

Long-term effects of thinning and fertilization on growth of red fir in northeastern California

Jianwei Zhang, William W. Oliver, and Robert F. Powers

Abstract: To determine the impact of fertilization and thinning on growth and development of red fir (*Abies magnifica* A. Murr.) stands, we established an experiment in a 60-year-old stand using a 2×3 factorial design with nitrogen-fertilized and nonfertilized treatments and three stocking levels. Plots were established in 1976 and were measured every 5 years for 26 years. The periodic annual increment in basal area was 97%, 51%, 38%, and 33% greater in fertilized trees than in nonfertilized trees during the first, second, third, and fourth 5-year periods, respectively. After 20 years, annual basal area increment was greater in nonfertilized trees. The response of annual volume increment to fertilization was not statistically significant until the fourth period. Yet, volume increases of the fertilized plots were 25%–92% greater than those of the nonfertilized plots from 1976 to 1996. Similarly, basal area increment was greater in lightly thinned plots than in unthinned plots from the second period on, until heavy mortality during 1996–2002. Basal area increment was greater in the heavily thinned plots from the fourth period on. Results indicate that red fir can respond to fertilization and thinning quickly and that both treatments speed stand development. In addition, fertilization increases the stand's carrying capacity. Therefore, forest managers can use these silvicultural practices to improve stand growth, to reduce fire fuels, and to accelerate stand development.

Résumé : Pour déterminer l'impact de la fertilisation et de l'éclaircie sur la croissance et le développement de peuplements de sapin rouge (*Abies magnifica* A. Murr.), nous avons établi, dans un peuplement de 60 ans, un dispositif expérimental de type factoriel 2×3 avec présence et absence de fertilisation et trois niveaux de densité. Les placettes ont été établies en 1976, puis mesurées à tous les 5 ans pendant 26 ans. Les arbres fertilisés ont eu un accroissement annuel périodique en surface terrière de 97, 51, 38 et 33 % supérieur à celui des arbres non fertilisés après les première, deuxième, troisième et quatrième périodes de 5 ans, respectivement. Après la quatrième période de 5 ans, les arbres non fertilisés ont eu une meilleure croissance annuelle en surface terrière. La réaction de l'accroissement annuel en volume à la fertilisation n'a pas été statistiquement significative avant la quatrième période de 5 ans. Malgré tout, les placettes fertilisées ont eu un accroissement en volume de 25 à 92 % supérieur à celui des placettes non fertilisées entre 1976 et 1996. De la même façon, les placettes légèrement éclaircies ont eu un accroissement en surface terrière supérieur à celui des placettes non éclaircies à partir de la deuxième période de 5 ans jusqu'à un épisode de mortalité intense survenu entre 1996 et 2002. Les placettes fortement éclaircies ont montré un accroissement en surface terrière supérieur à partir de la quatrième période de cinq ans. Les résultats indiquent que la réaction du sapin rouge à la fertilisation et à l'éclaircie est rapide et que ces deux traitements peuvent accélérer le développement du peuplement. De plus, la fertilisation augmente la capacité de support du peuplement. Par conséquent, les aménagistes forestiers peuvent utiliser ces pratiques sylvicoles pour améliorer la croissance des peuplements, réduire la quantité de combustible ligneux et accélérer le développement des peuplements.

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Introduction

With the increasing demand for wood products across the world, *Abies* forests at higher elevations and latitudes are regarded as a valuable and relatively untapped asset for wood production (Powers 1992). Rates of net primary production in these forests approach those of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests; however, a high proportion of production occurs below ground (Powers and Edmonds

1992). Slow growth is, however, usually related to cold temperatures and (or) summer drought, which not only reduce the growing season and water availability, but also affect litter decomposition and nitrogen (N) mineralization, and subsequently nutrient availability (Attiwill and Adams 1993; Liski et al. 2003; McColl and Powers 2003; Powers 1990; Powers and Edmonds 1992; Trofymow et al. 2002). In his altitudinal transect study conducted in the same region as our study, Powers (1990) found that the *Abies* forest had both the lowest absolute rates of net N mineralization in situ of any coniferous site in California, as well as the lowest specific rates of N mineralization per unit of substrate when temperature was the independent variable. In their 17-year study of the decomposition of thinning slash on the exact site of our study, McColl and Powers (2003) found no decline in N concentration in branches, although dry mass had declined by one third. The strong control of climate on the N cycle makes N a common limiting factor in high-elevation forests in the west-

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ern United States (Powers 1992; Powers and Edmonds 1992). Therefore, any silvicultural practices that increase soil warming and N availability at high elevations could increase above-ground productivity and accelerate stand development.

Common at high elevations in California and southern Oregon, red fir (*Abies magnifica* A. Murr.) is an important forest tree because it provides not only commercial wood but also watershed protection and recreation values (Laacke 1984). Although red fir grows slowly during the seedling and small sapling stage (Hallin 1957), growth often accelerates during the large sapling and pole stages. Natural fir regeneration often forms dense stands under openings in the overstory (Oliver 1986; Schumacher 1928), in which competition for sunlight, nutrients, and soil water can be intense. Upon release from competition, red firs respond quickly (Gordon 1973). For example, Oliver (1988) found that when a stand of fully stocked red fir and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) was thinned to 50% of its basal area, the growth of the remaining trees increased sufficiently, so that overall stand volume growth was not significantly reduced during the 10 years of the study.

Generally, stand net productivity rises when resource availability increases with fertilization in either thinned or unthinned stands. Yet, information on these practices in red fir is limited to a few studies. Powers (1981, 1992) and Miles and Powers (1988) reported that fertilization of red fir and white fir at the rate of 224 or 448 kg N/ha significantly increased 5-year growth more consistently than in any other forest type studied. For 22 test sites that included white fir and red fir, both thinned and unthinned stands fertilized with 224 kg N/ha grew 30% faster in total volume than unfertilized stands. Surprisingly, the growth of unthinned and thinned stands treated with 448 kg N/ha was only 18% and 9% greater, respectively, than that of unfertilized stands. Because they often grow at high elevations, *Abies* forests tend to be remote and develop to high stocking densities. The growth response of an unthinned stand of grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) suggests that the effect of fertilization with 224 kg N/ha was marginal and nonsignificant (Shafii et al. 1990), unless thinning was combined with fertilization. The effect of fertilization on growth has also been reported for balsam fir (*Abies balsamea* (L.) Mill.) (Weetman et al. 1976), white fir (Heninger 1982), Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) (Cochran et al. 1986), and noble fir (*Abies procera* Rehd.) (Powers 1992).

In this study, we report results from an experiment established in northeastern California 26 years ago. Using the long-term data collected from this study, we address the following questions: (1) How long does growth of red fir respond to N application? (2) Does thinning affect growth and mortality of red fir, and if so, how long does the effect last? (3) Is there an interaction between the effects of thinning and fertilization on growth and mortality, and if so, how does a specific combination affect growth and mortality? (4) What are the long-term effects of these treatments on stand structure?

Materials and methods

The study area

The study area is located on California's Medicine Lake Highlands, northeast of Mount Shasta within the southern

Cascade Range (41°34'N, 121°43'W) in the Klamath National Forest. The site is at 1890 m elevation on a northwest-facing 10% slope. The mean annual air temperature is 9 °C, with winter lows averaging -12.4 °C and summer highs averaging 30.3 °C. Annual precipitation averages 1000 mm, falling mainly as snow in the winter. The soil is derived from recent rhyolitic pumice overlying an older cobbly loam (cindery over medial-skeletal frigid, thapto-xerocheptic Vitrandepts) at about a 61-cm depth. Mineralizable soil N (Powers 1980) in the pumice averages 5 mg/kg at 20 cm, which is well below the deficiency threshold of 15 mg/kg (Powers 1992). Low soil N is mirrored by foliar N concentrations that average 1.05% in current-year needles, which is below the critical level of 1.15% N (Powers 1992). Site index, as measured from dominant trees before treatment, is 11 m at 50 years (Dolph 1991). However, site productivity may be somewhat underestimated in study tree because of the suppression of height growth by high stand density.

The 60-year-old stand of red fir saplings and poles was regenerated naturally after a wildfire. Remnant old-growth trees were harvested, leaving an even-aged stand with stand densities varying between 6000 and 29 800 stems/ha and averaging 17 000 stems/ha. The diameter at breast height (DBH) of the average dominant tree was 11 cm, and the height of the average dominant tree was 6.3 m.

Field design

Eighteen 0.0225-ha plots with a 5-m treated buffer were established within a 3-ha area in the fall of 1976. The plots were grouped into three blocks of six plots each on the basis of pretreatment stand density. Within each block two plots were thinned heavily to 1141 stems/ha ($\approx 3.0 \text{ m} \times 3.0 \text{ m}$ spacing), two plots were thinned lightly to 4445 stems/ha ($\approx 1.5 \text{ m} \times 1.5 \text{ m}$ spacing), and two plots were left unthinned with an average of 16 687 stems/ha ($\approx 0.8 \text{ m} \times 0.8 \text{ m}$ spacing). The three stocking levels were crossed factorially with the two fertilization treatments (non fertilization and 300 kg elemental N/ha) in a randomized block design (Table 1).

Stands were thinned by hand from below, and the most vigorous, well-formed individuals were left as potential crop trees as far as this was compatible with reasonably uniform spacing. Slash was left to decay on the site. Agricultural grade urea (46% N) was applied by hand to the moist forest floor 3 days after a light snowfall in November 1976. Conditions were favorable for solubilization of the urea. No granules were visible on dark surfaces the day following treatment.

Before the 1977 growing season, trees were tagged and measured according to a scheme that differed by thinning treatments. In the heavily thinned plots, all trees were tagged. In the lightly thinned plots, only every fourth tree, chosen systematically, was tagged because we felt it unnecessary to track the response of every individual tree throughout the study. Unthinned plots, containing up to 668 trees, were sampled with two 0.00416-ha circular plots, which were randomly located and covered 37% of the plot area. Within these subplots every fourth tree, again chosen systematically, was tagged.

All plots were measured for DBH to the nearest 0.25 cm. Total height, crown width, and height to live crown were measured to the nearest 0.3 m for the tagged trees. Crown class, tree damage, and diseases were noted. Measurements for stem volume were obtained from about six randomly se-

Table 1. Plot characteristics immediately after thinning and fertilizing a stand of red fir saplings and poles in 1976 and 26 years later in 2002, in northeastern California.

Block	Treatment		Plots in 1976				Plots in 2002			
	Fertilization (kg N/ha)	Thinning	Trees/ha	QMD (cm)	Height (m)	BA (m ² /ha)	Trees/ha	QMD (cm)	Height (m)	BA (m ² /ha)
I	0	Unthinned	14 062	6.2	2.9	43.34	3 846	16.6	3.8	83.27
		Lightly thinned	4 489	8.7	5.0	26.27	3 378	14.1	8.2	52.88
		Heavily thinned	1 156	11.4	6.3	11.75	1 111	24.7	11.3	53.42
	300	Unthinned	22 596	5.8	3.2	59.15	6 370	14.8	6.1	109.86
		Lightly thinned	4 578	8.8	5.6	27.55	2 978	17.6	14.8	72.25
		Heavily thinned	1 200	9.6	5.4	8.73	1 200	25.1	14.7	59.54
II	0	Unthinned	29 688	5.2	3.2	62.98	7 091	12.8	10.3	91.49
		Lightly thinned	4 444	8.6	5.1	25.61	2 756	15.4	10.4	51.06
		Heavily thinned	1 067	11.1	6.9	10.34	978	25.6	16.2	50.32
	300	Unthinned	17 788	4.5	2.8	28.35	5 529	10.7	8.4	49.59
		Lightly thinned	4 533	7.5	3.6	20.06	2 889	16.1	9.3	58.65
		Heavily thinned	1 156	9.7	5.5	8.48	1 022	24.8	15.6	49.52
III	0	Unthinned	9 976	6.9	4.7	37.56	3 005	16.1	7.8	61.04
		Lightly thinned	4 489	8.6	5.2	25.98	2 889	15.7	9.3	56.21
		Heavily thinned	1 111	12.5	8.7	13.57	1 111	24.9	15.9	54.18
	300	Unthinned	6 010	11.1	2.7	61.35	3 966	21.0	5.9	137.53
		Lightly thinned	4 311	8.5	4.3	24.45	2 711	17.4	9.5	64.71
		Heavily thinned	1 156	10.3	4.5	9.68	1 156	23.9	14.5	51.70

Note: QMD, quadratic mean diameter (i.e., the diameter at breast height of the trees of average basal area); BA, basal area.

lected trees per plot that had been measured for DBH and total height. A series of upper stem diameters and lengths were measured directly on trees less than 15 cm in DBH and by an optical dendrometer for trees with larger diameters. Total stem volumes in cubic metres inside bark were calculated by the Smalian formula for all stem segments except the last, which was treated as a cone. All measurements were repeated on the same trees after 5 (1981), 10 (1986), 15 (1991), 20 (1996), and 26 (2002) growing seasons, except that upper stem diameters and crown widths were not measured in the 26th growing season. Therefore, the 2002 volume was estimated with the 1996 volume equation.

Data analysis

Regression analysis was used to establish a volume equation as a function of DBH in English units with about 18 individual-tree volume measurements within each treatment and each measurement period:

$$V = e^{[a + b \ln(\text{DBH})]}$$

where V is volume, a and b are regression constants, which vary among treatment plots and periods ($-4.42 \leq a \leq -2.77$, $1.79 \leq b \leq 2.95$, $0.91 \leq r^2 \leq 0.99$), and $\ln$ is the natural logarithm. Using these equations, we estimated and converted stem volumes to cubic metres for all trees.

Stand density index (SDI), historically defined in English units (Reineke 1933), was calculated as

$$\text{SDI} = 10^{[\log(\text{TPA}) + 1.605 \log(\text{QMD}) - 1.605]}$$

where $\log$ is logarithm to the base 10, TPA is the number of trees per acre, and QMD is the quadratic mean diameter in inches at the stand level.

Then, we plotted total volume per tree against density per hectare on a log scale. A simple linear regression was fitted

with data in the unthinned plots, and the regression line was compared with the self-thinning line with a slope of $-3/2$ (Yoda et al. 1963).

The statistical significance of treatment and interaction effects on plot means was evaluated by a 2×3 factorial analysis of variance because the plot is regarded as our experimental unit. First, mean annual increment (MAI) during 26 years was analyzed for each variable. Then, to eliminate the initial size effect from the previous measurement, we used periodic annual increment (PAI) as a dependent variable for analysis of variance.

The following statistical model was used:

$$Y_{ijk} = \mu + B_j + F_i + T_k + FT_{ik} + e_{ijk}$$

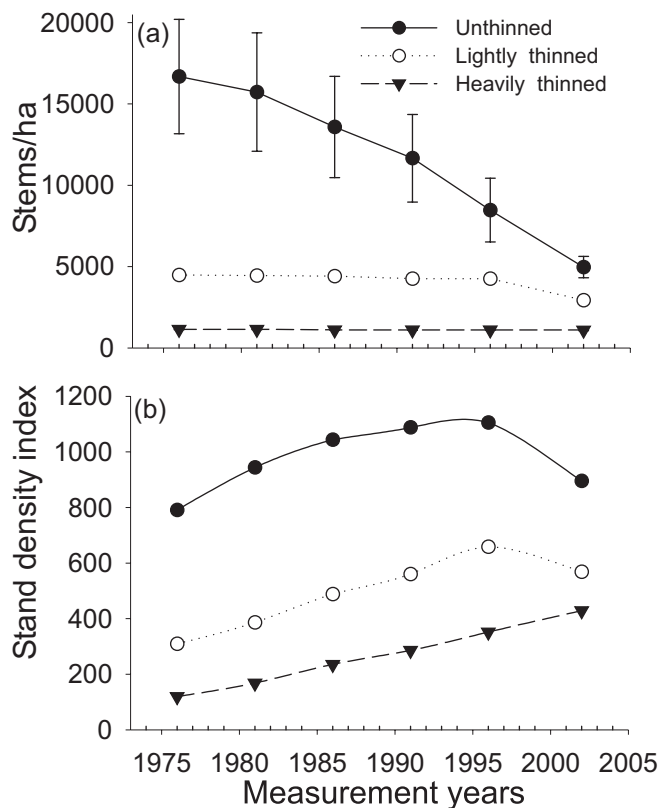
where Y is the dependent variable measured at the i th fertilizer level (F) within the k th thinning level (T) within the j th block (B), μ is the overall mean, FT is the fertilizer by thinning interaction, and e is the error term. All analyses were performed with SAS (SAS Institute Inc., Cary, North Carolina) with $\alpha = 0.05$ as a critical value of significance.

Results

Mortality

Few trees died in the thinned plots during the 26-year study, except for lightly thinned plots in the final period (Fig. 1a). Stand density was about 1111 (1067–1200) stems/ha in the heavily thinned plots and about 4444 (4311–4578) stems/ha in the lightly thinned plots. Between 1996 and 2002, about 31% of the trees died in the lightly thinned plots across all blocks. More mortality occurred in the fertilized plots (34%) than in the nonfertilized plots (28%) in both the heavily thinned and the lightly thinned treatments. The heavy

Fig. 1. Mean (± 1 standard error) number of trees per hectare (a) and mean stand density index (b) for five growth periods after thinning red fir saplings and poles to three levels of stocking in northeastern California. Standard errors for lightly thinned and heavily thinned treatments are too small to display.

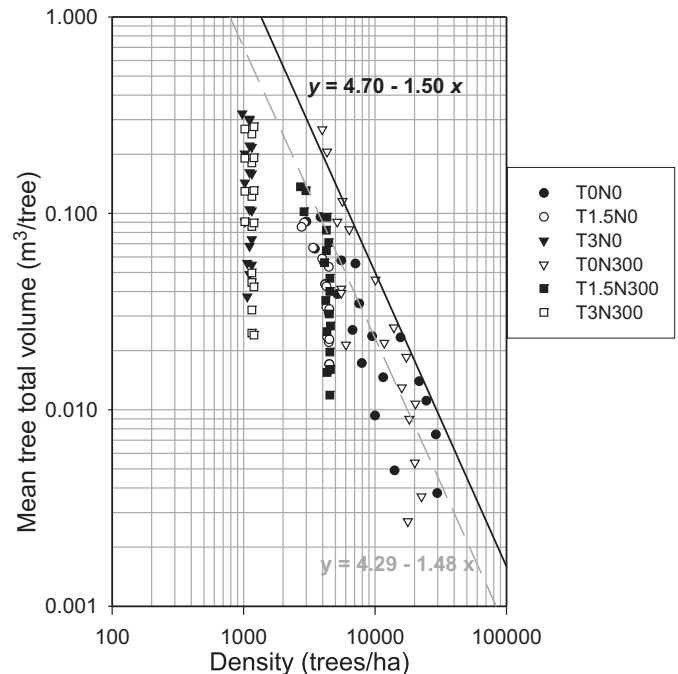


mortality was associated with high stand densities and was exacerbated by snow damage to the subordinate crown classes.

Unthinned plots experienced heavy mortality throughout the study period (Fig. 1a). At the beginning of the study in 1976, stand density averaged 16 687 stems/ha, but varied markedly from 6010 to 29 688 stems/ha among the six plots. By 2002, stand density averaged 4968 stems/ha (range 3005–7091 stems/ha), illustrating the steep decline in living stems. On average, density was greater in nonfertilized plots (17 909 stems/ha) than in fertilized plots (15 465 stems/ha) in 1976. Self-thinning reduction was 962 stems/ha (non-fertilized: 1763 stems/ha vs. fertilized: 160 stems/ha) for the first 5-year period, 2143 stems/ha (2564 vs. 1723 stems/ha) for the second 5-year period, 1923 stems/ha (2123 vs. 1723 stems/ha) for the third 5-year period, 3185 stems/ha (3245 vs. 3125 stems/ha) for the fourth 5-year period, and 3506 stems/ha (3566 vs. 3446 stems/ha) between 1996 and 2002. In contrast with the thinned plots, the unthinned fertilized plots had slightly lower mortality than the nonfertilized plots because of the lower initial density.

Heavy mortality throughout the observation period in the unthinned plots was to be expected because SDI exceeded 1000 (Fig. 1b), the maximum for the species (Oliver and Uzoh 1997), during the second 5-year period. The lightly thinned plots experienced heavy mortality during the fifth period after they reached the zone of imminent mortality, estimated to be at 55% of the maximum SDI (i.e., 550) (Drew

Fig. 2. Self-thinning plot for red fir saplings and poles that were unthinned (T0), lightly thinned (T1.5), or heavily thinned (T3) and fertilized (N300) or unfertilized (N0) from 1976 to 2002 in northeastern California. The regression line (broken) is fitted with data from unthinned plots ($r^2 = 0.73$). The self-thinning line is visually fitted with a theoretical slope of $-3/2$.



and Flewelling 1979). Heavily thinned plots were well below this zone, as they reached an SDI of only 429 during the last period of observation.

The slope of the regression line (-1.48) for unthinned plots was almost identical to the slope of the self-thinning theoretical line ($-3/2$) (Fig. 2). Fertilized unthinned plots appeared to follow the self-thinning law, as did the nonfertilized plots. Thinning postponed the self-thinning stage.

Fertilization effect

At the beginning of the study in 1976, differences in QMD, height, basal area, and volume were not significant between fertilized and nonfertilized plots. During the 26-year growth period, fertilization had a significant effect only for MAI of basal area ($P < 0.05$), not for MAI of QMD, height, and stem volume ($P \geq 0.11$) (Table 2). However, the fertilized plots accumulated substantially more BA and volume than did the nonfertilized plots after the study was initiated (Figs. 3a and 3c). Trends of average tree height and QMD were similar.

PAI of QMD and height responded significantly to fertilization for at least a decade after we applied 300 kg N/ha to this natural stand (Table 2). Variation in the PAI of QMD and height between fertilized and nonfertilized treatments was highly significant ($P < 0.01$) for the first 5 years and significant ($P < 0.05$) for the second 5 years (Table 2). After 10 years, the difference in PAI of QMD and height was no longer significant between N treatments.

PAI of basal area per hectare was significantly greater for fertilized trees than for nonfertilized trees (Fig. 3b) during the first ($P < 0.001$), second ($P < 0.01$), and third ($P < 0.05$) 5-

Table 2. Source of variation, degrees of freedom (df), mean squares (MS), and probability values for periodic annual increment (PAI) of quadratic mean diameter (QMD), height, basal area (BA), and stem volume for five measurement periods and for mean annual increments (MAI) for the entire 26 years after thinning and fertilizing red fir saplings and poles in northeastern California.

	Source of variation						
	Fertilization (df = 1)		Thinning (df = 2)		Fertilization × thinning (df = 2)		Error (df = 10)
	MS	<i>P</i> > <i>F</i>	MS	<i>P</i> > <i>F</i>	MS	<i>P</i> > <i>F</i>	MS
PAI QMD							
1976–1981	0.1110	0.0015	0.1616	0.0001	0.0237	0.0522	0.0059
1981–1986	0.0353	0.0270	0.3220	0.0001	0.0026	0.6239	0.0053
1986–1991	0.0038	0.3795	0.0736	0.0007	0.0045	0.4040	0.0045
1991–1996	0.0025	0.6243	0.1126	0.0025	0.0015	0.8571	0.0097
1996–2002	0.0016	0.7428	0.0413	0.0942	0.0077	0.5845	0.0137
MAI QMD (1976–2002)	0.0079	0.1067	0.1005	0.0001	0.0059	0.1471	0.0025
PAI height							
1976–1981	0.3351	0.0019	0.2001	0.0036	0.0004	0.9790	0.0192
1981–1986	0.2796	0.0204	1.0368	0.0001	0.0211	0.5819	0.0369
1986–1991	0.1304	0.2625	0.4077	0.0423	0.0140	0.8613	0.0924
1991–1996	0.0904	0.3314	0.8565	0.0043	0.0567	0.5408	0.0867
1996–2002	0.0327	0.7658	0.9296	0.1184	0.0878	0.7824	0.3492
MAI height (1976–2002)	0.1459	0.1167	0.6243	0.0018	0.0209	0.6670	0.0495
PAI BA							
1976–1981	4.9753	0.0001	1.4032	0.0019	0.3833	0.0751	0.1130
1981–1986	3.2563	0.0017	0.5726	0.0854	0.5793	0.0835	0.1801
1986–1991	1.1338	0.0462	0.2346	0.3792	0.4432	0.1831	0.2192
1991–1996	1.3873	0.0591	0.8583	0.1079	0.3643	0.3437	0.3060
1996–2002	0.7000	0.4361	13.2675	0.0019	0.6703	0.5523	1.0635
MAI BA (1976–2002)	1.0286	0.0484	0.1545	0.4935	0.1112	0.5957	0.2037
PAI volume							
1976–1981	20.3655	0.3024	327.5198	0.0004	4.3812	0.7803	17.2249
1981–1986	215.8855	0.1007	179.4046	0.1141	111.0417	0.2346	66.0145
1986–1991	143.0001	0.1079	6.7099	0.8657	94.6789	0.1777	45.8720
1991–1996	459.3553	0.0295	37.4629	0.6072	100.4822	0.2894	71.4016
1996–2002	0.2815	0.9428	352.3345	0.0138	16.6739	0.7330	52.0376
MAI volume (1976–2002)	104.8002	0.1332	59.2107	0.2674	40.0783	0.3947	39.2335

year periods (Table 2). During the fourth period (1991–1996), the difference was only significant at $\alpha = 0.06$ level ($P = 0.059$). The fertilization effect disappeared during the fifth period (1996–2002, Fig. 3). Basal area increases were 97%, 51%, 38%, and 33% greater in fertilized trees than in non-fertilized trees during the first, second, third, and fourth 5-year periods, respectively. In the last 6 years net PAI of basal area was greater in the nonfertilized plots than it was in the fertilized plots because more trees with larger diameters died in fertilized plots than in unfertilized plots. For the unthinned plots, total basal area reached 98.1 m²/ha in 1996 and 99.0 m²/ha in 2002 in the fertilized plots, compared with 75.8 m²/ha in 1996 and 78.6 m²/ha in 2002 in the non-fertilized plots (Fig. 3a).

PAI of volume differed significantly between fertilized and nonfertilized plots only during the fourth 5-year period (Table 2, Fig. 3d). Nevertheless, the fertilized plots produced 25%–92% more volume than did nonfertilized plots during the first four study periods. For the four 5-year periods, PAI of volume was 8.66, 8.44, 8.83, and 11.01 m³/ha for the nonfertilized trees and 10.79, 15.37, 14.47, and 21.11 m³/ha for the fertilized trees, respectively. In comparison, PAI of volume

was similar between the nonfertilized plots (7.78 m³/ha) and the fertilized plots (8.03 m³/ha) for the last period (1996–2002).

Thinning effect

Because we thinned from below, QMD and mean height were significantly higher for thinned plots than for unthinned plots at the beginning of the study (Table 2). Trees in the heavily thinned plots had significantly higher QMD and height than trees in the lightly thinned plots. Consequently, basal area and volume had opposite trends than QMD and height (Table 2, Fig. 4) because unthinned plots carried many more stems.

There were highly significant differences among thinning levels for MAI of QMD, height, and crown volume ($P < 0.01$), but not for MAI of basal area and stem volume ($P > 0.25$) (Table 2). We detected a significant variation in PAI of QMD and height among thinning levels during the first, second, third, and fourth 5-year periods (Table 2). Annual QMD and height increments were highest in the heavily thinned plots, followed by the lightly thinned plots, and the unthinned plots. The trends held relatively constant, except that net PAI of QMD in unthinned plots surpassed that in the lightly thinned plots during 1991–1996 and 1996–2002 peri-

Fig. 3. Mean (± 1 standard error) net basal area (BA) production (a), periodic annual increment (PAI) of BA (b), net volume production (c), and PAI of volume (d) among measurement years for fertilized (N300) and nonfertilized (N0) red fir saplings and poles in northeastern California. Gray lines in (a) without error bars indicate net BA production for unthinned N300 and N0 treatments.

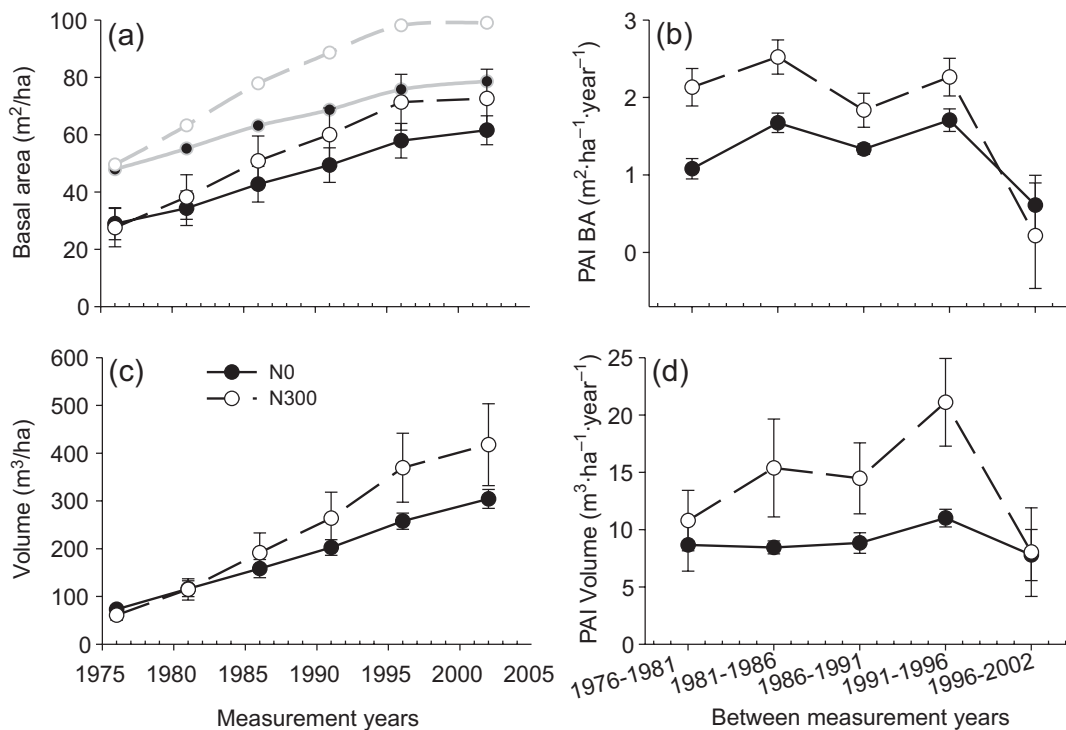
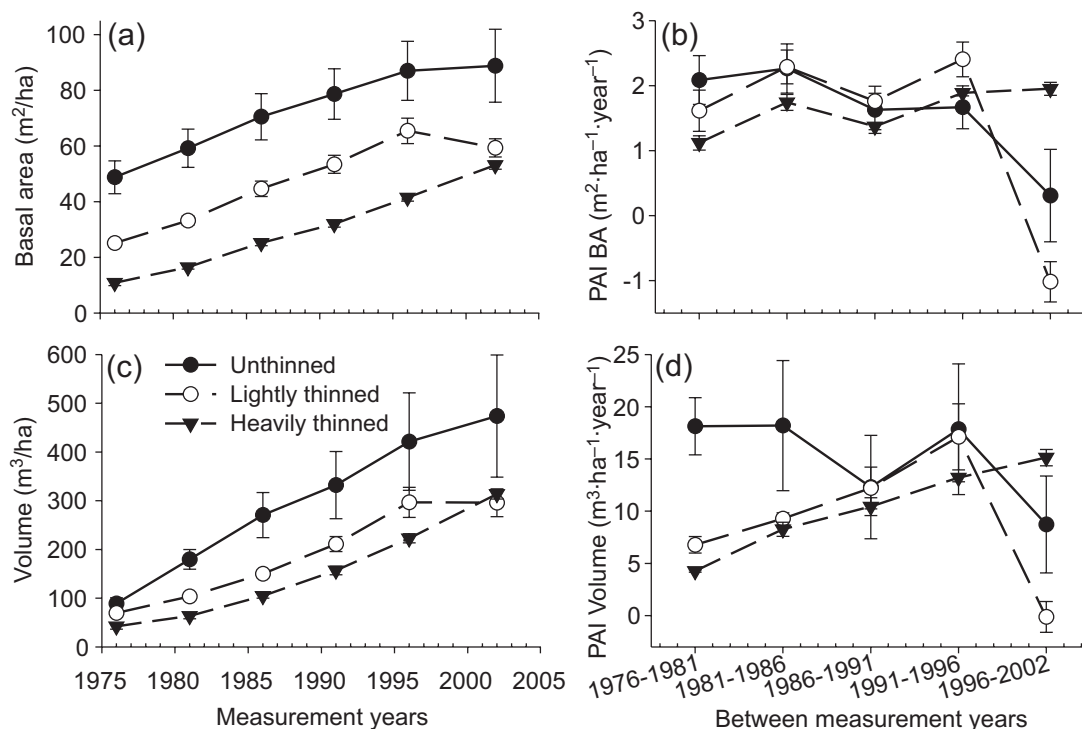


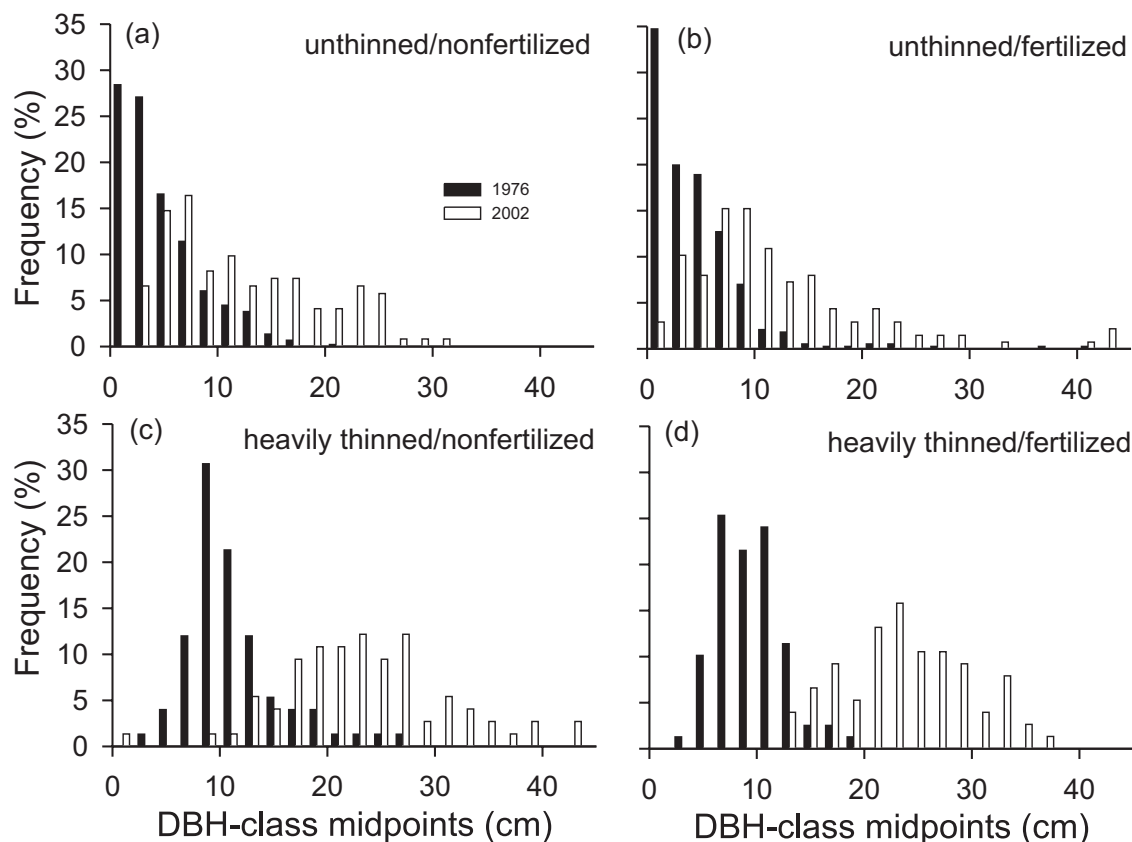
Fig. 4. Mean (± 1 standard error) net basal area (BA) production (a), periodic annual increment (PAI) of BA (b), net volume production (c), and PAI of volume (d) among measurement years for red fir saplings and poles in unthinned, lightly thinned, and heavily thinned stands from 1976 to 2002 in northeastern California.



ods because mortality was concentrated in trees with smaller diameters. During the first 15 years, PAI of QMD was 87% to 167% greater in the heavily thinned plots than in un-

thinned plots, whereas in the lightly thinned plots, PAI of QMD was 10% to 24% greater. Similarly, PAI of height was 96% to 241% greater in the heavily thinned plots and 40%

Fig. 5. Diameter-class frequency distributions for red fir saplings and poles in stands that were unthinned and nonfertilized (a), unthinned and fertilized (b), heavily thinned and nonfertilized (c), and heavily thinned and fertilized (d) in northeastern California.



to 126% greater in the lightly thinned plots than in the unthinned plots.

PAI of basal area varied significantly among thinning levels ($P < 0.01$) during the first and fifth 5-year periods (Table 2). Initially, basal area growth followed the order unthinned > lightly thinned > heavily thinned plots (Fig. 4a), reflecting the differences in numbers of trees per plot. However, the lightly thinned plots grew more than did the unthinned plots (Fig. 4b) from the second 5-year period on, until the stands experienced storm-caused mortality during the fifth period (1996–2002). Interestingly, basal area growth was greater in heavily thinned plots than in unthinned plots from the fourth 5-year period on.

As was the case for PAI of basal area, differences in PAI of volume among thinning levels were highly significant ($P < 0.001$) during the first 5-year period (Table 2) because of the thinning carryover effect. This significant difference disappeared after the first 5 years, although the ranks of thinning levels changed over time (Fig. 4d). PAI of volume was 74% greater in heavily thinned stands than in unthinned stands during the last period (1996–2002), yielding a significant difference among thinning levels ($P = 0.014$).

Effect of treatment interaction

No significant interaction between fertilization and thinning was found for any variable measured in this study (Table 2). However, both fertilization and thinning practices speeded stand diameter-class differentiation from either inverse “J” or skewed left to a more normal distribution (Fig. 5),

although the effect of fertilization was not as obvious as the effect of thinning for the heavily thinned plots.

Discussion

Nitrogen response

Results indicate that growth of red fir can be enhanced by improving N availability. The magnitude of fertilization responses was 33% to 97% for PAI of basal area and 25% to 92% for PAI of volume over the 20 years following treatment. This magnitude is comparable to the previous true fir studies (Heninger 1982; Miles and Powers 1988; Shafii et al. 1990; Weetman et al. 1976) and to averages for other sympatric forest species (Miles and Powers 1988; Weetman et al. 1976). Based on results from only a few test plots that were measured for less than 10 years, Powers (1981) concluded that urea fertilization could improve height growth by 30% to 80%. Remarkably, these estimates are similar to the responses in basal area or volume found in this long-term study.

The effect of N fertilization on periodic annual growth lasted for at least 20 years; the effect on the total growth should be much longer. PAI of basal area was significantly higher for the fertilized trees than for the nonfertilized trees from 1976 to 1996 (Fig. 3b), suggesting that N entered the system immediately. From 1996 to 2002, PAI of basal area was higher for the nonfertilized plots than for the fertilized plots in the unthinned and lightly thinned plots. Clearly, total basal area of fertilized plots reached a plateau earlier than that of nonfertilized plots (Fig. 3a), especially for the unthinned stands. Furthermore, fertilization can push the stand carrying capacity to a

higher level. For instance, total basal area was 75.8 and 98.1 m²/ha in 1996, plateauing at 78.6 and 99.0 m²/ha in 2002, for the unthinned nonfertilized plots and unthinned fertilized plots, respectively. A possible interpretation is that intertree competition was intensified to the point that N and (or) other nutrients could not meet the trees' demands. Therefore, basal area reaches a plateau at different levels under different N availabilities. The results demonstrate the value of a long-term study because we would not have provided these arguments for red fir with only 20 years of data.

On average, 224 kg N/ha is the application rate usually recommended for true fir and other forest types throughout the Pacific Northwest (Powers 1992). Yet, a rate of 300 kg N/ha was applied because the foliar N concentration (1.09%) was lower than the critical level of 1.15% (Powers 1981, 1992) and because of low levels of mineralizable soil N. Unfortunately, since we did not include more levels of N, a response surface could not be constructed. However, previous studies indicated that growth of true fir species was less at 448 kg N/ha than at 224 kg N/ha (Miles and Powers 1988). One possible explanation offered by Powers (1992) is that "the highest rates of fertilization cause some damage to surface fine roots and mycorrhizae from the alkalinity accompanying urea hydrolysis". This hypothesis is worthy of testing.

Does applied N enhance mortality? When plots were unthinned, we found that nonfertilized plots tended to have higher mortality than did the fertilized plots. This might be due to an initial variation of plot densities adapted from a natural stand. Yet, the trend changed for the lightly thinned plots. Most mortality occurred during the fifth 5-year period (1996–2002). Mortality was negligible in both fertilized and nonfertilized heavily thinned plots. Fertilizer-enhanced mortality was not found in a study of grand fir (Shafii et al. 1990).

The self-thinning relation closely followed the general prediction of the $-3/2$ power law. The regression parameters were remarkably similar to the parameters found in balsam fir (Bégin et al. 2001).

Thinning response

We found that PAI of QMD and height increased significantly in response to thinning (Table 2). During the first 15 years, PAI of QMD was 87% to 167% greater in heavily thinned plots than in unthinned plots, whereas in the lightly thinned plots PAI of QMD was 10% to 24% greater. Similarly, PAI of height was 96% to 241% greater in the heavily thinned plots and 40% to 126% greater in the lightly thinned plots than in the unthinned plots. Although the thinning created a significant difference for all variables initially (Table 1), we might have anticipated that in time, standing basal area would differ little between thinned and unthinned plots. From the second period on, we observed that basal area growth was greater in lightly thinned plots than in unthinned plots. Unfortunately, heavy mortality occurred in the lightly thinned plots, causing a net decrease in PAI of basal area during the fifth period (1996–2002). Basal area growth was greater in the heavily thinned plots from the fourth 5-year period on.

In general, natural forest stands, especially red fir and white fir, respond well to thinning because these forest stands tend to carry very high basal areas (Oliver 1986, 1988). Oliver

(1988) found that thinning 50% of the basal area from below in a well-stocked 100-year-old stand resulted in little or no loss of net volume production. Similar results were found in this study in that a significant difference in PAI of volume among the three levels of stocking was only detected during the first 5-year period (Table 2). After the first 5 years, significant differences in annual volume production were not detected, although PAI of volume was greater in the heavily thinned plots than in either the lightly thinned or unthinned plots during the last period (Fig. 4d).

Fertilization by thinning interactions

No interaction was found for any variable tested, for either MAI or PAI (Table 2). The lack of interaction suggests that regardless of the level of intertree competition (spacing level), N fertilization can enhance stand growth. Alternatively, no matter what the N level, a positive response to thinning can be expected. Mixed results were reported in the previous studies. Powers (1992) reported that red fir growth was lower in thinned and fertilized plots than in plots that were thinned but unfertilized in the northern Sierra Nevada in California. However, he also found that fertilizing thinned red fir had significantly enhanced growth compared with fertilizing unthinned red fir at a nearby location. His interpretation was that when foliar N concentration and mineralizable soil N were low and stand density was high, thinned stands would respond to fertilization. Otherwise, thinned stands would not respond to fertilization because wider spacing makes the limited N supply available to the residual trees. On reasonably fertile soils, extra N would probably be superfluous and lost from the system before roots had exploited the new soil volume. Results in our study indicate that N availability was so low that growth was severely constrained. Therefore, fertilization responses occurred on both thinned and unthinned plots.

In grand fir, fertilization effect was also greater for thinned trees than for unthinned trees because thinned trees were larger. Shafii et al. (1990) emphasized tree size and fertilization interactions to demonstrate merchantable volume response and the associated economic returns. However, Powers (1992) showed that on average, 5-year volume growth doubled for trees with a QMD <15 cm, increased 30% for 15–25 cm QMD trees and 10% for 25–35 cm QMD trees, and declined by 9% for >35 cm QMD trees. Whether grand fir (which normally grows at lower and warmer elevations) differs from red fir in response to thinning and fertilization is not clear. The contradictory results might relate to site quality, stand age, or other biotic and abiotic factors.

How do silvicultural practices like thinning and fertilization affect the stand structure? Although this study was not designed to address the question, an analysis of diameter distributions suggests that both treatments can accelerate stand development (Fig. 5). Leaving nature to take its course would slow the process and create abundant fuel that is a fire hazard to the forests.

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