	100		
	300	0.9	90	-0.1	-10
	600	1.2	120	0.2	20
60	0	0.7	70		
	300	1.1	110	0.4	57
	600	1.6	160	0.9	129

[a]Growth adjusted by covariance for differences in initial average tree volume among treatments.
[b]Percent of control.

Effect of Fertilization—During a 4-yr period, annual gains from fertilizing heavily thinned stands with 200 and 400 lb of N/acre, averaged 32 and 56 ft^3/acre, or 12% and 22%, respectively (Table 7). Yet orthogonal contrasts indicated the difference between control and fertilized was significant in only two of the ten installations and that the difference between the two N dosages was not significant at any location. These results demonstrate the insensitivity of two replications to detect statistically confirmed differences among treatments at a given location even when large differences apparently exist.

Although the annual gain per lb of applied N was apparently greater for the 200 lb dosage (0.16 vs. 0.14 ft^3), the difference was slight. This suggests that the 400-N dosage in these thinned stands was nearly as efficient as the 200-N dosage.

FOREST SERVICE—VOIGHT CREEK EXPERIMENTAL FOREST TRIAL

The Trial—Forest Service researchers tested two levels of fertilizing in unthinned and previously thinned plots on two soils, in a 60-yr-old, sites II to III stand near Orting, Washington. Response to fertilizing was measured on 0.2-acre plots. The trial was superimposed on a past test of thinning regimes (Reukema 1972); the most recent thinnings were 6 to 14 yr prior to fertilization, so stands had had time to adjust to these thinnings. Thinned plots had about 20% less volume than unthinned. Plots selected for the fertilizer trial were on two extremes of soil—a fertile silt loam, and a less fertile gravelly sandy loam. Urea was applied at rates of 0 or 200 lb of N/acre to 0.5-acre plots centered on the existing 0.2-acre measurement plots.

Each fertilizer treatment was randomly assigned to two plots which sample each of the four soil/thinning combinations. The assumed design was a completely randomized $2 \times 2 \times 2$ factorial with two replications. To account for pretreatment difference in rates of growth, we expressed response to fertilizer as the ratio of 7-yr posttreatment p.a.i. to 6- to 8-yr pretreatment p.a.i.

Table 7. Average response to increasing amounts of urea-N in thinned stands at 12 locations in western Washington and Oregon, per acre basis.[a]

Applied N lb	Annual growth[b] ft^3	Annual growth[b] %[c]	Annual gain ft^3	Annual gain per lb N
0	260	100		
200	292	112	32	0.16
400	316	122	56	0.14

[a]Data supplied by the Regional Forest Nutrition Research Project in February 1977. [b]Growth adjusted by covariance for initial differences in plot volumes after thinning. [c]Percent of control.

Volume Growth, All Trees—Orthogonal comparisons of growth ratios to assess 7-yr response to fertilizing indicate that the effect of fertilizing ($P < 0.001$) was highly significant, but the interactions, $F \times T$ ($P < 0.579$), and $F \times T \times S$ ($P < 0.140$), were not. Adjusted cubic-volume growth on the previously thinned plots equalled that on control plots (Table 8). Averaged over soils and thinning, the effect of fertilizing stands was a 17% increase in growth. Application of 200 lb N/acre apparently increased growth in the unthinned stand by 12%, or an annual gain of 39 ft^3/acre during the 7 yr after treatment. The same dosage of urea in the thinned stand, however, apparently provided a greater annual increase of 77 ft^3/acre.

FOREST SERVICE—NORTH UMPQUA RIVER TRIAL

The Trial—Forest Service personnel tested thinning and fertilizing in three 68-yr-old, site IV, Douglas-fir stands in the North Umpqua River drainage east of Roseburg, Oregon. In this 2×2 factorial, 150 lb N/acre as urea were applied to one of two 0.2-acre plots in a thinned portion of each of these stands, 1 to 4 yr after commercial thinning. These commercial thinnings from below removed about 30% of the initial volume. At the same time, one of two plots in the adjacent unthinned portion was refertilized with the same dosage and fertilizer. These unthinned plots had been initially fertilized 6 yr previously with 150 lb of N/acre as ammonium nitrate and with varying amounts of P, K, and S.

The periodic annual growth during an 8-yr period after fertilization or refertilization was analyzed as a randomized block design using site index before fertilization as a covariate.

Table 8. Average volume growth of a 60-yr-old Douglas-fir stand on the Voight Creek Experimental Forest, Washington, 7-yr period, per acre basis.[a]

Treatment: Thinned volume %	Treatment: Applied N lb	Annual growth[b] ft^3	Annual growth[b] %[c]	Annual gain relative to unfertilized ft^3	Annual gain relative to unfertilized per lb N
0	0	337	100		
	200	376	112	39	0.20
20[d]	0	337	100		
	200	414	123	77	0.38

[a]Growth adjusted for differences in pretreatment gross volume growth; derived by multiplying overall average 6- to 8-yr pretreatment p.a.i. (periodic annual increment) times the ratio posttreatment:pretreatment p.a.i. for each treatment. [b]Averaged over both soils. [c]Percent of control. [d]At the time fertilizer was applied, volume in the previously thinned stands averaged 80% of that in unthinned stands.

Volume Growth, All Trees—Orthogonal comparisons of the adjusted means indicated that the main effect of fertilizing was significant ($P < 0.036$), but effect of thinning ($P < 0.134$) and the interaction ($P < 0.822$) were not. The average annual gain from fertilization (thinned and unthinned) was 58 ft^3/acre.

In unthinned stands, the combined effect of the refertilization and previous fertilization apparently was to increase growth by 37% or an annual gain of 65 ft^3/acre during the 8 yr following refertilization. We are not able to determine how much of this response was the residual effect of the first fertilization; however, the growth rate after the refertilization was the same as that during the 6 yr following the first fertilization. Although fertilization in the thinned stand apparently increased growth by 52 ft^3/acre/yr over the 8-yr period (Table 9), the previous fertilization in the unthinned stands precluded our determining whether fertilizer efficiency was greater in the thinned stand.

CONCLUSIONS AND IMPLICATIONS

In these trials:

1. Precommercial thinning to release future crop trees initially reduced gross growth per acre; however, eventual gains in merchantable volume from precommercial thinning cannot be assessed from 5- to 10-yr response data.

2. Fertilizing consistently increased gross growth per acre more in lightly or moderately thinned than in unthinned stands. In stands where more than about 70% of the initial volume was removed however, response to fertilization was less than that in the unthinned stands. This suggests that the effects of thinning and fertilizing are more-than-additive in their interaction—provided thinning does not reduce growing stock excessively. Because the $T \times F$ interaction was usually statistically nonsignificant, the observed more-than-additive effect may have been due to chance; more likely, however, this nonsignificance illustrates that field experiments with two or three repli-

Table 9. Average gross annual growth of three 68-yr-old stands near the North Umpqua River, Oregon, 8-yr period, per acre basis.[a]

Treatment: Thinned volume %	Treatment: Applied N lb	Annual growth ft^3	Annual growth %[b]	Annual gain relative to unfertilized ft^3	Annual gain relative to unfertilized per lb N
0	0	177	100		
	150[c]	242	137	65	?
30	0	218	123		
	150	270	152	52	0.35

[a]Growth adjusted by covariance for initial difference in site index. [b]Percent of control. [c]Previously fertilized with NPKS.

cations and only two or three levels of each treatment are seldom sensitive enough to detect statistically significant differences in growth of this magnitude.

The implications from these results is that priority be given to fertilizing thinned stands; this has several rational bases. First, insufficient light and moisture are less likely to limit response to improved nutrition. Second, despite fewer trees to share site factors, thinning is likely to create greater demands by trees for nutrients because (a) other site factors are shifted toward optimum levels, (b) decomposition by microorganisms of slash and root systems of cut trees may create a greater need for available N, or (c) accelerated growth of subordinate vegetation may also increase the competition for nutrients. Third, the added growth from fertilization is concentrated on fewer, higher quality trees; this enhances the economic returns from fertilization.

3. Increased dosages of N generally resulted in greater volume gains in thinned than in unthinned stands. Although this suggests using higher dosages in thinned stands than the conventional 200 lb/acre, the manager should base this decision on the marginal return on each increment of fertilizer used. With one exception, these short term gains were greater for the first than the second 200 or 300 lb increment of N. Therefore, the first 200 to 300 increment is probably the more cost effective investment if total funding for fertilization is limited. Yet, the optimum dosage will likely shift to heavier dosage with longer periods after fertilization because duration of response appears related to the amount of N applied (Heilman 1971, Miller and Pienaar 1973).

4. A closer examination of the effects of these treatments on stand mortality and on growth of crop and noncrop trees is desirable. For example, why did thinning or fertilizing as separate treatments in some trials fail to increase growth of individual crop trees as expected?

5. Our sample of existing thinning/fertilizing trials indicated that improved experimental designs are needed in future trials to answer practical questions about these two silvicultural practices. Past trials have seldom been sensitive enough to detect practical differences in growth between treatments. Design improvements include (1) increasing the number of replications of each treatment, (2) adding more levels of one or more treatments, and (3) when investigating interactions have at least two nonzero levels of each factor.[1] Thus 3×3 factorials are more effective than 2×2 factorials.

Important questions that such improved designs could answer include:

1. At what range of stand density is response to fertilization maximum?

2. Does optimum density vary by site quality?

3. What are the volume yields by tree size at varying densities and N dosages?

4. What is the best timing or sequence of fertilizing and thinning operations? Existing trials test fertilization after or concurrent with thinning; but these options are not yet contrasted at any one location. Moreover, no trial compares fertilization 1 to 2 yr prior to precommercial thinning. This sequence may have some biological advantages, especially on overstocked and very N-deficient sites for the following assumptions: (a) most uptake of applied N probably occurs in the first 2 yr after application; (b) N status of the crop trees will be improved before thinning occurs; (c) this improved nutrition will lead to a more rapid crown expansion and help avoid or offset "thinning shock"; (d) slash and roots of felled trees are likely to decompose more rapidly if their N concentrations have been increased by fertilization.

5. Are young, low density plantations or natural stands equally as responsive to N fertilization as precommercially thinned stands?

6. Should thinning prescriptions be modified in anticipation of marked response to fertilization?

Collectively, land managers seek more cost-effective practices for increasing yields from Douglas-fir forests; therefore, new and improved field trials will be needed to provide direct, quantitative answers to their questions.

1. Written corespondence with Tim Max, Biometrician, Pacific Northwest Forest and Range Experiment Station, on March 5, 1980.

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