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Effect of stand densities on stand dynamics in white fir (*Abies concolor*) forests in northeast California, USA

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Abstract

Six white fir trials were established during the last half-century to develop guidelines for managing the existing natural stands across northeastern California. We analyzed data collected from these trials at about 5-year intervals since their installation. Because these trials were independent of each other, the design and treatments varied among the sites. Targeted density treatments were selected based on 40, 55, and 70% of normal basal area from early yield tables at three of the sites. More density treatments were included at the remaining three sites. We found a significant response in growth to different stand densities regardless of site qualities, ages, and stand histories. Periodic annual increment for basal area and volume varied significantly by periods for all sites except the basal area at one site. Regardless of site quality, thinning from below leaving about 64% of the original measure of basal area did not significantly reduce productivity. If performed early in the life of the stand, such a thinning will reduce the accumulation of flammable materials due to natural self-thinning. A logistic function of periodic annual increment for basal area to relative stand density fits the data well and can be a useful tool for forest manager.

Keywords: Growth; Logistic model fitting; Relative density; Stand structure; Thinning

1. Introduction

From the late 1960s to early 1980s, five stand density trials were established for white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), and one trial was established for a white fir and red fir (*A. magnifica* A. Murr.) mix, within their natural range across northeastern California. The goal was to develop guidelines for intensively managing natural stands to meet the future demands for wood and energy. Although timber production may not be the first priority in many of today's forests, other uses of these forests for water, wildlife, recreation, and aesthetics also require stand density management. Furthermore, because the threat of destructive wildfire has intensified in recent years, thinning stands from below has become a useful tool to reduce the buildup of hazardous fuels. Information on density management will guide forest managers in maintaining healthy true fir forests into the future.

In California, true fir forests represent approximately 27% of the total sawtimber volume (Oswald, 1970) and 32% of the net volume of growing stock in the northern interior (Bolsinger, 1976). The combined effects of fire exclusion during the last half century and the preferential harvesting of pine have resulted in abundant white fir regeneration. Perhaps, therefore, true fir represents an even greater proportion of the sawtimber volume in California today.

In the past, true fir was regarded as a weed species because of inherent characteristics of the wood, general lumber demand, and customer preference for other species (Gordon, 1978). Little attention was paid to its management or research. As a result, scant information on growth and yield as well as management specific to true firs exists (Gessel and Oliver, 1982). For example, the general rule-of-thumb to thin stands of most species to 55% of that shown in normal yield tables for that site quality and age (Cochran, 1982), has guided the thinning regimes for white and red fir in California for a long time if maximum production of usable volume is concerned (Oliver, 1988). With increasing demand for wood and other values of the true fir forests such as wildlife habitat, prime recreational opportunities, and storage and delivery of much of California's water supply, interest in managing these stands is also increasing.

In this report, we summarize data collected from six white and red fir trials established in northeast California from 1968

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to 1981. The objectives of these studies were: (1) to determine the effects of stand density on individual-tree growth and stand growth components, (2) to examine patterns of relationships between growth and stand density across different sites, and (3) to determine tree mortality and dead wood accumulations for various density levels.

2. Study sites and experimental design

Six independent trials are located at six sites in northeastern California (Table 1). Jennie Springs and Swain Mountain trials were established by the Forest Service, Pacific Southwest Research Station. Big Lake, Crater Peak, and Little Glass Mountain trials were established by the Pacific Southwest Region of the US Forest Service. The LaTour trial was set up jointly by the California Department of Forestry and Fire Protection and Pacific Southwest Research Station.

The stands at all but the Swain Mountain site contained a small proportion (<10%) of species other than white fir. These included ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.), Jeffrey pine (*Pinus jeffreyii* Grev. & Balf.), sugar pine (*Pinus lambertiana* Dougl.), and red fir, most of which were removed in the initial thinning. Despite the 50% mix of red fir at Swain Mountain, we regarded all trials as white fir throughout this report.

Living understory vegetation was absent from all sites at time of installation, but evidence existed of an abundant understory of snowbrush (*Ceanothus velutinus* Dougl. ex Hook) in the early life of the stands at Jennie Springs and Swain Mountain. Subsequent to initial thinning, low density plots were invaded by bush chinquapin (*Chrysolepis sempervirens* (Kell.) Dudley) at Crater Peak and by scattered regeneration of sugar pine, Jeffrey pine, and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) at Jennie Springs. Otherwise, the sites remained free of understory vegetation. A brief site description and design follows.

2.1. Jennie Springs

The site is located on a gentle southeast-facing slope on the Lassen National Forest near Westwood, Plumas County. The soil, derived from Pleistocene basic igneous rock and ash deposits, is similar to the Windy Soil Series (cindery, frigid, Typic Dystrandepts) and has 1.0–2.4 m in depth. The stand originated following a stand-replacing wildfire about 70 years ago.

Five basal area stand densities were achieved by thinning from below in the beginning of the study −18, 30, 40, 57 $m^2\,ha^{-1}$ and an unthinned control with 88 $m^2\,ha^{-1}$. Each basal area level was replicated three times (blocks) and randomly assigned to one of the five plots. All plots were square, 0.20 ha in size and buffered with at least a 10-m isolation strip. Logs 30 cm dbh and larger were skidded off the plots by horses (Fieber and Robson, 1985). The plots were not rethinned. Measurements were taken every 5 years from 1981 to 2001.

2.2. Swain Mountain

The site is located on a gentle slope on the Swain Mountain Experimental Forest near Westwood, Plumas County. The soil, derived from Pleistocene basalt, is similar to the Windy Soil Series (cindery, frigid, Typic Dystrandepts). The stand consists of about equal numbers of white and red fir that originated following a stand-replacing wildfire about 100 years ago (Oliver, 1988).

Table 1
Geographic locations, site characteristics, climate, and stand statistics[a] ($\mu \pm$ S.E.) prior to installation of the treatments for white and red fir studies along the southern Cascades in northeast California, USA

	Jennie Springs	Swain Mountain	Big Lake	LaTour	Crater Peak	Little Glass Mountain
Latitude (N)	40°24′	40°25′	40°37′	40°38′	40°43′	41°35′
Longitude (W)	121°5′	121°6′	121°37′	121°41′	121°40′	121°42′
Elevation (m)	1860	1950	1798	1728	1615	1890
SI (m at age 50)[b]	34	27	23	17	30	13
Stand age	70	100	90	80	68	90
Dominant species[c]	White fir	Red/w fir	White fir	White fir	White fir	White fir
Slope aspect	SE	NW	S, SW	N, E, NE	N, W, NW	NW
Slope (%)	2	10	20	35	12	16
Ann mean T (°C)[d]	6.3	5.8	6.3	6.7	7.2	3.3
Precipitation (mm)[e]	1165	1168	1097	1119	975	1205
Density (trees ha^{-1})	1187 (239)	1150 (73)	1130 (90)	6439 (495)	1432 (72)	–
QMD[f] (cm)	31.7 (3.6)	31.3 (1.3)	32.9 (1.3)	11.3 (0.3)	25.9 (1.0)	–
Basal area ($m^2\,ha^{-1}$)	88.1 (6.3)	83.8 (3.2)	93.0 (2.7)	64.2 (1.5)	75.1 (3.8)	–

[a] Statistics are from original surveys before the studies at Swain Mountain, Big Lake, and Crater Peak were established. Measurements of control plots were used for Jennie Springs and LaTour. No data were available for Little Glass Mountain.
[b] Site index (SI) was determined from both Dolph (1987) and Cochran (1979) depending on the age at breast height.
[c] Species comprising more than 10% of the trees.
[d] Annual mean temperature is estimated from the North California Climate model (Zhang et al., unpublished).
[e] Precipitation for Jennie Springs and Swain Mountain from Oliver (1988); for Big Lake, LaTour, and Crater Peak from a climate model (Zhang et al., unpublished); for Little Glass Mountain from Mt. Shasta city.
[f] Quadratic mean diameter (QMD).

The stand was vigorous before the treatments were installed in 1975, despite a high basal area of 84 $m^2\ ha^{-1}$. Live crowns of dominant trees averaged about 50% and mean tree dbh was 30 cm. Six stand densities were chosen—32, 39, 46, 53, and 60 $m^2\ ha^{-1}$ and an unthinned control. Each of the densities was randomly assigned to two 0.2-ha plots with a 10-m buffer. Logs 30 cm dbh and larger were harvested and removed by rubber-tired skidder. After the installation, the plots were rethinned to target density in 1995 except for the unthinned controls. Measurements were taken every 5 years from 1975 to 2000.

2.3. Big Lake

The site is located about 10 km northwest of Lassen Volcanic National Park in the Lassen National Forest, Shasta County. The soil is Typic Xerorthents-Yallani family association (ibid or Medial skeletal, frigid Andic Xerochrepts) at 1.0–1.5 m deep with cinders or basalt as their parent materials. The stand originated about 90 years ago.

The three density treatments of 34, 54, and 62 $m^2\ ha^{-1}$ of basal area were based upon 40, 55 and 70% of the normal basal area (96 $m^2\ ha^{-1}$) for this stand age and site quality following Schumacher (1926). These densities and an unthinned control (84 $m^2\ ha^{-1}$) were randomly assigned to eight plots with each treatment replicated twice. Plots were 0.2 ha in size, except for one with 0.17 ha, and buffered with a 10-m isolation strip. The plots were installed in 1976 and most plots were rethinned in 1988. Trees were measured about every 5 years from 1976 to 2003.

2.4. LaTour

The study was initiated in 1981 in an 80-year-old natural stand on the LaTour Demonstration State Forest, Shasta County. The soils are Windy or a Windy Variant series (Medial-skeletal, frigid Humic Vitrixerands) developed from either basaltic rock or unsorted andesitic and dacitic glacial debris.

Originally, ten plots were established in a uniform stand of white fir. Two plots were randomly assigned to each of five basal area stand densities 18, 30, 41, 53 $m^2\ ha^{-1}$ and an unthinned control (73 $m^2\ ha^{-1}$). Plot sizes varied between 0.02 and 0.03 ha with a 10-m isolation strip. Because initial thinning did not remove all designed cut trees, the stand densities were not achieved until after a rethinning in 1991. In addition, only three densities 18, 46, 59 $m^2\ ha^{-1}$ and an unthinned control with 73 $m^2\ ha^{-1}$ were achieved. Therefore, only data for the last two periods were analyzed for the thinned plots. Data from all periods was analyzed for the unthinned plots.

2.5. Crater Peak

The site is located 15 km northwest of Lassen Volcanic National Park in the Lassen National Forest, Shasta County. The soil is Sheld or Sheld moderately deep complex (medial-skeletal, frigid Andic Xerumbrepts) at about 0.7–1.5 m deep with andesite and basalt as their parent materials. The stand originated about 68 years ago.

Similar to Big Lake, the three density treatments of 37, 46, and 60 $m^2\ ha^{-1}$ of basal area were based upon 40, 55 and 70% of the normal basal area (96 $m^2\ ha^{-1}$) for this age and site quality following Schumacher (1926). These treatments were randomly assigned to nine plots with each treatment replicated three times. Plots were 0.2 ha in size with about a 10-m buffer. The plots were installed in 1978 and most plots were rethinned in 1989. Trees were measured about every 5 years from 1978 to 2003.

2.6. Little Glass Mountain

The site is located on the Medicine Lake Highlands, northeast of Mount Shasta in the Klamath National Forest, Siskiyou County. The soil is Belzar series (Loamy-skeletal, mixed, frigid Andic Xerochrepts) more than 1.5 m deep with a parent material of fractured andesite or basalt.

Plots were installed in a 90-year-old stand in 1968 by personnel of the Goosenest Ranger District, Klamath National Forest. Three densities were achieved—16, 20, and 37 $m^2\ ha^{-1}$ basal area. Plots were circular, 0.04 ha in size, unbuffered and unreplicated. Measurements were taken every 5 years from 1968 to 2002.

3. Measurements and analysis

Before the treatment plots were installed, the stands were surveyed and summarized at Swain Mountain, Big Lake, and Crater Peak (Table 1). At Jennie Springs and LaTour without original surveys, we used data in the unthinned controls. Neither pretreatment nor control data were available for Little Glass Mountain. The targeted stand densities were achieved by thinning from below, favoring true fir species with uniform spacing as the second consideration. Immediately after thinning, residual trees were tagged and measured to the nearest 0.25 cm dbh. About 20% of the trees in each plot, randomly chosen, were measured to the nearest 0.3 m for total height. In the unthinned controls at Jennie Springs, only every other tree was systematically tagged and measured. Stem deformities and evidence of insect and disease attacks were recorded for all measurement trees. Stem volumes were measured on about 10 trees per plot with a Barr-Stroud optical dendrometer to develop an allometric volume equation as a function of dbh at Jennie Springs, Swain Mountain, Big Lake, and Crater Peak. Cubic volume inside the bark above the stump was calculated by the Smalian formula (Husch et al., 1982) for all stem segments except the last, which was treated as a cone. Realizing volume equations could vary between tree-developmental stages, we statistically fit two equations at each site separated by 23 cm dbh. We used the volume equations developed from Crater Peak to estimate the total volume for trees at LaTour and Little Glass Mountain. All trees were measured about every 5 years after treatments were installed.

For each plot, mean stand height, quadratic mean diameter, basal area, volume, and number of trees were estimated. Tree mortality was calculated from the number of dead trees for each period. Stem volume was also calculated for these trees at

Jennie Springs, Swain Mountain, Big Lake, and Crater Peak. Cumulative dry weight for dead bole only was estimated for each density by assuming 0.37 of specific gravity (Jenkins et al., 2004). Stand density index (SDI) was calculated using a slope of −3/2 (Reineke, 1933). Then, relative stand density was calculated as SDI of the test plot divided by the maximum SDI of 2000 trees ha^{-1} found in our plots and reported by Oliver and Uzoh (1997). We treated plots as our experimental units. The statistical model to test density, period, and density by period effects is

$$\text{Response}_{ijk} = T_i + \text{period}_j + T \times \text{period}_{ij} + \text{plot}_k + e_{ijk} \quad (1)$$

Table 2
Stand statistics of height, quadratic mean diameter (QMD), basal area (BA), volume, and number of trees per hectare (TPH) for white fir grown at various targeted densities in northeastern California, USA

Site	Density ($m^2\ ha^{-1}$)	Age	Height (m)	QMD (cm)	BA ($m^2\ ha^{-1}$)	Volume ($m^3\ ha^{-1}$)	TPH
Jennie Springs	18	70	28.7	47.8	18.3	180.2	103
		91	33.0	65.7	27.8	290.5	82
	30	70	27.0	43.5	30.7	300.0	212
		91	31.3	58.0	43.0	440.7	173
	41	70	27.1	45.1	39.8	386.7	250
		91	31.5	56.5	51.5	532.4	220
	53	70	26.9	41.1	57.0	550.2	437
		91	31.1	50.5	75.1	765.9	398
	Control	70	21.6	31.7	88.1	779.8	1187
		91	28.6	42.9	96.1	957.2	740
Swain Mountain[a]	32	100	32.3	59.9	32.0	377.8	114
		125	38.7	80.7	37.9	481.6	74
	39	100	28.3	48.2	39.0	420.5	227
		125	35.4	65.3	44.2	540.5	133
	46	100	30.2	49.4	46.7	516.5	264
		125	36.8	67.2	55.7	683.9	163
	53	100	28.0	48.6	53.5	593.0	289
		125	34.8	65.4	65.6	802.9	195
	60	100	28.7	47.1	59.8	660.4	348
		125	35.5	63.1	73.3	890.7	235
	Control	100	18.4	33.4	84.6	819.5	981
		125	27.7	45.6	106.5	1190.0	670
Big Lake[a]	34	90	29.4	50.4	33.9	369.2	180
		117	35.0	71.5	24.5	284.4	64
	54	90	26.2	40.9	53.6	540.2	408
		117	29.9	54.4	43.0	477.2	200
	62	90	24.1	38.7	61.8	607.1	524
		117	29.8	49.7	55.3	600.4	321
	Control	90	23.8	33.2	83.9	783.0	988
		117	29.1	42.5	73.9	774.0	598
LaTour[a]	18	95	17.5	34.7	22.0	217.0	233
		100	19.1	37.7	26.0	265.7	233
	46	95	17.3	30.5	47.0	419.7	683
		100	19.1	32.4	53.0	488.2	683
	59	95	17.8	26.8	58.8	477.2	1049
		100	19.2	28.3	64.2	545.1	1049
	Control	80	6.9	11.3	64.2	310.3	6439
		100	11.9	17.5	75.9	498.8	3313
Crater Peak[a]	37	68	26.1	42.8	36.7	374.6	285
		93	32.2	65.4	36.1	413.6	128
	46	68	26.1	40.2	46.2	470.0	369
		93	31.4	57.0	50.0	567.3	201
	60	68	25.8	39.1	59.4	598.4	496
		93	31.9	52.0	65.1	725.8	328
Little Glass Mountain	16	86	9.7	17.4	15.9	87.6	667
		115	17.3	31.0	50.4	443.7	667
	21	86	8.8	14.7	19.8	94.0	1161
		115	16.6	25.8	59.3	461.3	1137
	37	86	11.9	18.7	36.6	215.2	1334
		115	18.6	28.4	76.6	641.3	1211

Data in the beginning and the last measurements are presented.
[a] Rethinning occurred at these sites.

where T is density effect, i is the number of densities, j is the number of periods, k is the number of plots, and e is the residual error. Plot effect was assumed to be random and T, period, and $T \times$ period were assumed to be fixed effect. e_{ijk} was assumed normally distributed, independent from each other and independent from other terms. Data were analyzed with SAS PROC MIXED (SAS Institute Inc., 2001). The Bonferroni approach was applied to compare treatments at an experiment-wise $\alpha = 0.05$.

A nonlinear three-parameter logistic model was fit to the individual plot data for all sites by using a nonlinear mixed-effects model package in R (Ihaka and Gentleman, 1996).

$$\text{PAI BA} = \frac{\beta_0}{\{1 + \exp[-(\text{RD} - \beta_1)/\beta_2]\}} \quad (2)$$

where BA is net basal area, RD is relative density (observed SDI divided by maximum SDI), β_0, β_1, and β_2 are fixed-effects parameters. Initially, we fit this with a random component for each period nested within sites for all three parameters. However, this model appeared over parameterized. We simplified the model to a single parameter random effect on the asymptote, β_0. With this parameterization, the asymptote was allowed to have a random component which varied by installation and period. The logistic model was selected from among several nonlinear asymptotic functions based on Akaike's Information Criterion (AIC). Because targeted densities were never achieved exactly, we used actual stand density as the independent variable and net PAI basal area as the dependent variable. Little Glass Mountain was excluded from the fitting for inadequate sample size ($n = 3$).

4. Results

4.1. Mortality

Mortality occurred on all sites regardless of site quality and stand age (Fig. 1). Competition-induced mortality (self-thinning) might have occurred only in unthinned controls (Fig. 2), although some higher density plots might have reached the zone of imminent competition mortality (Drew and Flewelling, 1979). The maximum stand density index was about 2000 trees ha^{-1}, as reported by Oliver and Uzoh (1997). Mortality in the lower stand densities, as high as 15% on some sites (Fig. 1, from TPH in Table 2), were due to other biotic and abiotic factors, principally annosum root rot (*Heterobasidium annosum*) and wind throw.

Treatments with higher mortality accumulated more dead bole wood (Fig. 3). No surprise, high density (lightly thinned or

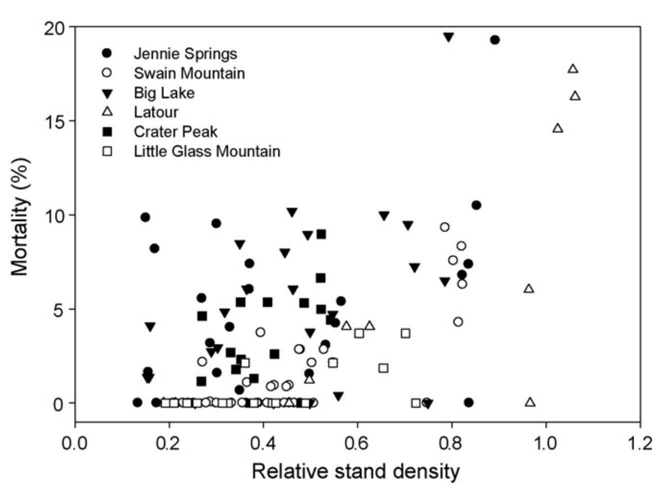

Fig. 1. Relationships between mortality and relative stand density as defined as stand density index of the study plot divided by maximum stand density of 2000 trees ha^{-1} for white fir grown under various stand densities at six sites in northeastern California, USA.

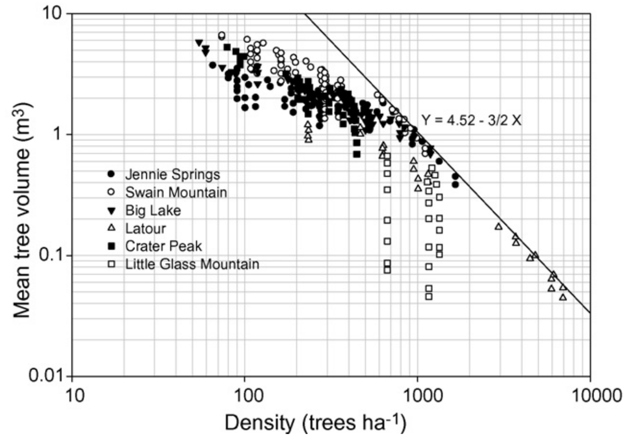

Fig. 2. Size-density trajectories plotted on log–log scales for white fir grown under various stand densities at six sites in northeastern California, USA. The self-thinning line is visually fitted with a theoretical slope of −3/2.

Table 3
Summary of type 3 tests of fixed effects including source of variation, degrees of freedom for both numerator and denominator, F-values and probability values for periodic annual increment (PAI) of basal area (BA) and volume (Vol) for white fir grown at various targeted densities in northeastern California, USA

Source of variation	d.f.	PAI BA		PAI Vol	
		F	$P\leq$	F	$P\leq$
Jennie Springs					
Density	4, 38	36.64	0.0001	32.14	0.0001
Period	3, 38	7.68	0.0004	18.63	0.0001
Density × period	12, 38	0.94	0.5194	1.80	0.0832
Swain Mountain					
Density	5, 24	5.56	0.0015	4.12	0.0077
Period	4, 24	22.79	0.0001	40.34	0.0001
Density × period	20, 24	0.99	0.4997	1.79	0.0869
Big Lake					
Density	3, 15	2.63	0.0883	1.92	0.1705
Period	4, 15	78.63	0.0001	37.52	0.0001
Density × period	12, 15	4.57	0.0035	2.46	0.0512
LaTour					
Density	3, 6	8.03	0.0160	12.52	0.0054
Period	1, 6	0.77	0.4151	6.03	0.0494
Density × period	3, 6	2.75	0.1350	4.03	0.0692
Crater Peak					
Density	2, 24	7.35	0.0032	9.03	0.0012
Period	4, 24	21.13	0.0001	16.99	0.0001
Density × period	8, 24	1.98	0.0932	1.54	0.1957

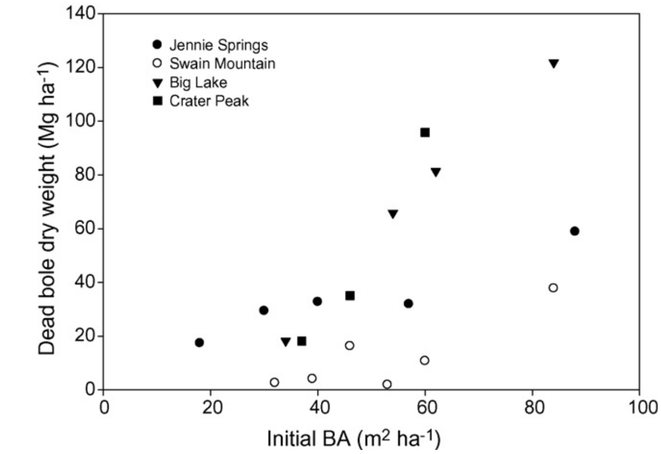

Fig. 3. Average cumulative dry weight for dead bole only based on density treatment from the beginning to the last measurements at four sties.

control) plots showed much higher dry weight than low density (heavily thinned) plots.

4.2. Growth

Significant differences in both PAI basal area and PAI volume were detected among stand densities at Jennie Springs, Swain Mountain, LaTour, and Crater Peak (Table 3). At Big Lake, PAI BA differed at a significance level of 0.09 among densities but no difference in PAI volume was detected. Little Glass Mountain was not included in the analysis due to lack of replications. We also found a significant period effect for both variables at all sites except for PAI BA at LaTour, where only two periods were valid for comparison. There was a lack of significant density by period interaction for PAI BA except at Big Lake. The interactions in PAI volume, however, were significant at $\alpha = 0.09$ for all sites except at Crater Peak. We also explored the multiple contrasts between densities or between periods (Fig. 4). On all sites, basal areas below

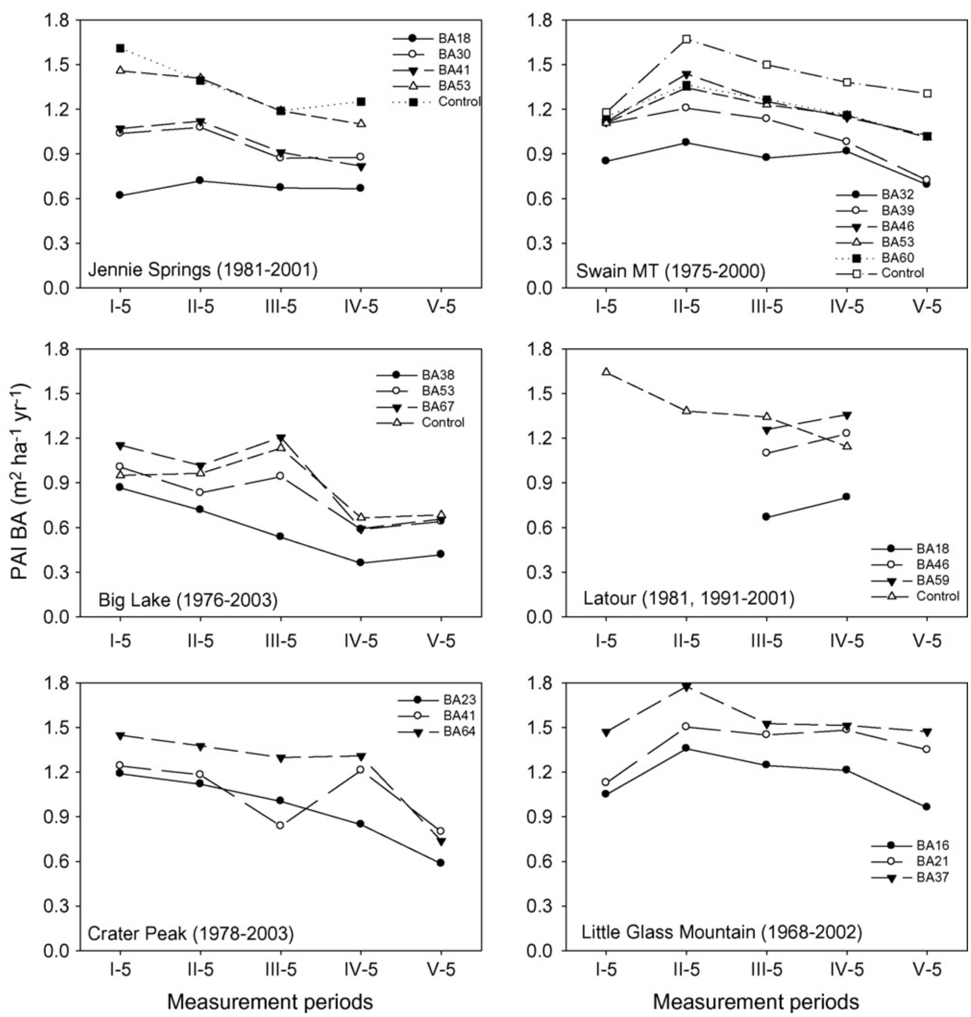

Fig. 4. Average periodic annual increment of basal area for the measurement periods for white fir grown under various stand densities at six sites in northeastern California, USA. The years after site legends refer to the data duration. Significant differences were found between the following contrasts. Jennie Springs—BA18 vs. others, BA30 vs. BA53 & control, and BA41 vs. BA53 & control; period 1 vs. 3 & 4, 2 vs. 3 & 4. Swain Mountain—BA32 & BA39 vs. control; period 1 vs. 2 & 5, 2 vs. 4 & 5, 3 & 4 vs. 5. Big Lake—BA34 vs. others, period 1 vs. 4 & 5, 2 vs. 4 & 5, 3 vs. 4 & 5. LaTour—BA 18 vs. others. Crater Peak—BA37 vs. BA60; period 1 vs. 3 & 5, 2 & 3 & 4 vs. 5. Little Glass Mountain—no contrast is possible.

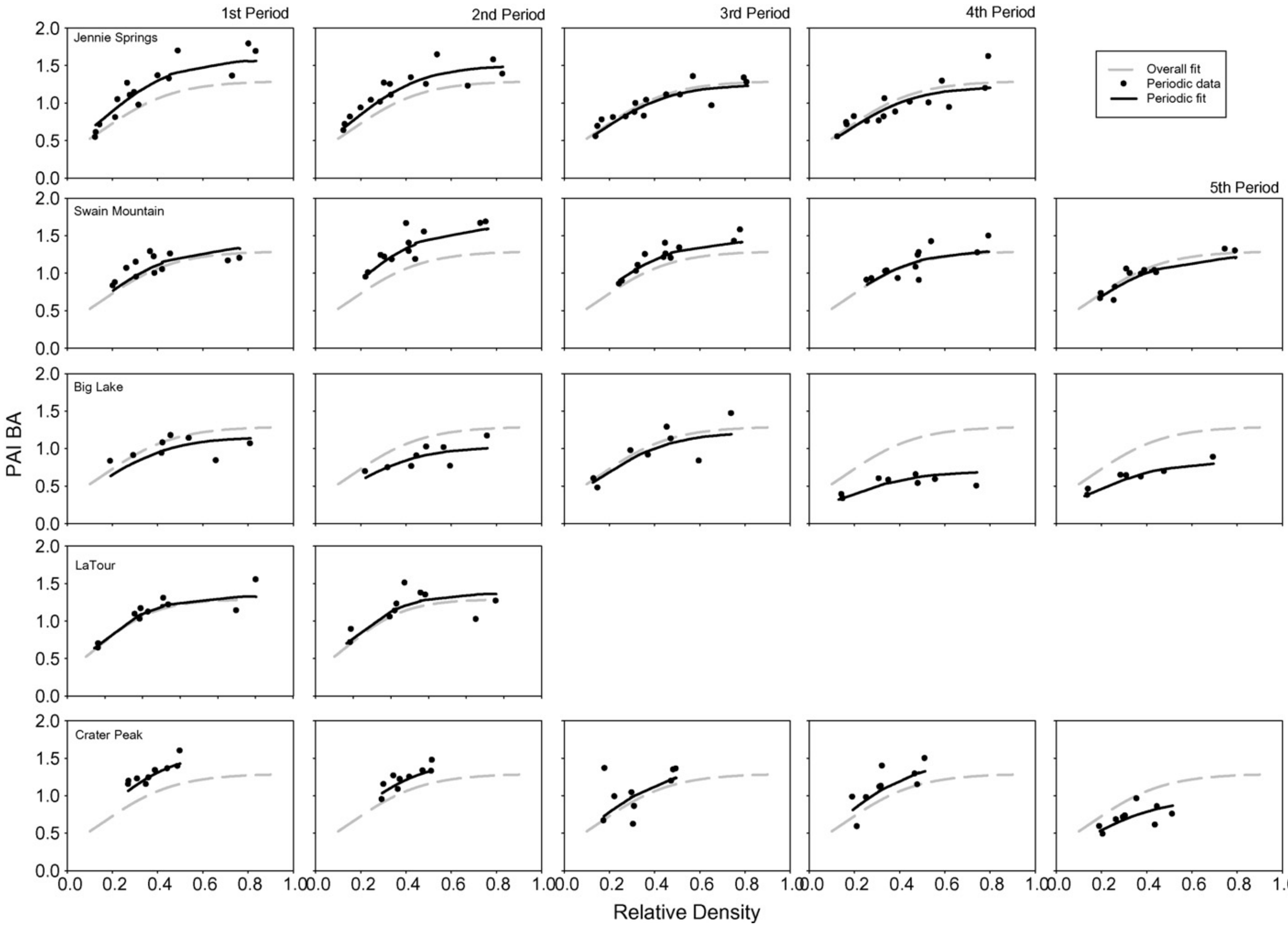

Fig. 5. Plot-level PAI BA response (model 1) to relative stand density at different measurement periods for white fir grown under various stand densities at five sites in northeastern California, USA. The gray dash curves represent the fixed-effects model and the solid line represents the random-effects change in asymptote.

39 m^2 ha^{-1} had significantly lower PAIs than did plots with higher basal areas. In contrast, there was no significant difference in PAI BA of plots on all sites when basal areas were higher than 46 m^2 ha^{-1}.

Parameter estimates for Eq. (2) were $\beta_0 = 1.294$, $P < 0.001$; $\beta_1 = 0.160$, $P < 0.001$; and $\beta_2 = 0.158$, $P < 0.001$ (Fig. 5). In the early years after the density was manipulated, the PAI BA asymptotes of individual sites were higher than that of the overall fixed effect model, except Big Lake. With random effect, asymptotes ranged from 0.701 to 1.621. In the later periods, the asymptotes tended lower. The trends held as plots were re-thinned such as the third period at Big Lake and Crater Peak. There was no clear trend relating site index and the periodic annual increment in this analysis, although the asymptote for Big Lake tended to be lower than for other sites.

4.3. Stand structure

Structural changes in the stands on all sites have been considerable over the 20–30 years since the studies were established (Table 2). As we expected, absolute increment in average tree size was larger in the lower density plots than in the higher density plots (Fig. 6). Clearly, DBH frequencies were bell-shaped even for all plots including control, in contrast to the finding in young red fir (Zhang and Oliver, 2006). Data are not presented for two locations—treatments were unreplicated at Little Glass Mountain and only two periods were analyzed for the density treatments at LaTour.

5. Discussion

We found a significant response of growth to different stand densities on each site even though these stands varied in age at the beginning of the studies from 68 years at Crater Peak to 100 years at Swain Mountain (Tables 2 and 3). Furthermore, the site indices varied between 13 m at Little Glass Mountain and 34 m at Jennie Springs (based on age 50 years) (Table 1). Unfortunately, age and site effects are potentially confounded making the site comparison very difficult. Nevertheless, responses of PAI to stand densities based on basal areas were similar (Fig. 5). Total volume production increased with stand density, following three stages of stand growth patterns (*sensu* Daniel et al., 1979, p. 318). At lower densities (heavily thinned) with no inter-tree competition, volume production increased rapidly with increasing density. At middle densities, volume production increased at a diminishing rate with increasing stand

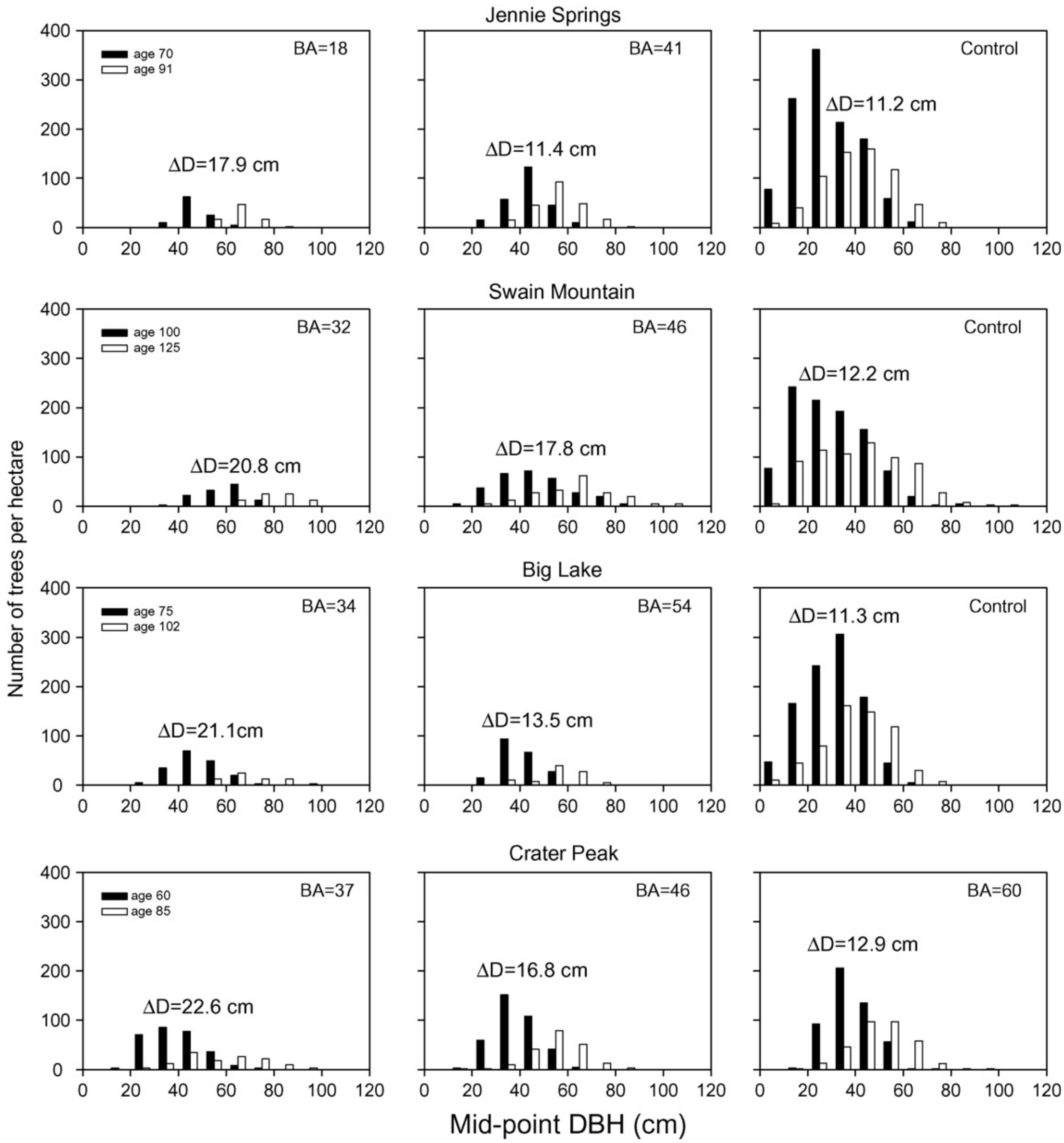

Fig. 6. Number of trees at 10-cm DBH classes under the lowest, intermediate, and highest stand densities for white fir grown at four sites in northeastern California, USA, at time of study establishment compared with last measurement. ΔD is QMD increment during the study.

density because of increasing inter-tree competition. At higher densities (lightly thinned or control), because the competition intensified, there is very little net increase in volume with density.

Although the general trend for PAI BA can be fitted with one equation, Big Lake was markedly different from other sites. The exact reasons for the discrepancies are unknown. We speculate several potential reasons. At Big Lake, the poorer growth across all densities might be associated with infection of *Hererobasidium annosum* before the study plots were installed (Byler et al., unpublished report, August 1977). Trees in this stand could have been weakened as indicated by heavy mortality in the later years (Table 2 and Fig. 1). Although we did not fit the model, PAI BA at Little Glass Mountain was one of the highest among sites (Fig. 4). Given the lowest site index at his site, stand carrying capacity appeared to be low with only 37 $m^2 ha^{-1}$ basal areas on a total of 1334 trees ha^{-1} in the highest density plot. At other sites, less than 400 trees ha^{-1} created the same basal area. More trees would be translated to larger PAI BA as it did within each site (Fig. 4). Therefore, PAI BA was the highest for a given initial basal area at Little Glass Mountain across sites. In addition, trees in this old stand grew constantly well in DBH after thinning based on tree-ring observations. Growth is still in the range of steep slope so that PAI BA has been high.

For all sites that we were able to analyze statistically, we found that thinning from below, leaving 30–49% of the original basal area, depending upon site quality, resulted in a significant loss of productivity (Fig. 4). In contrast, stands with 55% of original BA at Swain Mountain and 64% at other sites did not significantly reduce the productivity. Because of the nature of the statistical test, we were unable to decide if the lack of a difference was real or due to the small sample size. Nevertheless, 64% of original basal area (Table 2) should be a conservative density for any thinning operation if maximum volume production is a component of management goals. If the management objective were to maximize individual tree growth and size, such as promoting understory grasses for wildlife, an appropriate strategy would be to maintain the stand in a lower density. A mixed white fir and red fir stand and older stand age might cause the difference at Swain Mountain from other sites. Oliver (1988) reported a 50% cutting point, based on the first 10 years data at Swain Mountain. Because red fir tended to be larger in DBH, comprised more of the stand basal area, and dominants had grown faster (Oliver, 1988), the 50% or 55% found in this study may reflect the response of growth to thinning in red fir.

The recommended basal area for thinning these stands is within the 55–70% range of normal basal area suggested by Cochran (1982) for white and grand fir (*A. grandis* (Dougl. ex D. Don) Lindl.). This range has been used to manage true fir in California for the last two or three decades. We must caution the reader, however, that normal basal area, in this case, is dependent upon a correct determination of site index. If site index is wrong then the normal yield will be wrong. Determining an accurate site index is particularly difficult using a system based upon total age (Schumacher, 1926) rather than the much preferred breast-height age used currently. In addition, the normal yields associated with the site index are averages which may or may not reflect conditions for a specific stand. For example, normal basal area at Big Lake, as determined from the normal yield table, was 96 $m^2\ ha^{-1}$. The treatments applied of 40, 55, and 70% of 96 $m^2\ ha^{-1}$ were in actuality 40, 64, and 74% of the basal area of 84 $m^2\ ha^{-1}$ carried by this stand at time of treatment installation. In fact, maximum basal area never exceeded 91 $m^2\ ha^{-1}$ over the 27 years of observation, as determined by the unthinned controls. Therefore, we strongly suggest that the actual basal area carried by the untreated stand be used to guide the thinning intensity. A preferable method is to use relative stand density which is based upon the specific stand in question and avoids the problem of determining an accurate site index. The logistic function presented in this paper will guide forest managers in choosing an appropriate stand density based on their management goals (Fig. 5).

Productivity of the stands in this study is higher than that reported in south central Oregon (Hopkins, 1982). Depending on site quality, PAI volume for white fir in Oregon was between 3 and 12 $m^3\ ha^{-1}\ year^{-1}$ at site indices between 28 and 34 m at age 50. Whereas, depending on the site in the current study, PAI volume varied between 7 and 22 $m^3\ ha^{-1}\ year^{-1}$ for the unthinned control plots. PAI volume was never smaller than 3 $m^3\ ha^{-1}\ year^{-1}$ even in the heavily thinned plots. Favorable site quality and climates in California compared to central Oregon might explain this discrepancy.

Maintaining tree vigor and reducing hazardous fuel buildup may be a concern for managers. Nearly a century of fire exclusion and often minimal management has placed many white fir stands in jeopardy. Data from this report suggest that fuels were significantly reduced by reducing stand density through thinning. Without thinning, we estimated that 41, 35, and 50 $Mg\ ha^{-1}$ more dry stem wood would be accumulated on the control than on the lowest density (the most heavily thinned) treatment at Jennie Spring, Swain Mountain, and Big Lake, respectively (Fig. 3). At Crater Peak, there was 78 $Mg\ ha^{-1}$ more on the highest density (lightly thinned) stand than on the lowest density (heavily thinned) plot. If branches and leaves were considered, even more combustible materials would be shown to have accumulated in the unthinned stands.

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