Long Term Results of Early Density Management of a Third Growth Redwood Stand[1]

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Abstract

Precommercial or early thinning of regenerating redwood forests can support management objectives including maximizing yield, forest structure restoration, and promoting carbon sequestration. We present data collected over 30 years following a precommercial thinning (PCT) in a 19 year-old naturally regenerated and planted coast redwood (*Sequoia sempervirens*(D. Don) Endl.) and coast Douglas-fir (*Pseudotsuga* menziesii (Mirb.) Franco var. *menziesii*) stand. The study site is typical of most regenerating redwood forests with spatial variation in tree distribution from stump sprouting (coppice) redwood interspersed with planted and natural regeneration. Three replicates of six density treatments (100, 150, 200, 250, 300 trees per acre (TPA) and unthinned control) were established in 1981 and re-measured repeatedly. Plot size was reassessed in 2011. Post-thinning density had a lasting effect. Thirty years after PCT, average diameter at breast height (DBH) and stand density index (SDI) still differed among PCT treatment levels. When focusing on the largest trees (140 TPA), basal area (BA) and cubic foot volume results were significantly affected by post-thin TPA resulting in the highest production from treatments ranging from 120 to 250 TPA. A new method of characterizing site productivity by indexing redwood BA growth revealed that variations in species composition and site quality explained differences in growth and yield between plots. Multiple linear regressions revealed that post-thin TPA, species composition (percent redwood SDI), and site quality in terms of BA growth index all had a lasting influence on redwood productivity monitored over three decades after PCT.

Key words: precommercial thinning, *Sequoia sempervirens*, silviculture, site quality, stand density management

Introduction

Reducing stand density of redwood (*Sequoia sempervirens* (D. Don) Endl.) forests via commercial timber harvest is well understood to influence both residual tree growth and the forest's structure and subsequent development (Berrill and O'Hara 2014, Oliver et al. 1994, Webb et al. 2012). Tree growth can also be enhanced by precommercial thinning (PCT) to adjust the density of younger redwood stands (Lindquist 1998, 2004, 2007; O'Hara et al. 2015). PCT is also used to enhance representation of desired species or to favor improved planting stock by preferential removal of less desirable trees, to improve stand condition by removing unhealthy or malformed trees, and to modify the spatial arrangement of residual trees. A PCT study in young third-growth redwood stands in North Fork Caspar Creek Watershed on Jackson Demonstration State Forest (JDSF) found significant differences in individual tree attributes 12 years after the 8 to 11 year-old trees were thinned (O'Hara et al. 2015). Factors listed that can contribute to variability are inter- and intra-specific competition, animal damage, and differing vegetation management during stand establishment. Young redwood stands are inherently variable because of the clumpy nature of both redwood and hardwood stump sprout regeneration. Complex regional topography may contribute to fine scale variability in site quality and growth as well (Berrill and O'Hara 2016).

Lindquist (1998, 2004, 2007) reported findings from a PCT experiment designed to determine the response of coast redwoods to a variety of stocking levels following precommercial thinning and help determine optimum density for different management objectives. When contrasting the different PCT

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TPA retention levels, Lindquist found that average diameter remained significantly different through time, but stand increment and measures of basal area or volume were not significantly different. The question as to when or how thinning young redwood stands affects the volume or basal area increment remains unclear. This paper examines patterns of stand development by combining Lindquist's data with recent data from the same experiment.

Methods

Study Design

The PCT study site was installed on JDSF at the site of the l960 Caspar Cutting Trials clearcut (Lindquist 1988) as a cooperative study by the U.S. Department of Agriculture Forest Service and the California Department of Forestry and Fire Protection. Three blocks were established on the east-facing mid to lower slope. The northern block had been partially burned. Prior to thinning treatment, the middle block had four times as many Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco as the northern block. Six density treatments based on number of trees retained (100, 150, 200, 250, 300 TPA and unthinned control) were implemented on adjacent 1.6 ha (0.4 ac) treatment areas. The 0.2 acre square measurement plots were installed within the treatment areas. One replicate was randomly assigned to each of the three blocks (fig. 1). Thinning was implemented in 1981 by individual plot quadrant; retaining targeted number of trees, with a preference for larger thrifty redwoods. The redwood stump sprouts were thinned to leave at least 0.61 m between stems. Plots were initially measured in 1981, and then remeasured in 1984, 1986, and 1998 by Lindquist and in 2011 by Green Diamond Resource Company inventory staff. The 2011 remeasurement used laser and hypsometer to more accurately measure plot size and map stems. We performed ANOVA tests for differences among plots, PCT treatment levels and replicate blocks (north, central, and south replicates of each PCT treatment level).

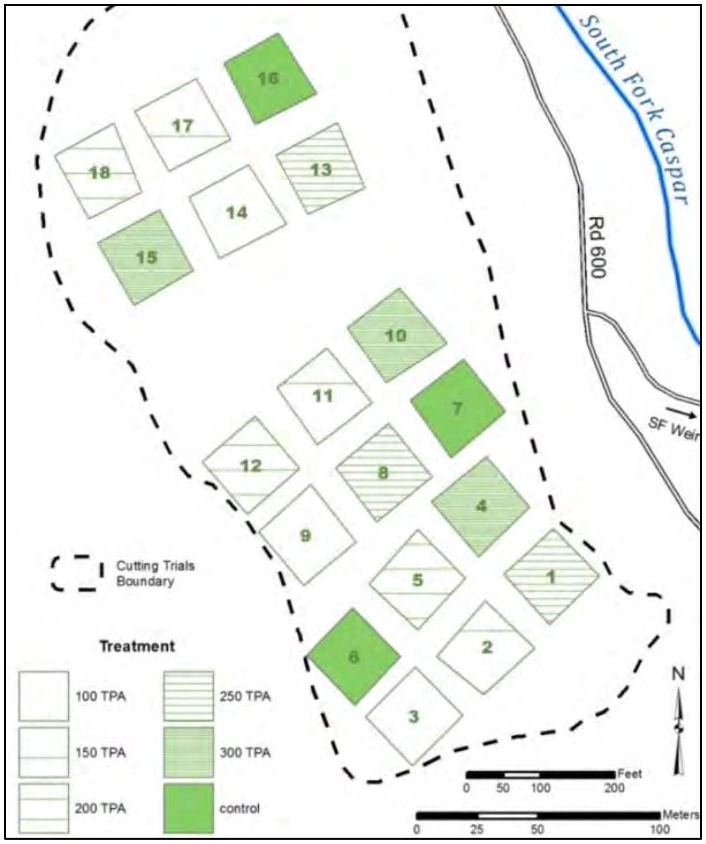

Figure 1–Plot layout with 1981 PCT treatment as TPA retention levels. Each of the 3 blocks has one each of the treatment levels.

The term 'crop trees' describes the largest or best-formed trees expected to become a component of a future commercial harvests or the dominant canopy trees in restored stands. Studying their growth separately is useful because trees of lower stature such as ingrowth and low vigor trees not expected to attain merchantable size are ignored. In redwood-dominated stands, stand density index (SDI) is expected to attain approximately 600 before competition-induced mortality of redwood trees is imminent (Long 1985, Reineke 1933). This threshold will not be surpassed until stands with 140 TPA have exceeded 61 cm average diameter at breast height (DBH; 1.37 m), when harvesting some these so-called crop trees would be of interest. Therefore data for crop trees only, defined as the largest-DBH 140 TPA in each plot was analyzed or for the 100 TPA PCT treatment all trees were analyzed.

Volume Estimates

A slightly different method was used to calculate volume than Lindquist (2004, 2007) used, since all heights were measured in 2011, whereas in the past, limited numbers of tree heights had been measured. For redwoods, height-diameter relationships were derived by measure year then used to estimate missing heights. Because very few Douglas-fir were present, a regression fitted to available height-diameter data for all measurement years was used to predict missing heights. Other volume calculations were consistent with Lindquist's (2007) methods and used Wensel and Krumland (1983) equations.

Assessing Site Quality and its Effect on Growth in Each Plot

SDI was calculated for the entire plot (all species) and for the redwood component in each plot. This gave species composition in terms of redwood percent SDI. We used this percentage to calculate the approximate plot area occupied by redwood. We then used this "SDI-adjusted plot area" as the expansion factor to calculate SDI and basal area increment (BAI) for all redwood trees in the plot, giving redwood SDI and BAI on a per acre basis. For each plot, we calculated two alternate site quality variables: (1) dominant redwood height (i.e., average height of 40 largest DBH redwood per acre at age 49 years), and (2) redwood BA growth index (RBAGI) (i.e., how much redwood BA growth deviated from an 'expected' modeled value for any plot SDI; Berrill and O'Hara 2014). To test for differences in average site quality among plots receiving different thinning prescriptions, we constructed ANOVA tests for dominant redwood height among treatments and BAI index among treatments. To investigate the possibility that species composition or site quality had influenced growth of redwood in each plot, we regressed redwood BAI for each plot against treatment (TPA after thinning) and candidate predictor variables: redwood composition, dominant redwood height, and RBAGI. The high TPA in control plots relative to all other treatments caused problems (skewness) when TPA was used as a covariate in the multiple linear regressions. Therefore we excluded data for the three control plots in these regressions. We compared Akaike's Information Criterion (AIC) among regressions (Burnham and Anderson 2002) to identify the combination of variables most likely to explain observed differences in redwood BAI between plots (after accounting for the thinning treatment effect by including post-thin TPA as a covariate in each regression).

Results

Ingrowth and Mortality

Implementation of the PCT treatments resulted in the actual TPA in each plot immediately after PCT was close to the prescribed TPA goal. Ingrowth was variable and consisted of Douglas-fir seedlings and redwood stump sprouts. Mortality occurred primarily in Douglas-fir with the exception of the unthinned plots where mortality occurred across all species (table 1).

Table 1—Ingrowth and mortality 30 years after precommercial thinning (PCT) treatment in 19 year old stand, and actual vs planned treatment TPA

Plot	Block	Treatment TPA 1981	Actual TPA 1981	Ingrowth TPA 2011	Species ingrowth[a]	Mortality TPA 2011	Species mortality
14	N	100	97	19	RW	15	DF
9	M	100	106	19	RW	0	
3	S	100	109	5	TO	0	
17	N	150	148	15	RW	0	
2	S	150	157	0		0	
11	M	150	159	5	RW	31	DF
12	M	200	199	5	RW	5	DF
5	S	200	208	0		0	
18	N	200	208	0		42	DF
8	M	250	255	0		15	DF
13	N	250	267	0		42	DF
1	S	250	292	0		0	
15	N	300	290	10	RW, DF	39	DF
4	S	300	296	0		10	DF
10	M	300	302	0		74	DF
16	N	Control	789	5	RW	368	RW,TO,DF
6	S	Control	891	0		443	RW,TO,DF
7	M	Control	935	0		455	RW,TO,DF

[a] RW = redwood, D = Douglas-fir, TO = tanoak.

Diameter

The 1981 PCT treatment had a lasting effect on DBH development. As measured in 2011 (age 49), thinning to lower densities significantly enhanced average DBH for redwood (p = 0.0002), but not Douglas-fir (p = 0.15) (fig. 2).

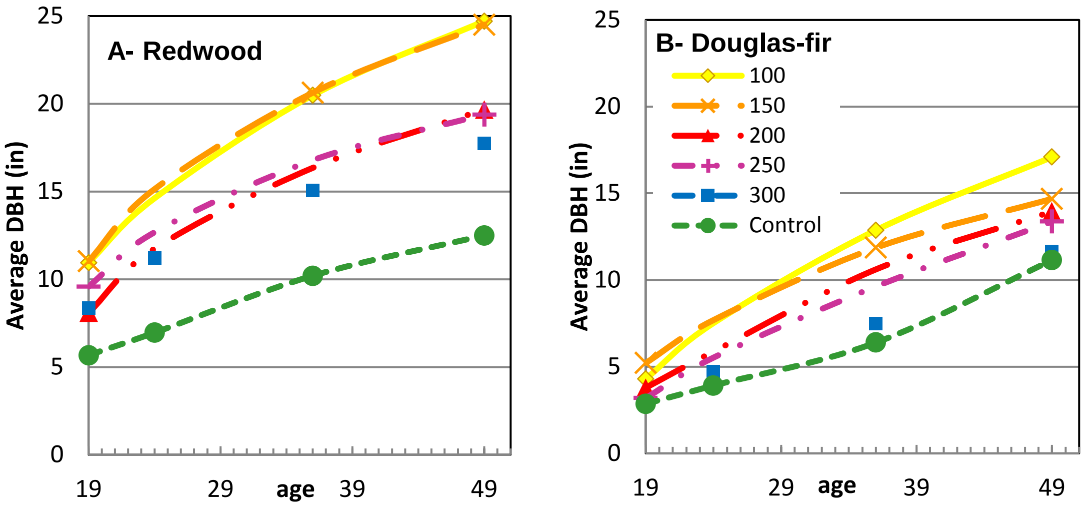

Figure 2—Change in DBH through time by species, A - redwood and B - Douglas-fir, and PCT treatment (TPA retained: 100, 150, 200, 250, 300 and unthinned control).

Basal Area

The 1981 PCT reduced TPA and BA in thinned plots (fig. 3). After PCT, BA development proceeded at slightly different rates, presumably as a consequence of differences in tree size, vigor, and site quality. The unthinned control and 100 TPA treatments showed relatively slow BA development, and the 250 TPA treatment had more rapid BA development relative to the other treatments. Thinning did not result in significantly different BA at age 49 among the three replicate blocks where each PCT treatment was repeated.

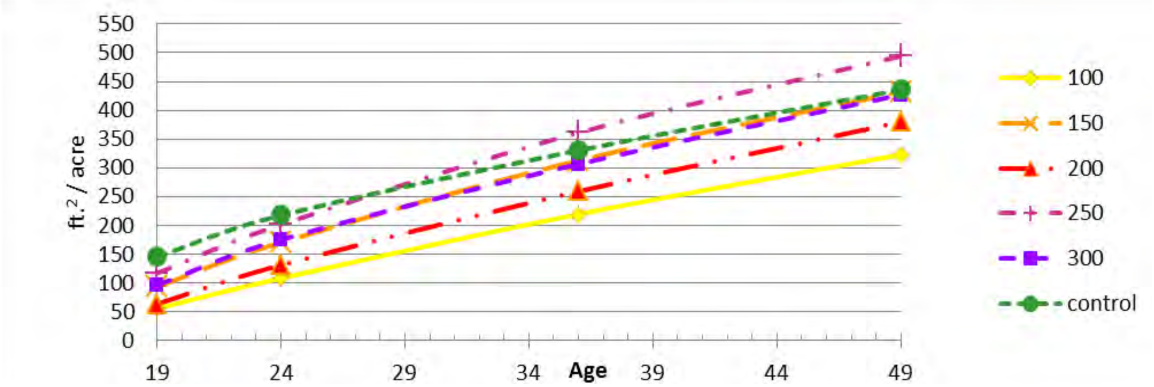

Figure 3—Average basal area (BA) over time by 1981 PCT treatment TPA retention levels.

When the tests were repeated for crop trees (i.e., 140 largest TPA), both the PCT treatment (p = 0.027) and the replicate blocks (p = 0.032) were significantly different. The 150 TPA thinning resulted in the greatest BA (table 2). BA of crop trees was lower three decades after PCT in the controls, which was expected, and in the 100 TPA treatment where the penalty of having fewer than 140 TPA counting towards BA was not overcome by more rapid individual tree growth.

Table 2—Evaluation of the 140 largest TPA (i.e., crop trees) by PCT TPA for the 49 year old stand

PCT TPA	BA ft^2/acre crop tree	ft^3/acre crop tree	ft^3 crop % total	range ft^3 crop tree%	Bf/acre crop tree	Bf crop % total[a]	range Bf crop tree%
100	322	11,358	100%	100%	61,777	100%	100%
150	432	15,213	99%	99-100%	82,051	99%	99-100%
200	338	11,035	91%	83-99%	56,255	92%	84-99%
250	388	13,657	79%	74-86%	72,242	80%	76-88%
300	325	10,962	80%	75-85%	56,168	82%	77-86%
control	289	9,628	71%	65-79%	48,521	75%	69-82%

[a] The volume “crop % total” refers to ratio of volume present in the 140 largest TPA to the total volume per acre expressed in percent.

Cubic Volume

Cubic foot volume increased exponentially through time (fig. 4A). The PCT treatment did not have a significant effect on cubic foot volumes in the 49 year-old stand. When only the 140 largest TPA were considered, both PCT treatment (p =.046) and replicate block (p =.023) were both significant determinants of crop tree volume per acre. The crop tree evaluation had different trends than total volume; the former had lowest volume for control (table 2) and the latter had lowest volume for 100 TPA PCT. This was expected as the result of relatively fewer large trees in the 100 TPA vs the abundant number smaller trees in the control.

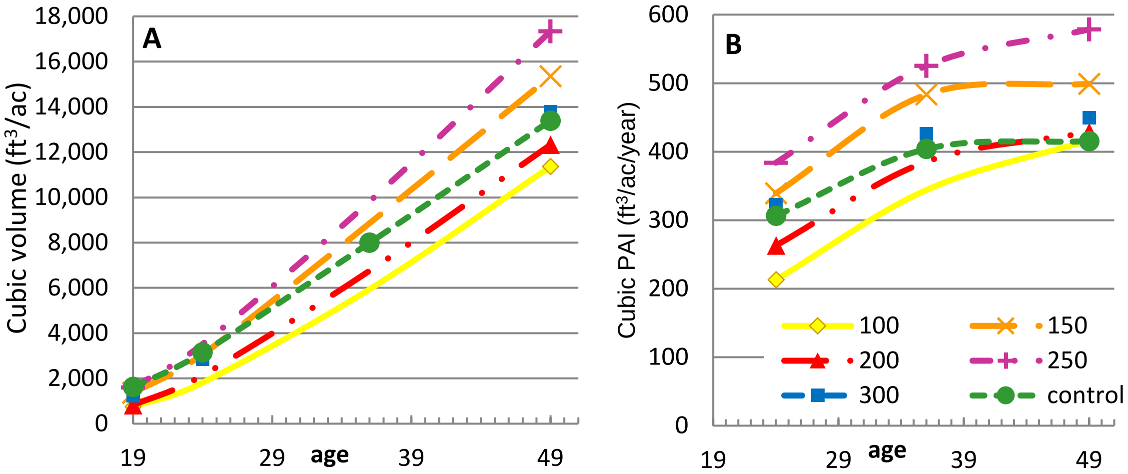

Figure 4—Average cubic foot volume per acre through time by 1981 PCT treatment TPA retention levels. A (left) is total volume per acre (ft³/ac). B (right) is periodic annual volume increment (PAI) between measurement periods (ft³/ac/year).

The cubic foot periodic annual increment (PAI) per year for each period between consecutive measurements indicated that stand growth rate was greater in later periods. However, counter to expectations, cubic volume PAI was not proportional to post-thin TPA (fig. 4B). Presumably, high variability among plots prevented detection of significant differences among PCT treatment levels and replicate blocks.

Merchantable Volume

Board foot volume (Bf) is an estimate that applies to the merchantable portion of the tree. On a per acre basis, merchantable volume exhibited the same trends as cubic foot volume (fig. 5). Thirty years after PCT to 250 and 150 TPA, these age-49 plots carried more Bf volume than any other treatment. The ANOVA test detected no difference among thinned TPA treatments or blocks. However, when the analysis of the 140 largest crop trees per acre was conducted, Bf volume differed among the replicate blocks (p = .022) and the PCT TPA (p = .053). The positive effect of PCT treatment focusing growth on the larger crop or canopy trees is evidenced as the Bf volume of crop trees at age 49 for the 150 TPA treatment had almost twice the volume as the control (82,051 vs 48,521 Bf/ac). Periodic annual increment (PAI, annual Bf growth over period between consecutive measurements) for Bf volume per acre had similar trends as PAI for cubic foot volume.

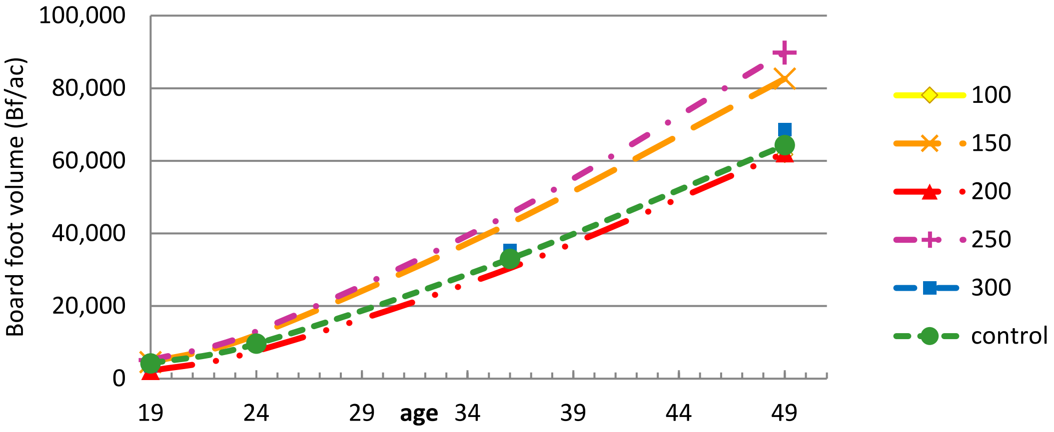

Figure 5—Average board foot volume (Bf) per acre by 1981 PCT TPA levels through time.

Species Composition and Stand Density Index

The proportion of other species to redwood can be characterized using SDI as a proxy for the amount of growing space occupied by each species. The proportion of redwood SDI to total SDI varied from 80 percent to 91 percent. Figure 6 shows the variation in stand density by treatment for the major species (fig. 6A) and displays total SDI development through time for the different PCT treatments levels (fig. 6B). SDI at age 49 years differed significantly among the thinning TPA treatment levels (p = .014). Much like stand BA, SDI did not follow the expected pattern of proportionality to post-thin TPA (actual SDI by PCT TPA ranked from lowest to highest: 100 < 200 < 150 < 300 < 250 < control). Immediately after PCT at age 19, all the plots were below full site occupancy for redwood. SDI of 350 is 35 percent of maximum SDI for redwood and over 50 percent of maximum SDI for Douglas-fir (Long 1985, Reineke 1933). The 49 year old stand has SDI greater than 600 for the higher retention PCT treatments. SDI of 600 is 60 percent of the maximum SDI for redwood and 100 percent of maximum SDI for Douglas-fir so the mortality shown in table 1 high density retention, seems to validate the concept of imminent mortality for this redwood - Douglas fir stand (Drew and Flewelling 1979, Long 1985).

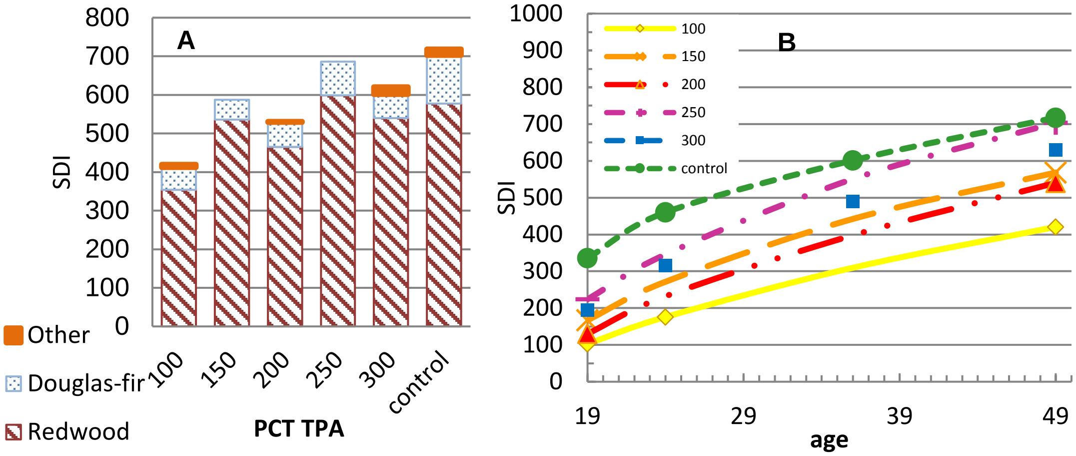

Figure 6–Stand Density Index (SDI) in 2011 (age 49) by PCT treatment, TPA retained and species, where “other species” mainly included grand fir and tanoak (A), and SDI for all species through time by PCT treatment (B).

Species Composition and Site Quality Affect Growth in Each Plot

Examining the development of redwood in each plot provided insight into factors affecting growth of the dominant stand component (i.e., redwood component). Plot-level redwood BAI was at or above the expected BAI curve developed for JDSF in a prior study (Berrill and O’Hara 2014), indicating that this was a very good redwood site. However, redwood BAI per acre was also highly variable among plots, as it ranged from 5 percent to 85 percent above the expect BAI for plot SDI (fig. 7A). Redwood BAI varied widely among plots and treatments (fig. 7B). Dominant redwood height at age 49 years also varied among plots (fig. 7C), and appeared to be lower in the 200, 300, and 500 TPA treatments, but did not differ significantly among the different thinning prescriptions (p = 0.53; fig. 7D). Species composition and site quality were correlated. Plots with a greater proportion of redwood SDI also had taller dominant redwood trees ($R^2 = 0.34$; p = 0.007; fig. 7C) and higher values of BA growth index for redwood (RBAGI) ($R^2 = 0.29$; p = 0.01; fig. 7E). Greater redwood BAI was found in plots with higher RBAGI ($R^2 = 0.80$; p < 0.001) and taller dominant redwood trees ($R^2 = 0.33$; p = 0.007). RBAGI and dominant redwood height in each plot were correlated, but not strongly ($R^2 = 0.33$; p = 0.008). The RBAGI values (describing site quality, in terms of deviation from the expected

BAI) varied among plots (fig. 7E) but did not differ significantly among thinning prescriptions (p = 0.33; fig. 7F). This was consistent with other basal area measurements where variation across the site (i.e., variation among plots and replicate blocks) may have obscured treatment effects.

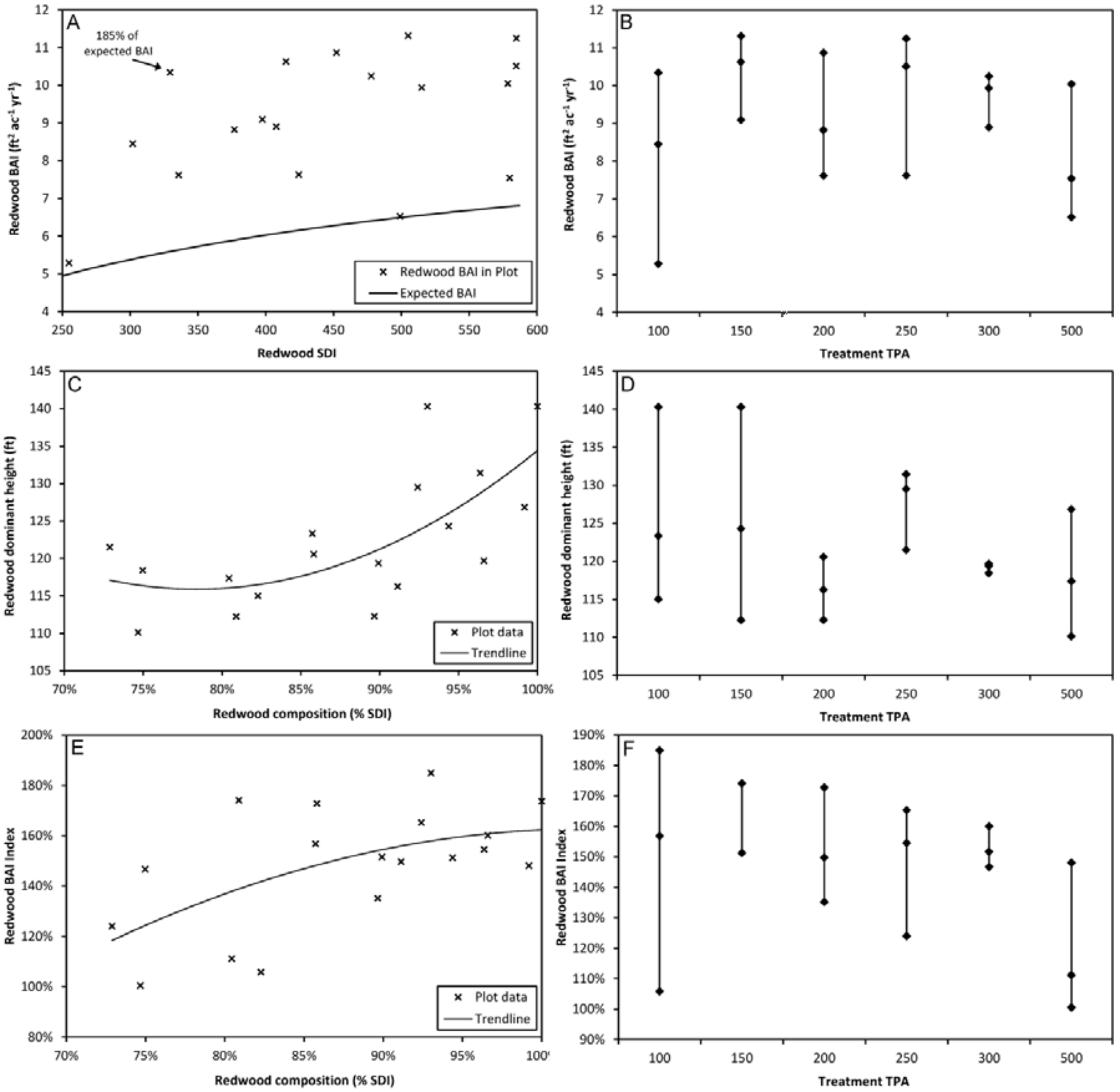

Figure 7—Plot data for redwood basal area increment (BAI) between 1998 and 2011 in PCT treatment plots, as a function of SDI for redwood component in each plot (A), and for each treatment post-thin TPA (B). Dominant redwood height (average age-49 height of 40 largest redwoods per acre in each plot) and composition in terms of redwood as a proportion of total plot SDI (C), and in each prescribed treatment in terms of post-thin TPA (D). Redwood BAI Index (RBAGI; redwood BAI indexed against expected BAI for SDI in each plot; Berrill and O'Hara 2014) and redwood composition (E) and in each PCT treatment (F).

After removing data for unthinned control plots (500 TPA prescription, actually ~900 TPA; table 1), there was no discernable treatment effect on redwood BAI between the two most recent measurements (1998 to 2011) across the range of post-thin densities (100 to 300 TPA) (ANOVA: p = 0.37). The thinning treatment effect on BAI was revealed only after accounting for differences between plots in terms of species composition and site quality. Species composition (percent redwood SDI) had a significant positive influence on redwood BAI. Plots with greater dominant redwood height also had higher BAI. The best combination of factors predicting redwood BAI in multiple linear regressions was post-thin TPA, species composition (percent redwood SDI), and site quality in terms of RBAGI (table 3).

Table 3—Comparing goodness of fit among redwood basal area increment (BAI per acre) models for experimental treatment plots between 1998 and 2011, including candidate predictor variables

Candidate models[a]	**R^2**	**AIC**	**ΔAIC**
$BAI=\beta_0+\beta_1TPA$	0.062	-26.89	-
$BAI=\beta_0+\beta_1TPA+\beta_2RW\%$	0.344	-30.24	-3.35
$BAI=\beta_0+\beta_1TPA+\beta_2DomHT$	0.403	-31.68	-1.44
$BAI=\beta_0+\beta_1TPA+\beta_2RW\%+\beta_3DomHT$	0.470	-31.46	0.22
$BAI=\beta_0+\beta_1TPA+\beta_2\,RBAGI$	0.934	-64.61	-33.15
$BAI=\beta_0+\beta_1TPA+\beta_2RW\%+\beta_3RBAGI$	0.944	-65.24	-0.63
$BAI=\beta_0+\beta_1TPA+\beta_2RW\%+\beta_3RBAGI+\beta_4DomHT$	0.949	-64.63	0.61

[a] TPA = post-thin trees per acre in each plot, RW% = redwood as a proportion of total plot SDI, DomHT = average age-49 height of 40 largest redwoods per acre in each plot, RBAGI = redwood basal area growth index, the actual plot BAI for all redwood indexed against expected BAI for SDI in each plot (Berrill and O'Hara 2014). Smaller AIC is better.

Site Quality Gradient Across Site

Lindquist calculated traditional site index (Lindquist and Palley1963; base age 100) for each block, finding significant difference in site quality among blocks. Analyzing site index calculated using the same equation applied to the 1998 height data with a two way ANOVA with block and PCT TPA found marginally significant differences in site quality among blocks (p = .053). Two way ANOVA of site index calculated using Wensel and Krumland (1986) equations with base age 50 years for 2011 data detected differences among blocks (p = .022) but not PCT treatments. The north block had higher site than the other blocks according to all aforementioned site index estimates and the index of redwood BA growth (fig. 8).

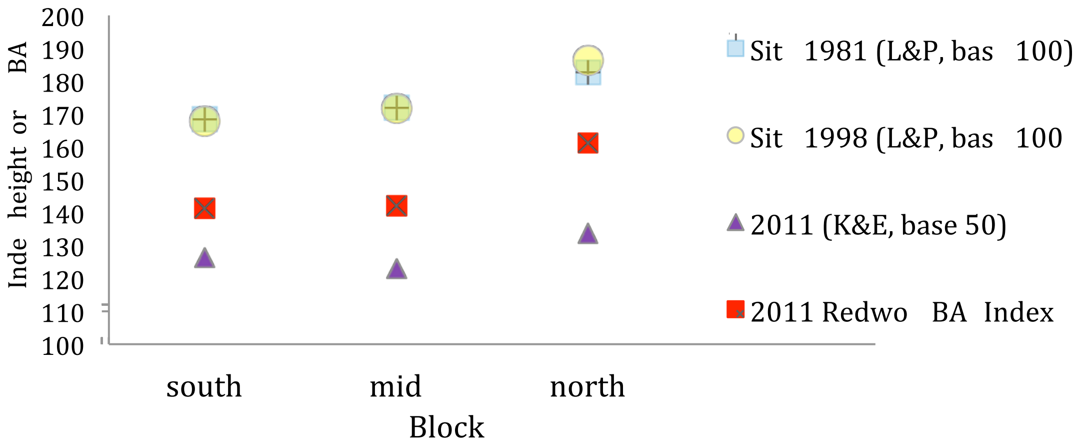

Figure 8—Comparison of the site index tabulations from stands at 19 and 36 year-old (Lindquist, 2004) as well as from 49 year-old stand. 1981 and 1999 calculations used Lindquist and Palley (1963). Wensel and Krumland (1986) and RBAGI (redwood BAI index) used 2011 data.

Discussion

As the stand age approached 50 years old, some trends from the stand establishment phase persisted and new trends were emerging. The significant differences among treatments continued for DBH and for replicate block's site quality. The north block's history of burning and resultant stimulation of *Ceanothus* appeared to have impacted the development of regenerating Douglas-fir seedlings, reflected in a significantly higher 'site quality' (i.e., productivity) for redwood. It was tempting to conclude that more rapid DBH development after heavier thinning appeared to compensate for the BA reduction with enhanced BA development in some thinned plots (fig. 3). Stand BA in the 150 and 250 TPA treatments appeared to “catch up” to BA in plots with the highest densities. However, the reduced BA development in 100 and 200 TPA is consistent with the expectation that reducing stand density by thinning reduces growing stock and therefore stand growth and yield in the near term. More likely was that BA growth was influenced by site effects that differed among plots and blocks.

The redwood BAI evaluation helped tease apart the influences of site, species, and density on productivity. By focusing only on per-acre BA growth of the redwood component (RBAGI) we bypassed the confounding influence of differences in species composition among plots. The RBAGI index of site quality also negated the confounding influence of stand density in each plot which can also obscure differences in site quality. This helped reveal differences in site quality between experimental plots thinned to different densities decades earlier. There was general agreement between RBAGI and redwood dominant height (equivalent to site index) which both indicated that site quality was poorer in the unthinned controls, and varied widely among plots. Agreement was also found when plots with higher proportions of redwood had both higher RBAGI and site index. This correlation between site quality and species composition had been suggested in previous studies (Lindquist 2004, 2007). The per-acre basal area growth of redwood in each plot was best modeled by the combination of thinning TPA, proportion of growing space used by redwood, and RBAGI. That RBAGI was a better predictor than site index is consistent with a different study on JDSF (Berrill and O’Hara 2014) which also demonstrated the utility of the RBAGI to account for the inherent variability in natural redwood stands not related to site index (Berrill and O’Hara 2014, 2016). In both studies, this disagreement between RBAGI and site index was found in plots where redwoods were relatively short but had above-average BA growth and vice versa. Site quality metrics can change over relatively short distances in redwood forests (Berrill and O’Hara 2012, 2015). Though the north block was only 91.4 m (300 ft) from the middle block, the effects of early stand management (i.e., control burning) may be influential as there was no apparent difference in abiotic factors that influenced site quality nor did aerial photos of the prior stand show differences that would explain the significant influence of site quality (in terms of site index and RBAGI) on growth of the redwood component decades after PCT. The weak correlation between site index and RBAGI indicated that height and BA growth proceeded somewhat independently, suggesting they may be controlled by a different suite of biophysical variables (Berrill and O’Hara 2016).

The most striking finding from this remeasurement was that thinning intensity had a lasting impact on average redwood DBH over 3 decades. Focusing on the 140 largest TPA revealed significant, long-lasting, effects of PCT intensity on BA and cubic foot volume. Prior analyses of earlier remeasurements of these plots (Lindquist 2004, 2007) had not identified a thinning effect on unit area basis.

Returning to the original intent of the study; it provided useful observations of the response of a precommercially thinned naturally regenerated redwood forest. When densities above 250 TPA are retained, a smaller proportion of the total volume is present in larger trees (69 to 86 percent crop trees as a percentage of total Bf). This means that a greater fraction of the stand capacity is being used by trees that may not reach the canopy and that provide a less efficient economic return because of their small size. Conversely if management goals were cubic foot carbon stock in the short term (stand less than 50 year old), the lowest PCT retention of 100 TPA did not fully utilize the growing space (fig. 6,) until age 30. Given that specific management goals may change as stands develop, choosing a thinning density in the 150 to 250 TPA range will provide for future flexibility. The unthinned control plots provide an example of when thinning is not undertaken or foregone in lieu of commercial harvest at/after age 50. In this case, even growth of the largest 140 TPA was negatively impacted and board foot volume production suffered.

The study site was one of few locations where PCT in redwood forests has been studied long-term. Maintaining this study will allow for another decadal measurement (year 2021). Remaining questions include; whether the lower stocked (TPA) plots will increase growth rate as they fully occupy the growing space, and how higher density plot growth rate and mortality will proceed given that SDI is now in excess of 600 (fig. 6).

Conclusions

Precommercial or early thinning focused growth on fewer TPA which grew larger up to the latest measurement at age 49 years. Stand production was not proportional to post-thinning density (TPA) alone. Stand history, species mix and site quality were important. Stand production was higher in certain plots and blocks with higher site quality and proportionally more redwood. PCT enhanced development of dominant trees which are expected to be important stand components for both economic and restoration goals.

Given the confounding factors of site history, site quality, and species mix, the study did not identify one optimum density for precommercial thinning. Moderate thinning (150 to 250 TPA retained) did provide reasonable individual tree growth, utilization of growing space, and options for future management. Control plots showed that deferring thinning resulted in ongoing mortality and smaller tree size than any of the PCT treatments.

Acknowledgments

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Literature Cited

Berrill, J-P.; O'Hara, K.L. 2012. Influence of tree spatial pattern and sample plot type and size on inventory estimates for leaf area index, stocking, and tree size parameters. In: Standiford, R.B.; Weller, T.J.; Piirto, D.D.; Stuart, J.D., tech. coords. Proceedings of coast redwood forests in a changing California: a symposium for scientists and managers. Gen. Tech. Rep. PSW-GTR-238. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 485–497.

Berrill, J-P.; O'Hara, K.L. 2014. Estimating site productivity in irregular stand structures by indexing basal area or volume increment of the dominant species. Canadian Journal of Forest Research. 44(1): 92–100.

Berrill, J-P.; O'Hara, K.L. 2015. Spatial variation in dominant height and basal area development in a coast redwood forest: implications for inventory and modeling. Biodiversity Management and Forestry. 4(4): 1–6.

Berrill, J-P.; O'Hara, K.L. 2016. How do biophysical factors contribute to height and basal area development in a mixed multiaged coast redwood stand? Forestry. 89: 170–181.

Burnham, K.P.; Anderson, D.R. 2002. Model selection and multimodel inference: a practical information-theoretic approach. New York: Springer-Verlag.

Drew T.J.; Flewelling, J.W. 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. Forest Science. 25: 518–532.

Lindquist, J.L. 1988. The Caspar cutting trials; a case study report 25 years after harvest. California Forestry Note No. 99. Sacramento, CA: Department of Forestry and Fire Protection. 25p.

Lindquist, J.L. 2004. Precommercial stocking control of coast redwood: seventeen-year status report (1981-1998). California Forestry Report No. 2. Sacramento, CA: Department of Forestry and Fire Protection. 24 p.

Lindquist, J.L. 2007. Precommercial stocking control of coast redwood at Caspar Creek, Jackson Demonstration State Forest. Proceedings of the redwood region forest science symposium: What does the future hold? In: Standiford, R.B.; Giusti, G.A.; Valachovic, Y.; Zielinski, W.J.; Furniss, M.J., eds. PSW-GTR-194. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 295–304.

Lindquist, J.L.; Palley, M.N. 1963. Empirical yield tables for young-growth redwood. Bulletin 796. Berkeley, CA: University of California, Berkeley, Division of Agriculture and Natural Resources, Agricultural Experiment Station. 47 p.

Long, J.N. 1985. A practical approach to density management. Forestry Chronicle. 61: 23–27.

O'Hara, K.L.; Narayan, L.; Cahill, K.G. 2015. Twelve-year response of coast redwood to precommercial thinning treatments. Forest Science. 61(4): 780–789.

Oliver, W.W.; Lindquist, J.L.; Strothmann, R.O. 1994. Young-growth redwood stands respond well to various thinning intensities. Western Journal of Applied Forestry. 9(4): 106–112.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46(7): 627–638.

Webb, L.A; Lindquist, J.L.; Wahl, E.; Hubbs, A. 2012. Whiskey Springs long-term coast redwood density management; final growth, sprout, and yield results. In: Standiford, R.B.; Weller, T.J.; Piirto, D.D.; Stuart, J.D., tech. coords. Proceedings of coast redwood forests in a changing California: a symposium for scientists and managers. PSW-GTR-238. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 571–581.

Wensel, L.C.; Krumland, B. 1983. Volume and taper relationships for redwood, Douglas-fir, and other conifers in California's north coast. Bulletin 1907. Berkeley, CA: University of California, Berkeley, Division of Agriculture and Natural Resources, Agricultural Experiment Station. 39 p.

Wensel, L.C.; Krumland, B. 1986. A site index system for redwood and Douglas-fir in California's north coast forest. Hilgardia. 54(8): 1–14.