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Stand structure and growth of *Abies magnifica* responded to five thinning levels in northeastern California, USA

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Abstract

A 60-year-old red fir stand with 23,950 stems/ha was thinned to five stand densities. Thinning occurred in 1972, 1976, and 1980. Height, dbh, and crown characteristics were measured seven times at 4–7-year intervals from 1972 to 2002. Tree rings were measured retrospectively to determine growth of individual years. Periodic annual increment (PAI) was analyzed for quadratic mean diameter (QMD), height, crown volume, and basal area per ha. We found significant difference for all variables among thinning levels and among measurement periods ($P < 0.002$). Trees in heavily thinned plots grew more in height, dbh, and crown volume than trees in lightly thinned plots. The trends were true for the eight tallest trees per plot (=100 trees/ha) for height and dbh. Yet, both total and PAI stand basal area were greater in the lightly thinned plots than in the heavily thinned plots. Thinning intensity accelerated the transformation in diameter distribution from either reverse 'J' or skewed shape to a bell-shape. In addition, the heavier thinned plots increased stand vigor and health as indicated by less snow damage and stem deformities than the lighter thinned plots. Annual diameter growth was significantly related to average minimum temperature during the growing season. We conclude that thinning young red fir stands to a wide spacing will enhance stand development and minimize damage to the residual trees.

Keywords: Growth response; Minimum temperature; Red fir; Stand structure; Thinning

1. Introduction

Red fir (*Abies magnifica* A. Murr) is an important component of natural forests from the southern Cascade Range in Oregon through the Sierra Nevada of California. It covers about 800,000 ha in these highlands between latitude 43°35′ and 36°50′N (Franklin and Dyrness, 1973; Barbour and Woodward, 1985; Barbour, 1988). Lower elevational limits, at 1620–1800 m in the Cascade and Siskiyou Mountains, increase toward the south, reaching 2130 m in the southern Sierra Nevada. Upper elevational limits also increase to the south, from 2010 to 2190 m in the north to 2740 m in the south (Laacke, 1990). Because of its beauty and prominence in recreation areas, sheltering of snow packs and wood of commercial value, red fir forests are managed for a wide range of uses.

Red fir can regenerate prolifically under light overstories and in canopy gaps created by partial cuts and wind throws (Gordon, 1970; Parker, 1986). Often dense clumps of small seedlings are established. Competition can be very intense for sunlight, soil moisture, and nutrients within these clumps. In addition, red fir forests are characterized by low temperatures, short growing season, low nutrient availability, and growing-season moisture deficits. As a result, red fir grows slowly in its early stage. To release these understory seedlings, forest managers often use overstory removal to enhance growth rate of understory advance reproduction. Many previous true fir studies indicated that this practice was necessary in order to accelerate young stand development sooner (Ferguson and Adams, 1980; Gordon, 1973; Herring, 1977; Herring and Etheridge, 1976; Helms and Standiford, 1985; Seidel, 1980; Tesch and Korpela, 1993).

Growth of dense stands of saplings and poles can be increased further with thinning and fertilization (Ker, 1981; Oliver, 1986; 1988; Powers, 1981; Zhang et al., 2005). A 60-year-old stand near Medicine Lake, 200 km north of the current study, responded to thinning significantly (Zhang et al., 2005). Oliver (1988) reported that a 100-year-old red and white fir (*Abies concolor* (Gord. & Glend.) Lindl.) stand thinned to 50% of "normal" stand basal area still retained near maximum volume production.

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Winter snow packs that can usually accumulate to 2.4 m in depth by 1 April in northeastern California (Gordon, 1979) can also cause slow early growth. When air temperatures are high enough for a positive net photosynthesis after April, small seedlings are often buried in deep snow. In addition, heavy snow packs deform red fir seedlings and saplings, which decreases growth because energy is diverted to straightening stems during an already short growing season (Williams, 1966). Therefore, these two natural obstacles suggest that seedling growth may relate to the snow depth of the previous winter and temperature influencing snow duration in the early months of the growing season.

Although heavy snow may be detrimental to seedling growth and development, growth of large saplings and pole-sized trees may benefit from the deep snow because of increased soil water availability during the growing season. This is true especially for red fir that has shallow to moderately deep root systems and low drought resistance compared to other *Abies* and western tree species (Hinckley et al., 1982). Hallin (1957) reported that growth accelerated in large saplings and poles 4–5 m in height, a size in which crowns are mostly free of the snow pack.

The purpose of the current study was to determine whether a stand with 'suppressed old small trees' responds to thinning and what thinning intensity is the most suitable for not only capturing available growing space but also for minimizing injury by the release.

2. Materials and methods

2.1. Study area

The study area was on the Swain Mountain Experimental Forest (latitude 40°25′N, longitude 121°6′W), Plumas County, California. The area lies near the summit of Swain Mountain's northeast face, at an elevation of 2044 m. Slopes within the 4 ha study area range from nearly level to about 30%. The soil, derived from Pleistocene basalt, is similar to the Windy Soil Series (cindery, frigid, Typic Dystrandepts). Site index is 14 m at 50 years (Dolph, 1991).

Average annual precipitation is about 1200 mm (Oliver, 1986). Most of the precipitation between November and April falls as snow. Based on more than 50 years of records in Chester, CA, about 16 km south of the study site (latitude 40°30′N, longitude 121°22′W and elevation 1381 m), annual mean maximum temperature is 16.9 °C and minimum temperature is −0.6 °C. Because temperature generally decreases 6 °C with every 1000 m increase in elevation, the actual temperature may be much colder at the study area.

A decadent overstory of old-growth red fir heavily infected with dwarf mistletoe was removed in 1960, leaving a dense stand of suppressed saplings. When the study was begun 12 years later, sapling stand density was about 23,950 stems/ha. These small trees at an average age of 60 years were mostly free of dwarf mistletoe, but stem deformities caused by heavy snow loads were ubiquitous. More than half of the trees had butt sweep, a deformity common in sapling stands on similar slopes at this elevation.

2.2. Experimental setting

In dense portions of the stand, ten 0.08 ha plots were arbitrarily established as part of the study. Pretreatment stand density and mean tree height were estimated from two 0.004 ha measurement plots located at random within each 0.08 ha plot.

In fall 1972, two plots randomly chosen from all 10 plots were thinned to 1.4 m × 1.4 m and the remaining eight plots were thinned to a uniform spacing of 1.8 m × 1.8 m. In fall 1976, six of the eight 1.8 m × 1.8 m plots were randomly selected for

Fig. 1. The plot pictures taken from this red fir study on the Swain Mountain Experimental Forest, Plumas County, California in 1972 (upper two photos) and in 2004 (lower two photos). Left two photos were taken in a plot with 1.4 m × 1.4 m spacing and right two photos were taken in a plot with 3.9 m × 3.9 m spacing.

thinning to 2.7 m × 2.7 m spacing. In fall 1980, two of the six 2.7 m × 2.7 m plots were thinned to 3.9 m × 3.9 m spacing and two were thinned to 5.5 m × 5.5 m spacing. Therefore, we had a total of five spacing levels, two plots of each by the 1981 growing season: 1.4 m × 1.4 m, 1.8 m × 1.8 m, 2.7 m × 2.7 m, 3.9 m × 3.9 m, and 5.5 m × 5.5 m. Wherever possible, well-formed dominant and codominant saplings, free of defect and disease and with live crown ratios of 50% or greater were selected as leave trees. Yet, because such trees often were lacking in areas

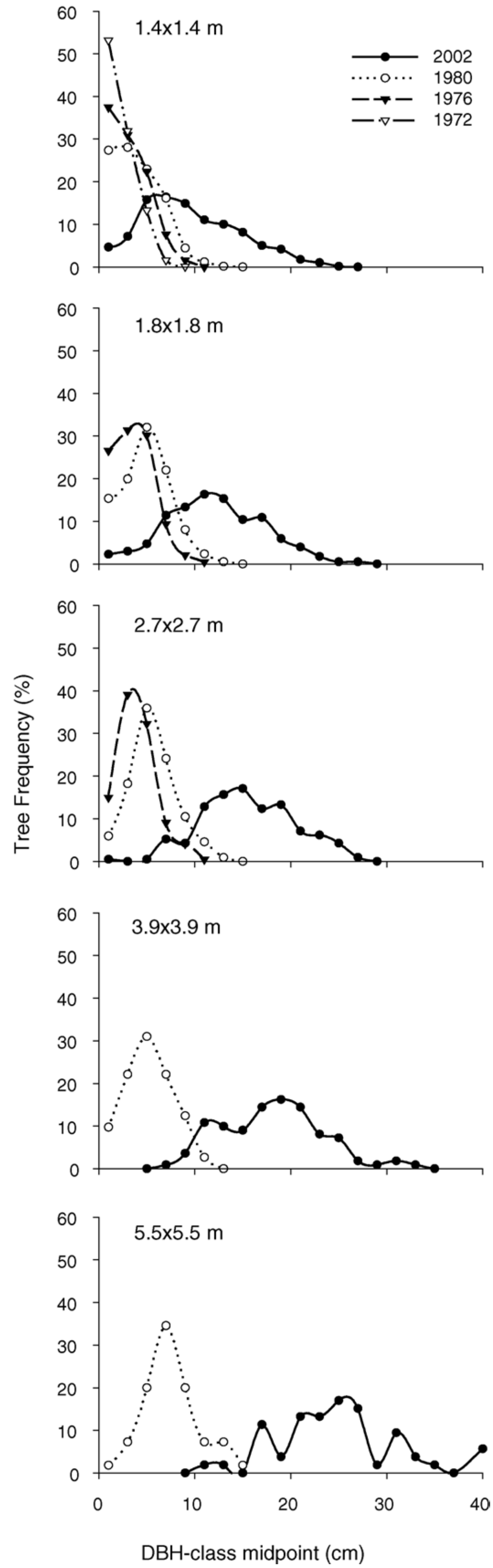

Fig. 2. Tree frequencies (%) at various dbh classes under five different thinning levels for red fir saplings and poles grown at the Swain Mountain Experimental Forest, Plumas County, California from the beginning year to the end of 2002 growing season. For the comparison purpose, 1972 and 1976 growing seasons are included at the lightly thinned plots.

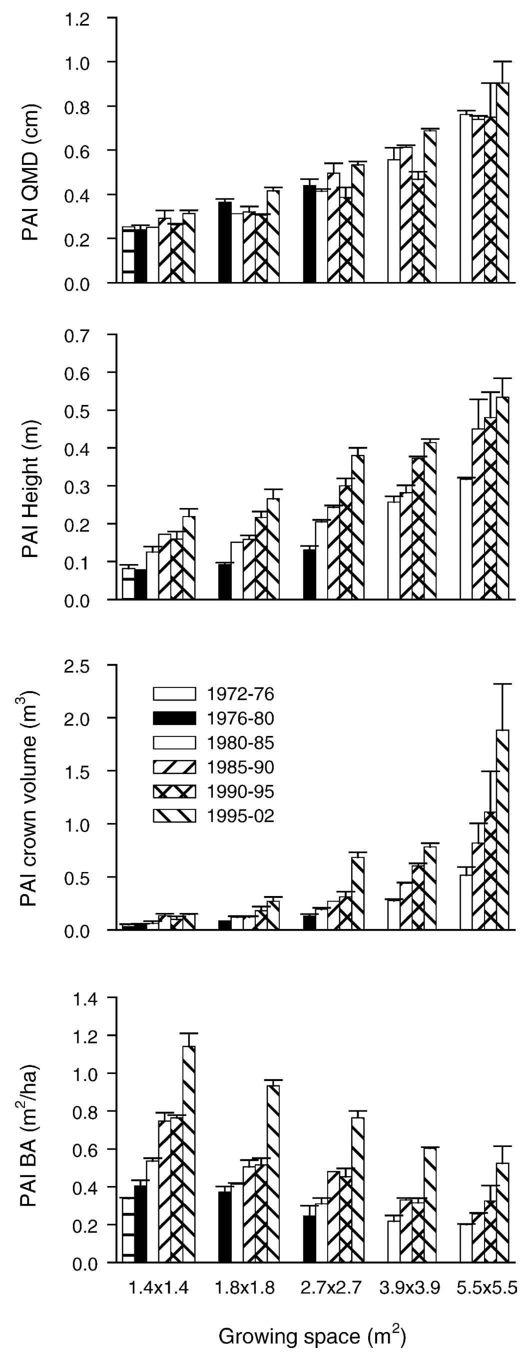

Fig. 3. Means (+1 S.E.) of periodic annual increment (PAI) for quadratic mean diameter (QMD), height, crown volume, and basal area (BA) for red fir saplings and poles among five thinning levels grown on the Swain Mountain Experimental Forest, Plumas County, California during various measurement periods.

with high stand densities, suppressed saplings with shorter crowns were used to obtain the targeted spacing. The purpose of thinning in three steps was to minimize sun scald and snow bend and breakage often prevalent when dense stands are heavily thinned.

2.3. Measurements

All trees in the plots were measured for dbh and tree condition, which included stem deformity, mistletoe presence, snow bend, and sun scald. Height, crown width, and height to first all-live whorl were measured on every fifth tree in the 1.4 m × 1.4 m (99 trees) spacing plot, every fourth tree in both the 1.8 m × 1.8 m (52 trees) and 2.7 m × 2.7 m (32 trees) plot, every third tree in the 3.9 m × 3.9 m (20 trees) plot, and every other tree in the 5.5 m × 5.5 m (11 trees) plot. Because these treatments were installed at different years, we measured only two plots in 1972, six plots in 1976, and all 10 plots in 1980, 1985, 1990, 1995, and 2002.

To determine percentage of annual diameter growth within each growth period, we harvested 10 trees in October of 2004 from 4 to 30 cm in dbh from the buffer of the various plots. Two discs were taken, one from the 1.4 m position and another from ground level. These discs were sanded and ring width was measured at four directions with a TA UniSlide tree ring measurement system (TA 4040H1-S6, Metronics Inc., Bedford, NH, USA). After ring widths were measured, an annual percentage of growth within each measurement period was calculated for each of four directions on each disc. Then, annual percentages were averaged for each period. The product of annual percentage and periodic increment for a particular period yielded an annual growth for a specific year.

2.4. Data analysis

Basal area per ha (BA) was calculated from dbh and quadratic mean diameter (QMD) was calculated from basal area. Crown volume was calculated with a cone volume equation. Due to the small trees in the study, individual-tree and stand stem volumes were not calculated and analyzed. Because we consider the effect of the previous size on the current variables, analysis of variance was conducted with periodic annual increment (PAI) as dependent variables. We treated plots as our experimental units. The statistical model for estimating mean responses per year and overall standard error is

$$\text{Response}_{ijk} = T_{ij} + \text{Plot}_k + e_{ijk}$$

where i = 1–5, j = 1972, 1976, 1980, 1985, 1990, 1995, and 2002, k = 1, 2 (number of plots), T_{ij} is the effect from ith thinning level and jth year, plot effect (Plot: assumed to be a random effect) and e is the residual error.

Since the completed thinning levels were achieved in 1980, we were able only to include data from 1980 and later in our analysis. The statistical model is

$$\text{Response}_{ijk} = T_i + \text{Period}_j + T \times \text{Period}_{ij} + \text{Plot}_k + e_{ijk}$$

Table 1
Summary of type 3 tests of fixed effects including source of variation, degree of freedom for both numerator and denominator, F-values and probability values for periodic annual increment (PAI) quadratic mean diameter, height, crown volume, and basal area after thinning red fir saplings and poles on the Swain Mountain Experimental Forest, Plumas County, California

Source of variation	d.f. (numerator)	d.f. (denominator)	PAI QMD (cm)		PAI height (m)		PAI crown volume (m^3)		PAI BA (m^2/ha)	
			F	P	F	P	F	P	F	P
Thinning level	4	15	41.36	≤0.001	21.45	≤0.001	10.29	≤0.001	56.26	≤0.001
Period	3	15	7.87	≤0.002	62.66	≤0.001	38.79	≤0.001	150.54	≤0.001
Thin × period	12	15	0.57	≤0.833	2.56	≤0.045	7.86	≤0.001	2.20	≤0.076
Comparisons										
1.4 vs. 1.8				≤0.204		≤0.400		≤0.721		**≤0.001**
1.4 vs. 2.7				**≤0.001**		≤0.004		≤0.158		**≤0.001**
1.4 vs. 3.9				**≤0.001**		**≤0.001**		≤0.029		**≤0.001**
1.4 vs. 5.5				**≤0.001**		**≤0.001**		**≤0.001**		**≤0.001**
1.8 vs. 2.7				≤0.018		≤0.025		≤0.280		≤0.023
1.8 vs. 3.9				**≤0.001**		**≤0.001**		≤0.058		**≤0.001**
1.8 vs. 5.5				**≤0.001**		**≤0.001**		**≤0.001**		**≤0.001**
2.7 vs. 3.9				≤0.015		≤0.166		≤0.365		≤0.002
2.7 vs. 5.5				**≤0.001**		**≤0.001**		**≤0.001**		**≤0.001**
3.9 vs. 5.5				**≤0.001**		≤0.004		≤0.005		≤0.275
P1985 vs. P1990				≤0.293		**≤0.001**		≤0.027		**≤0.001**
P1985 vs. P1995				≤0.414		**≤0.001**		**≤0.001**		**≤0.001**
P1985 vs. P2002				**≤0.002**		**≤0.001**		**≤0.001**		**≤0.001**
P1990 vs. P1995				≤0.073		**≤0.001**		≤0.054		≤0.648
P1990 vs. P2002				≤0.019		**≤0.001**		**≤0.001**		**≤0.001**
P1995 vs. P2002				**≤0.001**		**≤0.001**		**≤0.001**		**≤0.001**

Bonferroni approach: individual α (alpha) levels are 0.0025 (0.05/(2 × 10)) for 10 thinning level comparisons and 0.0042 (0.05/(2 × 6)) for six period comparisons. Bold numbers show the significant difference between two thinning levels or two periods. Multiple comparisons are presented among thinning levels and among measuring periods.

where i and k are the same as above, and j = 1980–1985, 1985–1990, 1990–1995, and 1995–2002. Thinning effect T_i, period effect Period_j and the interaction $T \times \text{Period}_{ij}$ were assumed to be fixed effect and plot effect Plot_k was assumed to be a random effect. SAS mixed procedure (SAS V.9.1.3, 2004) was used for estimation and treatment comparisons. The Bonferroni approach was applied to compare treatments at an experiment-wise $\alpha = 0.05$. In addition, correlation coefficients among growth and climatic variables were presented as Pearson's r.

3. Results

3.1. Stand development

After 30 years, individual tree growth and stand development was substantial in these plots (Fig. 1). Heavily thinned plots grew more in diameter than the lightly thinned plots. Thinning clearly accelerated the transformation of the diameter distribution from either reverse 'J' or skewed shape to a bell-shape (Fig. 2). However, variation of tree frequency among different diameter classes increased with increasing growing space due to decreased sample sizes.

3.2. Growth

We found that periodic annual increment was significant for QMD, height, crown volume, and basal area among five thinning levels and among periods from 1980 to 2002 (Table 1). Interactions between thinning level and period were significant for only PAI height and crown volume (Table 1) although both variables were measured only on selected trees and the standard error was high for crown volume (Table 2). As we expected, heavily thinned plots increased more in diameter than the lightly thinned plots (Fig. 3). The same trends occurred for PAI height; trees accelerated in height growth more in the heavily thinned plots than trees in the lightly thinned plots, as did annual growth in crown volume. In contrast, PAI basal area was significantly higher in the lightly thinned plots than in the heavily thinned plots for all measurement periods (Table 2, Fig. 3). However, multiple comparisons revealed that only the 5.5 m × 5.5 m thinning level differed significantly from other thinning levels for all four variables except for 5.5 versus 3.9, for which only PAI QMD was significant (Table 1). In addition, only the last period differed from the previous periods for all variables except for PAI QMD

Table 2
Mean estimates and overall standard errors for QMD, basal area, height, and crown volume for red fir saplings and poles grown on five thinning levels at the Swain Mountain Experiment Forest, Plumas County, California

Thinning level	Measurement year	Plot density (trees/ha)	QMD (cm)	Height (m)	Crown volume (m^3)	Basal area (m^2/ha)
1.4 m × 1.4 m	1972	5475	2.62	1.82	0.27	1.45
	1976	5475	3.63	2.15	0.46	2.80
	1980	5400	4.59	2.46	0.67	4.41
	1985	5350	5.85	3.08	0.98	7.09
	1990	5237	7.30	3.94	1.65	10.82
	1995	5087	8.61	4.74	2.15	14.64
	2002	5000	10.80	6.27	3.16	22.62
1.8 m × 1.8 m	1976	2737	4.09	2.35	0.58	1.77
	1980	2737	5.54	2.72	0.91	3.26
	1985	2725	7.11	3.47	1.51	5.33
	1990	2675	8.71	4.27	2.11	7.85
	1995	2575	10.24	5.35	3.01	10.43
	2002	2537	13.15	7.21	4.90	16.96
2.7 m × 2.7 m	1976	1375	4.30	2.64	0.98	1.02
	1980	1375	6.06	3.17	1.50	2.00
	1985	1375	8.13	4.19	2.46	3.55
	1990	1362	10.61	5.41	3.80	5.95
	1995	1350	12.54	6.91	5.37	8.21
	2002	1325	16.28	9.56	10.16	13.56
3.9 m × 3.9 m	1980	712	5.72	3.06	1.46	0.90
	1985	712	8.51	4.35	2.82	1.99
	1990	700	11.57	5.75	5.02	3.64
	1995	700	13.91	7.62	8.04	5.21
	2002	700	18.71	10.51	13.52	9.44
5.5 m × 5.5 m	1980	350	7.93	3.81	2.42	0.84
	1985	350	11.74	5.39	5.00	1.84
	1990	337	15.44	7.65	9.08	3.12
	1995	337	19.18	10.04	14.64	4.75
	2002	337	25.51	13.78	27.83	8.41
S.E.			0.46	0.42	1.60	0.39

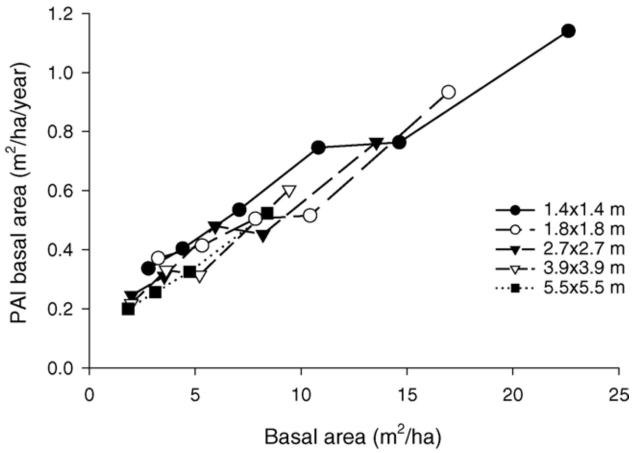

Fig. 4. Relationships between basal area and periodic annual increment of basal area for red fir saplings and poles on the Swain Mountain Experimental Forest, Plumas County, California from 1972 to 2002.

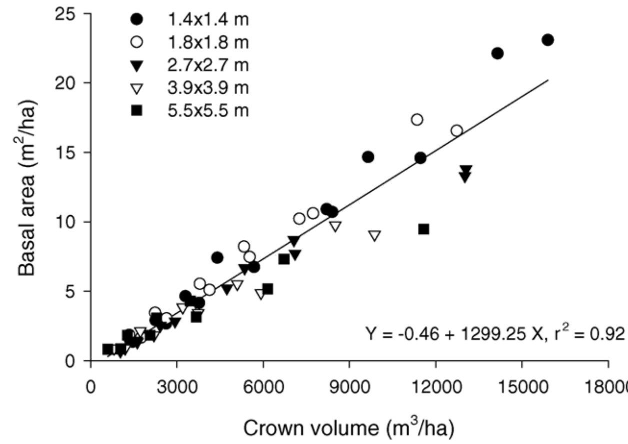

Fig. 6. Relationship between stand basal area and stand crown volume of red fir saplings and poles grown on the Swain Mountain Experimental Forest, Plumas County, California from 1972 to 2002.

(Table 1). Other significant levels were not consistent and therefore, no pattern was found. It has been more than 20 years since 1980 when all thinning levels were installed. Since then, we have found that the greater growth of the fewer trees in the heavily thinned plots could not compensate for the less growth on the many more trees in the lightly thinned plots. A strong positive relationship between stand basal area and PAI basal area also suggests more stand basal area growth in the highest stand basal area. This trend may continue until the onset of self-thinning with strong inter-tree competition (Fig. 4).

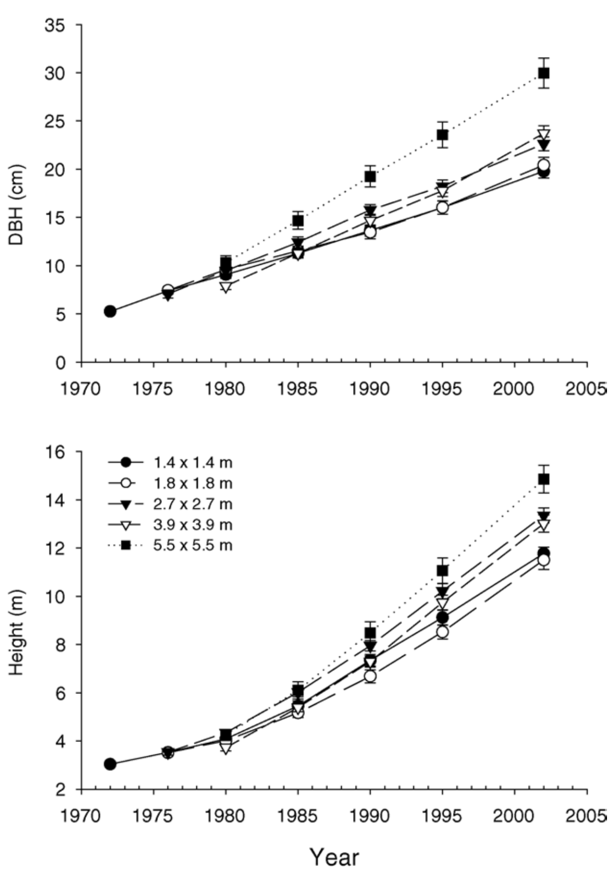

Fig. 5. Means and standard errors of DBH and height of the eight tallest red fir saplings and poles among five thinning levels grown on the Swain Mountain Experimental Forest, Plumas County, California during various measurement periods.

From an analysis of the eight tallest (dominant) trees from each plot (equivalent to 100 trees/ha), we found ranks of average height and dbh were 5.5 > 3.9 > 2.7 > 1.8 > 1.4 m spacing (Fig. 5). However, the two lowest thinning intensities (1.4 and 1.8 m) appeared similar and so did the two intermediate intensities (2.7 and 3.9 m).

Stand basal area was significantly correlated to stand crown volume ($r^2 = 0.92$, $P < 0.0001$) (Fig. 6). The trend is the same as the relationship between individual-tree basal area and crown volume. As a tree allocates more carbon to foliage, which increases the photosynthetic areas, more carbon will be assimilated and stem growth increases. Thinning a stand would not change this relationship.

3.3. Tree damage

We found that as many as 43% of the trees showed stem deformities such as butt sweep, “S” curves, and “dog legs” caused by the heavy snowpack (Table 3). The deformities occurred in all plots and treatments although the lightly thinned plots included more trees with defective form throughout the study periods. Trees released from intensive competition by thinning, tended to out grow this problem. Nevertheless, snow continues to bend and damage trees. We found that as many as 9% of the trees in the most lightly thinned plots during the 1990–1995 period were bent by snow (Table 3). Two heavy snow years occurred in 1993 and 1995. In 1995, maximum precipitation records were set for January, March, and annual totals in Chester, CA, 16 km from the study site.

Sun scald is another common problem when a dense sapling stand is thinned regardless of thinning level (Table 3). The cambium on the lower stem will be damaged or killed when

Table 3
Percentage of deformity, snow bend, and sun scald for red fir saplings and poles in a natural stand thinned to five levels of growing space on the Swain Mountain Experimental Forest, Plumas County, California during 1972–2002 growing periods

Damage categories	Measurement year	1.4 m × 1.4 m	1.8 m × 1.8 m	2.7 m × 2.7 m	3.9 m × 3.9 m	5.5 m × 5.5 m
Deformity	1972	40.3	–	–	–	–
	1976	30.9	41.4	22.3	–	–
	1980	41.6	42.6	20.5	43.4	30.9
	1985	36.2	42.5	13.7	28.3	9.1
	1990	21.9	24.4	9.7	5.4	5.6
	1995	33.7	20.2	10.2	7.2	3.8
	2002	22.3	15.6	4.7	5.4	7.5
Snow bend	1972	1.6	–	–	–	–
	1976	4.5	1.6	0.0	–	–
	1980	4.4	1.6	0.5	0.0	0.0
	1985	4.4	0.7	0.0	0.0	0.0
	1990	2.6	0.7	0.5	0.0	0.0
	1995	9.3	6.6	1.9	1.8	0.0
	2002	5.6	4.2	2.8	1.8	0.0
Sun scald	1972	3.0	–	–	–	–
	1976	31.3	34.3	19.1	–	–
	1980	3.2	0.5	0.5	2.7	16.4
	1985	0.0	0.0	0.0	0.0	10.9
	1990	1.3	0.0	0.0	0.0	0.0
	1995	0.6	0.5	0.0	0.0	0.0
	2002	0.5	1.2	1.4	0.0	0.0

Table 4
Correlation coefficients among annual diameter growth for different levels of thinning and climatic variables in a red fir study at the Swain Mountain Experiment Forest, Plumas County, California

	Annual diameter growth				
	1.4 m × 1.4 m	1.8 m × 1.8 m	2.7 m × 2.7 m	3.9 m × 3.9 m	5.5 m × 5.5 m
Growing-season, T_{max}	0.32	0.28	0.34	0.30	0.27
Growing-season, T_{min}	0.77***	0.45*	0.61**	0.57**	0.59**
Annual precipitation	−0.24	−0.35	−0.38	−0.35	−0.30
Winter snowfall	−0.18	−0.30	−0.34	−0.34	−0.21
Annual diameter growth					
1.4 m × 1.4 m	1.00***	0.85***	0.94***	0.93***	0.93***
1.8 m × 1.8 m		1.00***	0.98***	0.95***	0.97***
2.7 m × 2.7 m			1.00***	0.98***	0.89***
3.9 m × 3.9 m				1.00***	0.91***
5.5 m × 5.5 m					1.00***

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

exposed suddenly to full insolation. The symptoms are more severe in thin-barked saplings than in larger size classes. A long-term effect could be detrimental if rot fungi infect the trees through the wounds.

3.4. Annual diameter growth and climate

Annual diameter growth was consistently related to growing season (June–September) mean minimum temperature (Table 4) when tree-ring width was used to estimate the annual diameter growth within each thinning level. Yet, relationships between growth and mean maximum temperature, precipitation, winter snow fall, or any combinations as a function were either non-significant or inconsistent. We also found that correlations between any two levels were significant in diameter increment (Table 4, $0.85 \leq r \leq 0.98$, $P < 0.001$).

4. Discussion

The response to thinning in growth and stand structure was significant in the current study as well as in previous studies in stands of various ages (Oliver, 1986, 1988; Zhang et al., 2005). Advance regeneration is common under old-growth stands of red fir and usually these stands demonstrate poor vigor due to intensive competition for the site's resources. When an overstory is removed, diameter growth may not respond for 3 years and height growth may not respond for 5 years for conditions found in his study (Gordon, 1973). Similar trends were found in grand fir (*Abies grandis* (Dougl.) Lindl.) in northern Idaho and central Oregon (Ferguson and Adams, 1980; Seidel, 1980), in white fir in California and Oregon (Helms and Standiford, 1985; Tesch and Korpela, 1993), and in Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) (Herring and Etheridge, 1976) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) (Herring, 1977) in British Columbia, Canada. All these studies agree that responses of trees to overstory removal mainly depend on the condition of the trees before release. Clearly, stands with initial densities as high as 23,950 stems/ha, as in the current study, will not show a great response to the release (Oliver, 1986). Therefore, these dense stands must be thinned in order to enhance growth and stand development.

Thinning enhances the growth of not only small trees, but also the dominant trees (Fig. 5). If we assume that a 1 ha mature stand contains 100 trees, we can enhance the stand development by thinning heavily at an early age. For example, average height was 15 m for dominant trees in the heaviest-thinned plots, 13 m in the intermediately thinned plots, and 12 m in the lightly thinned plots. Similar trends existed for dbh (Fig. 5). Nevertheless, damage caused by release must be considered (Ferguson and Adams, 1980; Herring and Etheridge, 1976; Tesch et al., 1993).

Thirty years after thinning, lightly thinned plots still showed the highest stand productivity measured as basal area per ha (Table 2, Fig. 3). PAI basal area was double that of the heaviest thinned plots. We do not expect this trend to continue, however. As unmanaged stands develop, inter-tree competition intensifies and self-thinning begins reducing net productivity to levels found in the thinned stands. Unfortunately, since the current study does not include unthinned controls, we cannot know if net productivity was reduced by thinning to a 1.4 m × 1.4 m spacing—the lightest thinning treatment.

Thinning from below increases stand vigor and health by removing the most defective trees. The heavily thinned plots showed less deformity and snow bend than the lightly thinned plots (Table 3). Two explanations follow. (1) Individual trees in the heavily thinned plots grew faster and stronger than they did in the lightly thinned plots, resulting in less snow damage. (2) Selection of the best trees to leave was more intense in heavily thinned plots. Thus, fewer deformed trees had to be selected as leave trees to meet the treatment targets. Sun scald caused by thinning or overstory removal can be a serious problem, which is affected not only by the targeted stand density and physical location, but also by individual tree condition before thinning. It was reported to correlate significantly with percent live crown suggesting that more live crown will protect stems from the sun's direct beam (Oliver, 1986).

Regardless of stand density, diameter growth was significantly related to average minimum temperature during the June–August period (Table 4). Obviously, we would expect that precipitation and growth would be strongly correlated (Hallgren and Helms, 1992). Based on dbh measurements on 200 trees from 1972 to 1980, Oliver (1986) found that more growth was associated with less precipitation. He argued that the most important factor controlling growth in this area was the length of growing season; less precipitation (snow) suggests a longer growing season. Yet, this relationship was not significant when all the data from 1972 to 2002 was used, although a negative trend did exist during this whole period. The reason for the non-significant relations might be due to the change in response of saplings to snow at the different developmental stages. The crowns of small saplings can be completely or partially covered by a typical snow pack. When saplings become larger, more of the crown is exposed, allowing for some winter and early spring photosynthesis. Furthermore, because tree growth and minimum temperature were significantly related, growth and stand development of these red fir stands may benefit from a warming climate.

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