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Overstory Response to Alternative Thinning Treatments in Young Douglas-fir Forests of Western Oregon

Abstract

An increase in land dominated by young second-growth Douglas-fir forests in the Pacific Northwest has coincided with heightened concerns over loss of old-growth habitat. In search of options for managing young forests to provide late-successional forest structures, the Young Stand Thinning and Diversity Study was designed to test the effectiveness of modified thinning in acceleration of late-successional structural characteristics. Thinning treatments included: a control, a light thin (typical of standard commercial thins), a heavy thin (densities lower than typically prescribed), and a light thin with gaps (stands thinned lightly with the addition of 0.2 hectare patch cuts evenly spaced throughout the stand). Early response (maximum of 5-7 years post-treatment) of overstory vegetation was examined. Average growth of Douglas-fir increased in all thinned stands, but growth of the largest Douglas-fir trees was only accelerated in the heavy thin. After thinning, the canopy of all thinned treatments was initially more open than the control, but after 5-7 years the light thin was no longer significantly different from the control. The light with gaps thin had the highest variation in overstory canopy cover. Differentiation of vertical canopy structure among treatments was not evident. There was no difference in mortality among any of the treatments for most species tested; those that did had highest mortality in the control. Our results indicate that thinning can be effective in hastening development of some, but not all late-successional attributes, but such acceleration is not equivalent among the different thinning treatments.

Introduction

During recent decades, young managed forests have become a dominant feature in the Pacific Northwest landscape, especially in western Oregon and Washington. Mainly composed of planted Douglas-fir (*Pseudotsuga menziesii*) trees between the ages of 30-50 years, these stands have often replaced what was once dominated by late-successional or "old-growth" habitat (Bolsinger and Waddell 1993). These young stands often lack structural characteristics of old-growth forests, such as large living trees, snags, and a multi-layered canopy that includes an abundant and heterogeneous understory (Franklin and Spies 1991a, 1991b; Spies 1991; Spies and Franklin 1991; Halpern and Spies 1995; Franklin et al. 2002). Without this suite of structural attributes, young stands may not provide the variety of habitats necessary to support a high diversity and abundance of native species (Spies 1991, Halpern and Spies 1995).

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The management of young stands in order to promote late-successional habitat has remained a topic of considerable debate. In response to this debate, the Young Stand Thinning and Diversity Study (YSTDS) was initiated in 1994. As a comprehensive and integrated long-term ecological study, the YSTDS was designed to test the efficacy of thinning young stands to accelerate development of late-successional habitat. Though retrospective studies have investigated whether thinning promotes late-successional habitat (Bailey et al. 1998, Thomas et al. 1999, Thysell and Carey 2000), few studies have implemented thinning with the intent of ecological enhancement (Thysell and Carey 2001). This paper examines short-term responses to thinning treatments designed to accelerate late-successional habitat characteristics.

By opening the canopy and releasing resources, thinning promotes growth of remaining overstory trees and establishment of a prominent understory layer, thereby adding complexity to these young stands and perhaps accelerating development of late-successional habitat (Muir et al. 2002). Enhancing stand complexity results in increased microhabitat heterogeneity and improvement of habitat suitability for many organisms (Carey and Johnson 1995, Hagar et al. 1996, Bailey and Tappeiner 1998, Rambo and Muir 1998, Carey and Harrington 2001, Hagar et al. 2004). Over time, development of large trees and snags combined with a layered canopy and understory may result in thinned stands becoming more similar to old-growth faster than unthinned stands (Muir et al. 2002).

Thinning has not traditionally been used to achieve ecological objectives. It has mainly been a tool for enhancing timber production (for examples see the Level-of-Growing-Stock studies; Marshall and Curtis 2002). Thinning treatments implemented in this study were similar to traditional low thinnings used for timber production, but were modified to address the goal of accelerating several late-successional stand attributes. These attributes include tree species diversity and initial low density conditions of old-growth stand development (Tappeiner et al. 1997, Poage and Tappeiner 2002), and spatial diversity due to small-scale mortality patterns (Franklin and van Pelt 2004).

It is not known if these thinning prescriptions will be successful in acceleration of all late-successional features. For example, accelerating development of the dominant overstory component (Franklin and Spies 1991a) requires dominant trees to increase diameter and height growth following thinning (Staebler 1956, Miller and Williamson 1974, Oliver and Murray 1983). However, the intensity at which thinning reduces competition among the largest trees to accelerate their growth is uncertain. It is also not known whether thinning to very low densities results in high mortality from windthrow or other agents. While thinning may eventually promote establishment of a multi-layered canopy by encouraging crown extension and understory release and regeneration (Bailey et al. 1998), in the short-term low thinning may simplify crown structure by removing many of the suppressed and intermediate trees (Smith et al. 1997). In addition, some conifer and hardwood species may be adapted to a shaded understory and experience high mortality upon canopy removal or as a result of harvest damage (Tucker and Emmingham 1977, Tucker et al. 1987).

To address these questions, the overall objective of this study was to characterize early overstory response following alternative thinning treatments in young Douglas-fir stands. Specifically, this includes a 5-7 year post-thinning comparison among four treatments of: (1) overstory cover (2) vertical crown structure (3) growth of all Douglas-fir trees (4) growth of the largest Douglas-fir trees that may eventually provide the dominant component of late-successional habitat in the stand matrix and near gaps, and (5) differences in mortality of individual tree species due to stand instability, harvesting damage, and competition.

Methods

Study Design and Description

The study is a randomized block design comprised of four blocks with each block containing one replication of four treatments. Study blocks are designated as: Cougar Reservoir (CR), Christy Flats (CF), Sidewalk Creek (SC), and Mill Creek (MC). Blocks were selected for homogeneity in overstory composition, stand age, similar management history, and size (> 56 ha). All blocks are located in the Willamette National Forest on the western slope of the Cascade Range of Oregon (400 to 900 m elevation) and are composed of 40-50 year old (at the time of study initiation) planted Douglas-fir stands occurring within the Western Hemlock (*Tsuga heterophylla*) zone (Franklin and Dyrness 1973). Mean annual precipitation is 230 cm, with only 5% falling between July and October. The average yearly temperature is 10.1ºC. Soils are generally well developed, ranging from thin silty loams/clay loams to thin gravelly loams.

Within each block, each of the four treatments were assigned randomly to a treatment unit, providing a total of 16 treatment units. Treatment units range from 15 to 53 ha in size, and have varied slope and aspects (Table 1). Within a block, treatment units were selected for homogeneity in size, elevation, slope, aspect, site index, soil type, and dominant plant association (Table 1).

In addition to Douglas-fir, stands contained a small component of other conifer (e.g., western hemlock) and hardwood (e.g., bigleaf maple (*Acer macrophyllum*)) species. Baseline pre-treatment stand exam data were collected in 1993 and showed pre-treatment basal areas (BA) and densities (trees per hectare (tph)) were comparable among treatment units within blocks (Table 2).

Treatment Description

The four treatments in each block are: Control, Light thin, Heavy thin, and Light with Gaps thin (hereafter abbreviated as C, LT, HT, and LG, re-

TABLE 1. Site characteristics for each treatment unit. (CR = Cougar Reservoir Block; MC = Mill Creek Block; CF = Christy Flats Block; SC = Sidewalk Creek Block).

Block	Treatment	Area (Ha)	Age	Elev. (m)	Slope (%)	Aspect	Site Index[1]	Dominant Plant Association[2]	Total# of Plots
CR	C	30.0	40	805	18.8	E	107	Tshe/Gash	23
CR	HT	19.4	40	792	24	E	105	Tshe/Bene	13
CR	LT	37.2	38	610	17.1	E	107	Tshe/Bene	26
CR	LG	14.6	40	792	16	ENE	105	Tshe/Bene	29[3]
MC	C	52.6	42	902	21.1	SSEE	105	Tshe/Bene	25
MC	HT	34.8	42	658	22.9	SE	105	Tshe/Bene	23
MC	LT	37.2	43	524	20	S	105	Tshe/Bene	30
MC	LG	19.8	42	439	8.9	SSW	106	Tshe/Bene	29[3]
CF	C	30.8	39	878	6.2	SE	117	Tshe/Bene	23
CF	HT	20.2	36	905	0	SE	120	Tshe/Bene	15
CF	LT	32.0	39	902	5.3	SE	117	Tshe/Bene	24
CF	LG	38.9	40	905	5.3	SSEE	118	Tshe/Bene	30
SC	C	51.0	37	634	11.4	N	114	Tshe/Rhma-Gash	17
SC	HT	19.0	35	652	16	NW	115	Tshe/Rhma-Gash	13
SC	LT	22.3	33	646	21.8	NNE	122	Tshe/Rhma-Gash	15
SC	LG	30.4	39	671	14.5	N	111	Tshe/Rhma-Gash	30

[1]Dominant tree height at 50 years, King's Site Index Tables

[2]Tshe = western hemlock; Bene = Oregon grape (*Berberis nervosa*); Rhma = western rhododendron (*Rhododendron macrophyllum*); Gash = salal (*Gaultheria shallon*)

[3]One stand matrix plot was removed from study because it was located out of study area.

TABLE 2. Description of thinning treatments.

Block	Treatment	Pre-treatment Density[1] (tph)	Post-treatment Density[1] (tph)	Pre-treatment BA[1] (m^2 / ha)	Post- treatment BA[1] (m^2 / ha)
CR	C	929	753	30	53
CR	HT	800	151	27	14
CR	LT	865	312	39	21
CR	LG	891	221	36	19
MC	C	402	655	35	40
MC	HT	466	283	36	13
MC	LT	339	415	40	25
MC	LG	335	346	36	18
CF	C	737	869	42	47
CF	HT	880	133	48	21
CF	LT	871	207	39	32
CF	LG	855	198	40	27
SC	C	756	792	28	39
SC	HT	820	165	25	12
SC	LT	800	277	26	20
SC	LG	743	225	30	15

[1]Pre-treatment measures include all trees ≥ 5 cm dbh. Post-treatment measures include all trees ≥ 8 cm dbh. Pre-treatment data was also sampled differently from post-treatment data. Therefore, these numbers are not presented in order to make direct pre-/post-treatment comparisons, but to illustrate similarities of pre-treatment conditions within each block.

spectively). The LT reflected current conventional thinning for timber production, while the HT and LG aimed at increasing understory vegetation by further reducing overstory densities using different spatial arrangements. Residual target densities (tph) for the thinning prescriptions were: C = unthinned (approximately 650 tph); LT = 250-300 tph; HT = 125 tph; and LG = 250-300 tph with additional cutting of 0.2 hectare circular gaps evenly dispersed every 2 ha (Table 2). Final post-treatment basal areas were close to those of the prescriptions (Table 2). Areas within the LG are stratified into 3 sub-treatments: (1) Gap: 0.2 ha gap; (2) Edge: a doughnut-shaped area surrounding the gap; (3) and Stand Matrix: the remainder of the treatment unit (Figure 1; hereafter abbreviated as G, E, and SM, respectively). More information on theses sub-treatments is provided under Sampling Methods.

Treatments were applied between 1995-1997. Due to the large treatment size, buffering between treatments was not always possible, but treatments were occasionally separated by roads or other terrain barriers. At the CR and MC blocks, thinning was done with a combination of tractor and skyline systems. A ground-based harvester and forwarder system was used at the CF block and a skyline system was used at the SC block.

All thinning treatments used a low thinning prescription with the added objective to leave species other than Douglas-fir. The C provided a reference for stand development without management intervention. The LT was similar to a typical commercial thin commonly used throughout western Oregon except for the retention of species other than Douglas-fir to encourage species mix. The HT opened the canopy substantially more than common commercial thins and reflected recent findings that some old-growth stands initiated at very low densities (Tappeiner et al. 1997). The LG was intended to provide spatial diversity by simulating gap-phase mortality and created open patches within a stand matrix thinned to the same density as the LT.

Sampling Methods

"First-year" post-thinning vegetation sampling occurred in the summer of 1995-1997, depending on the time of harvest completion. In most cases,

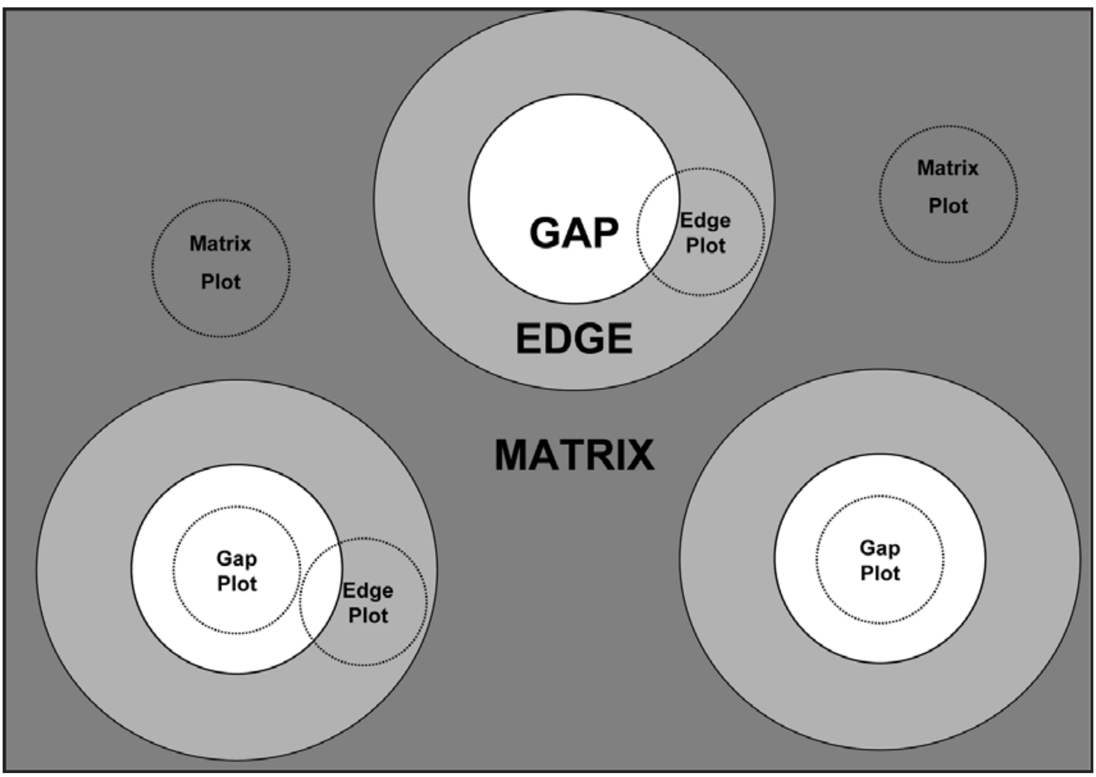

Figure 1. Schematic of sampling design in LG treatment.

this was the first growing season following harvest (for more information on harvest and sampling schedule refer to Beggs 2004). Resampling was completed during the summers of 1999 and again in 2001, depicting vegetation response 3-5 growing seasons and 5-7 growing seasons post-harvest. For ease of communication, these data will be used to depict “first-year”, “third-year”, and “fifth-year” post-treatment vegetation response, respectively.

Sampling was done using 0.1 ha (17.84 m radius) circular permanent plots randomly located along transects that were systematically placed through treatment units. In C, LT, and HT treatment units, approximately 7.5 % of the area was sampled (see Table1 for total plot numbers).

Sampling for each LG treatment unit used 30 plots in order to capture variation among the three sub-treatments. For each treatment unit, 10 gaps and 10 edges were randomly selected and one plot was placed in each. Gap plots were centered in the gap, allowing only the gap interior to be sampled by these plots. Edge plots were centered in a random direction at 35.7 m from gap center so that each edge plot extended 7.5 m into the gap and 28.2 m into the remainder of the stand. For each gap, only one plot was permited to be placed in the surrounding edge. Ten plots were also located in the stand matrix. These plots were randomly placed throughout the remainder of the treatment unit with the criteria that plot center was located at least 71.4 m from the center of any gap, permitting sampling of all area at least 53.5 m from gap center (Figure 1).

Within each plot, overstory cover was measured at plot center and at four locations 10.25 m from plot center in each cardinal direction using a “moosehorn” densiometer (Cook et al. 1995). Overstory cover included live foliage and tree bole, limbs, and snags. Diameter at breast height was also measured for of all trees $\geq$ 5 cm dbh in each plot. Overstory cover and dbh were measured during each year of sampling. In addition, a random subsample of trees in each treatment unit that were measured for dbh was also measured for height and crown length in 1999. Another random subsample of trees in each treatment unit that were selected for height and crown measurements was cored at breast height in 1999 to determine stand age.

Overstory Cover

With the exception of the LG treatment units, average overstory cover of each treatment unit was calculated by averaging the plot means. In the LG, the number of plots in each sub-treatment (G, E, and SM) was the same; however, each sub-treatment did not occupy an equal proportion of the total treatment unit area. To adjust for this, a weighted average of sub-treatment means was used to calculate the treatment unit means. Weights for each sub-treatment were based on the proportion of areas in each sub-treatment to total treatment unit areas. The coefficient of variation (CV), an indicator of variation in overstory cover, was used to compare variation in overstory cover among treatments. The variation of cover was illustrated by comparing frequency diagrams of overstory cover in each treatment.

Vertical Canopy Structure

Assessment of vertical canopy structure required heights and crown lengths for all trees within the sample of the study. Because these measurements were only available for a subsample of the data, height and crown length were predicted for the remaining trees using species-specific non-linear regression. We used equation forms from Hanus et al. (1999) and Ritchie and Hann (1987), but estimated parameters from trees sampled in this study. Because of small sample size concerns, a species was combined with the species most closely resembling its growth pattern when fewer than 10 trees of the species were available. Therefore, grand fir (*Abies grandis*) was combined with Douglas-fir; mountain hemlock (*Tsuga mertensiana*) was combined with western hemlock; Oregon ash (*Fraxinus latifolia*), cascara buckthorn (*Rhamnus purshiana*), and willow spp. (*Salix* spp.) were combined with bigleaf maple. The addition of these minor species did not affect parameter estimates for the dominant species.

These estimates were then used to calculate live crown ratios (LCR) and the foliage height diversity (FHD) index (MacArthur and MacArthur 1961) for each treatment unit. LCR gauges vertical length of the crown relative to tree height and assumes continuous vegetation throughout the entirety of the crown. The FHD index assesses diversity of vertical distribution of foliage using two components: richness and evenness, similar to the Shannon-Weiner diversity index. Richness, in this case, is the number of 5-meter layers occupied by tree crowns in the stand. A 5-meter interval was selected because smaller intervals would not have compensated for the error incurred with estimations of height and crown length measures. Evenness is the relative abundance of tree crowns within these intervals. Like the Shannon-Weiner index, FHD can be strongly influenced by unbalanced dominance of richness or evenness (Hill 1973). To examine if richness or evenness was controlling FHD, both were tested separately.

Diameter Growth

Annual adjusted diameter growth between first-year and fifth-year post-thinning of all Douglas-fir trees ≥ 5 cm dbh was compared among treatments. To calculate annual adjusted diameter growth (expressed as % increase from initial dbh), absolute diameter growth (cm/yr) was first calculated by subtracting first-year dbh from fifth-year dbh and dividing by the number of years between measurements, accounting for offsets in timing of first-year measurements. Annual adjusted diameter growth was then calculated by dividing absolute diameter growth by the first-year dbh and multiplying by 100. Adjusted diameter growth was used because absolute diameter growth did not account for initial differences in dbh among treatments that were an artifact of thinning (thinning removes smaller trees, inherently increasing average dbh in thinned treatments relative to the unthinned treatment regardless of differences in growth).

To specifically assess response of the largest Douglas-fir trees, i.e., trees that likely will make up the dominant stand structure, absolute diameter growth between first-year and fifth-year post-thinning of trees with the largest dbh was compared among treatments. This was done for the largest 10, 15, 20, 25, and 30 tph in order to simulate a range of large-tree densities typical of old-growth stands (Franklin and Spies 1991a). To examine the largest 10 tph, the largest tree from each 0.1 ha plot was selected. Likewise, the 2 largest trees were selected from each 0.1 ha plot to examine 20 tph, and the largest 3 for 30 tph. For the intermediate 15 and 25 tph, half of the plots were randomly selected and the largest 2 or 3 trees, respectively, from these plots were combined with the largest 1 or 2 trees, respectively, from all plots. Absolute diameter growth was calculated as previously described and averaged for each treatment unit. Absolute diameter growth was used instead of adjusted diameter growth because average initial dbh of the largest trees did not differ among treatments.

In the LG, no Douglas-fir were present in the gaps. Thus, growth is representative only of trees in the SM and E. To evaluate potential effects of the gaps on tree development, adjusted diameter growth of all Douglas-fir trees ≥ 5 cm dbh and absolute diameter growth of the largest 10, 20, and 30 tph of Douglas-fir trees were compared between the E and SM sub-treatments. Calculations were done as previously described.

Mortality

Mortality of individual tree species as well as all hardwood species combined was compared among treatments. In each treatment unit, percent mortality of each species was computed between first-year and fifth-year sampling. Percent mortality was calculated for trees ≥ 5 cm dbh and for small trees (trees between 5 –10 cm dbh) in order to determine (a) if species experienced differences in mortality among treatments and (b) if a difference in mortality was limited to small trees, i.e., competition related. Due to concerns about small sample sizes, mortality for a species was only assessed if more than 10 trees of that species were present in each treatment during first and fifth-year sampling.

For all trees ≥ 5 cm dbh, the following species were tested for differences in mortality among all treatments: bigleaf maple, golden chinquapin (*Chrysolepis chrysophylla*), Pacific dogwood (*Cornus nuttallii*), bitter cherry (*Prunus emarginata*), Douglas-fir, Pacific yew (*Taxus brevifolia*), western red cedar (*Thuja plicata*), and western hemlock. Fewer than 10 red alder (*Alnus rubra*) and incense cedar (*Calocedrus decurrens*) were observed in the HT, so comparisons of mortality were only made among the LT, LG, and C. The following species did not have enough trees in any treatment to permit separate comparisons and were only included in the combined hardwood analysis: Pacific madrone (*Arbutus menziesii*), Oregon ash, black cottonwood (*Populus trichocarpa*), cascara buckthorn, and willow species.

For small trees, bitter cherry had too few trees to permit separate treatment comparisons (in addition to the species listed above) and golden chinquapin did not have enough trees in the LT, so comparisons were only made among the C, HT, and LG. These species were still included in the combined hardwood analysis.

Data Analysis

All analyses were done using SAS v. 8.2 statistical software (SAS Institute 2001). Comparisons among treatments were performed with ANOVA using a randomized complete block model. The Tukey-Kramer adjustment was used for all multiple comparisons. Prior to ANOVA, all data were checked for normality. Small sample sizes (n = 16 for comparisons among treatments; n = 12 for LG sub-treatment comparisons) made assessment of normal distributions difficult; however, under the central limit theorem, such distributions approach normality (Thysell and Carey 2000). Therefore, no transformations were performed. The significance level for all analyses was set at $P \leq 0.05$, and $P \leq 0.10$ was considered to be marginally significant.

For mortality comparisons, several species were more frequently observed in the C than thinned treatments, resulting in more precise mortality estimates of these species in the C. To account for decreased precision in thinned treatments, a weighted ANOVA was used to weigh average mortality by total trees (for each species) in each treatment.

Time trends in overstory cover were investigated using a repeated measures analysis. A time * treatment interaction was used to test whether changes in overstory cover were equal among treatments over time.

Results

Overstory Cover

As expected, thinning opened up the overstory canopy. During the first and third years post-thinning, all thinned treatments had less overstory cover than C (Figure 2; Year 1: $P < 0.001$ for HT,

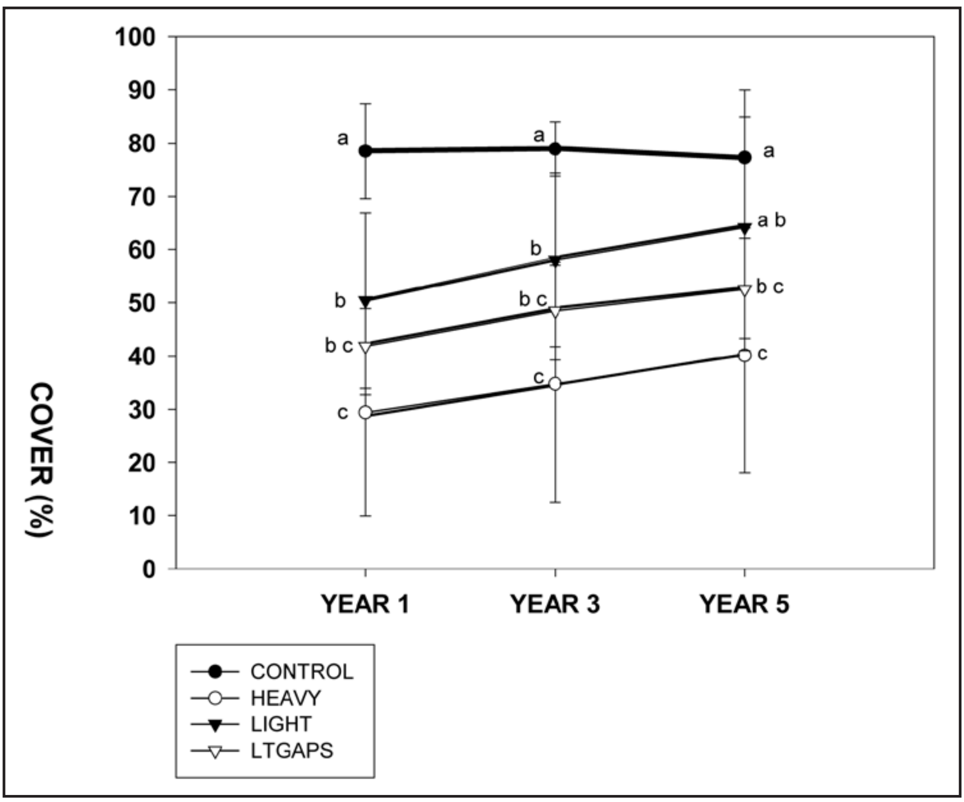

Figure 2. Overstory cover over time (includes 90% confidence intervals). Letters indicate significant differences among treatments (treatments with same letter do not differ at $P \leq 0.05$ level).

LT, and LG; Year 3: $P < 0.001$ for HT and LG, $P = 0.010$ for LT). The thinning treatments differed, as HT had less overstory cover than the LT (Year 1: $P = 0.004$; Year 3: $P = 0.005$). Cover in the LG did not significantly differ from the LT ($P > 0.100$ for both years) but was marginally higher than the HT (Year 1: $P = 0.076$; Year 3: $P = 0.084$). The trends in overstory canopy development differed among treatments (Time*Treatment interaction: $P = 0.021$; Figure 2) and five years after thinning, the HT and LG still had less average cover than the C (HT: $P < 0.001$; LG: $P = 0.003$), but no longer differed from each other ($P = 0.121$). Also, the LT was no longer significantly different from the C ($P = 0.103$; Figure 2). Within the LG, overstory cover was significantly less in the G than the E and SM during all years of measurement ($P < 0.001$ for all years) while the E and SM did not differ from each other ($P > 0.100$ for all years).

Gap creation increased variation in overstory cover distribution. During the first year post-thinning, variation of overstory cover throughout the stand differed among all four treatments ($P < 0.001$). The C had the least amount of variation while the LG had the most. By third-year post-thinning, however, variation in the LT no longer differed from the C ($P = 0.214$). The HT and LG remained more variable than the C ($P < 0.001$ for HT and LG), and the LT (HT: $P = 0.014$; LG: $P < 0.001$) with variation in the LG being greater than variation in the HT ($P = 0.006$). These results did not change by the fifth-year post-thinning. While other treatments displayed normal distributions (for illustrations, see Beggs 2004), the greater variation in the LG is primarily a result of low overstory cover in the gaps and intermediate cover through the remainder of the stand (Figure 3).

Vertical Structure

Differentiation of crown layers did not seem to be significantly impacted by thinning. By third-year post thinning, FHD and LCR did not differ among treatments ($P = 0.85$ and $P = 0.26$, respectively; Table 3). No difference among treatments was found in richness or evenness ($P = 0.783$ and $P = 0.473$, respectively) of canopy layers.

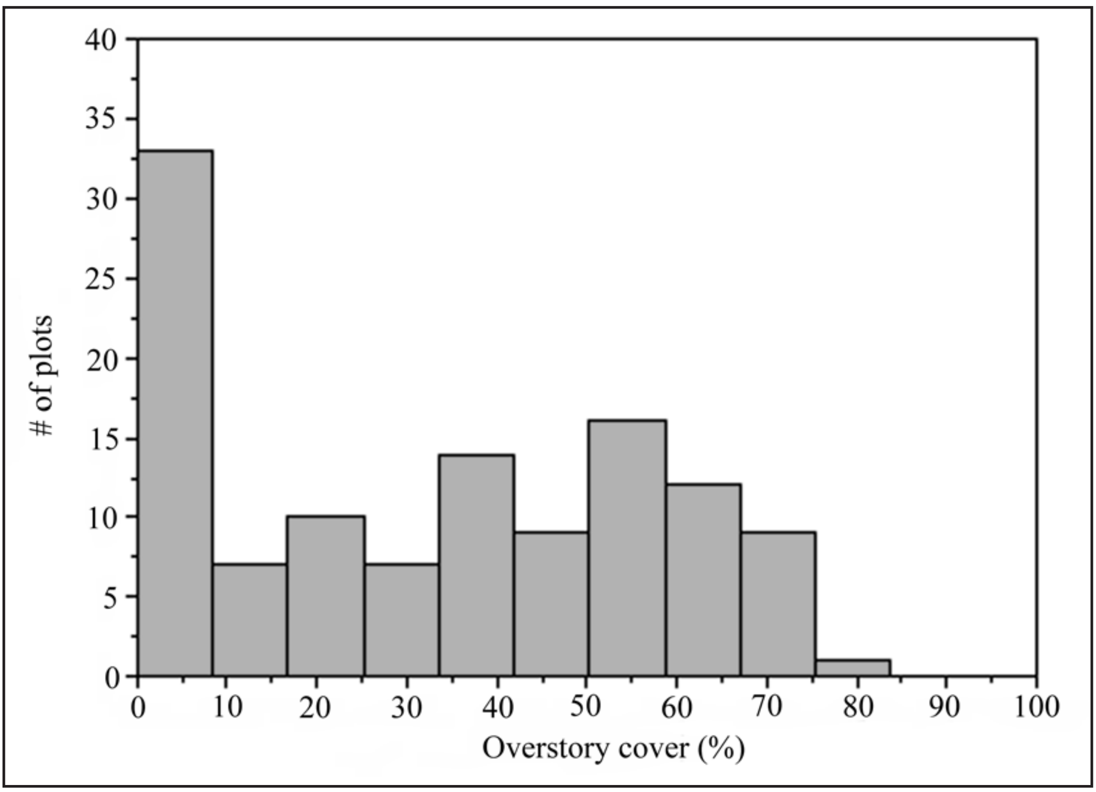

Figure 3. Frequency distribution of overstory cover for LG treatment.

TABLE 3. Overstory Results: (1) FHD = Foliage Height Diversity Index; (2) LCR = Compacted Live Crown Ratio; (3) ADG = adjusted diameter growth of all Douglas-fir ≥ 5 cm dbh; (4) AG = absolute diameter growth of largest 15 tph Douglas-fir trees (results did not differ for ≥ 15 tph). Numbers in parentheses provide 90% confidence intervals of estimates.

Treatment	FHD	LCR	ADG (% increase from initial dbh)	AG of Largest 15 tph (cm/yr)
C	1.57 [a] (1.51 - 1.63)	0.53 [a] (0.50 - 0.55)	1.3 [a] (1.0 - 1.6)	0.70 [a] (0.61 - 0.78)
HT	1.58 [a] (1.52 - 1.64)	0.55 [a] (0.52 - 0.58)	2.4 [b] (2.1 - 2.7)	0.94 [b] (0.84 - 1.0)
LT	1.57 [a] (1.51 - 1.63)	0.51 [a] (0.49 - 0.54)	1.8 [a] (1.5 - 2.1)	0.78 [a] (0.66 - 0.84)
LG	1.60 [a] (1.54 - 1.65)	0.52 [a] (0.50 - 0.55)	1.9 [a] (1.6 - 2.3)	0.85 [a] (0.72 - 0.89)
ANOVA *P*-value[1]	0.854	0.200	0.003	0.033

[1] *P*-value is for overall test of difference among treatment.

Diameter Growth

Heavy thinning was effective in increasing adjusted diameter growth of Douglas-fir. Adjusted diameter growth of Douglas-fir trees ≥ 5 cm dbh differed among treatments by the time of fifth-year measurement ($P = 0.003$; Table 3), but only the HT had significantly higher adjusted diameter growth than the C ($P = 0.002$). The increase in adjusted diameter growth in the LG compared to the C ($P = 0.060$) and in the HT compared to the LT ($P = 0.057$) was marginally significant. Within the LG, adjusted diameter growth in the E was slightly, but marginally significantly higher than in the SM (2.0 vs. 1.8, respectively; $P = 0.064$).

Large Douglas-firs also responded to improved growing conditions provided by heavy thinning. For the largest 15 tph, absolute growth was higher in the HT than in the C ($P = 0.027$) but did not differ between the LT and C ($P = 0.854$) or the LG and C ($P = 0.405$). Results were the same for the largest 20, 25, and 30 tph. For the largest 10 tph, absolute growth of the largest Douglas-fir trees did not differ significantly among any treatments ($P = 0.228$). Within the LG, absolute growth of the largest Douglas-firs did not differ between the E and the SM (10 tph: $P = 0.648$; 20 tph: $P = 0.460$; 30 tph: $P = 0.305$).

Mortality

Tree mortality was reduced following thinning. For trees ≥ 5 cm dbh and small trees, mortality of Douglas-fir and combined hardwoods was higher in the C than all other treatments (Table 4). Within the LG, neither Douglas-fir nor combined hardwood species differed in mortality among sub-treatments ($P > 0.150$; comparisons only between E and SM sub-treamtens for Douglas-fir; for all combined hardwoods, comparisons made with and without G sub-treatment). The same pattern held for golden chinquapin ≥ 5 cm dbh except the difference between the C and LT was not significant (Table 4). Within the LG, mortality of golden chinquapin did not differ among sub-treatments ($P > 0.200$; comparisons made with and without G sub-treatment). None of the other species tested showed significant differences in mortality among treatments.

Discussion

Our results indicated that thinning can place young managed stands on a trajectory to develop several late-successional stand attributes, such as large diameter trees. Other attributes, such as a diversified crown structure, were not rapidly accelerated by thinning; but favorable conditions for eventual development of such structure were created. In addition, leaving tree species other than Douglas-fir was effective in maintaining these species in the overstory and prevented initial simplification of canopy structure.

The thinning treatments differed in terms of their impact on overstory cover, and thus associated characteristics. Light thinning, similar to current timber management practices, did not maintain canopy opening beyond three years. Substantial reduction in stand density, like that of the HT treatment, is necessary to ensure canopy opening is maintained for several years. Open

TABLE 4. Comparisons of mortality (%) among treatments. Results only reported for species with significant differences among treatments. Numbers in parentheses provide 90% confidence intervals of estimates.

	Treatment	Douglas-fir	Golden chinquapin	Combined hardwoods
All Trees (≥ 5 cm d				
	C	14.0 [a]	27.1 [a]	36.1 [a]
		(12.3 - 15.8)	(19.4 - 34.9)	(28.4 - 43.8)
	HT	4.7 [b]	7.8 [b]	18.0 [b]
		(0.1 - 9.3)	(-1.1 - 16.7)	(8.9 - 27.0)
	LT	5.9 [b]	15.1 [a b]	15.3 [b]
		(3.1 - 8.8)	(1.5 - 28.8)	(9.0 - 21.6)
	LG	4.0 [b]	4.4 [b]	13.4 [b]
		(0.8 - 7.2)	(-3.6 - 12.5)	(7.0 - 19.7)
	ANOVA *P*-value[1]	< 0.001	0.010	0.001
Small Trees (dbh = 5 - 10 cm)	C	43.9 a	27.1 a	43.3 [a]
		(39.7 - 48.2)	(-25.8 - 80.0)	(33.7 - 52.8)
	HT	18.3 [b]	14.9 [a]	22.5 [a]
		(5.4 - 31.2)	(-49.8 - 79.5)	(11.2 - 33.8)
		(13.9 - 33.1)	----	(16.4 - 36.9)
	LG	14.7 [b]	14.6 [a]	16.8 [b]
	ANOVA *P*-value[1]	< 0.001	0.781	0.004

[1] *P*-value is for overall test of difference among treatments

canopy conditions permit more light to reach the forest floor (Parker et al. 2001) and, with fewer trees transpiring, generally increase soil moisture (Everett and Sharrow 1985). This can result in enhanced development of understory shrubs and herbs and associated wildlife habitat (e.g., Alaback and Herman 1988, Thysell and Carey 2001, Hagar et al. 2004).

A concern with evenly spaced thinnings is that the uniformly open canopy will encourage a homogenous understory dominated by a few species instead of a patchy and heterogeneous understory (Tappeiner and Zasada 1993, Huffman and Tappeiner 1997, Thysell and Carey 2000, but see Thomas et al. 1999). Thinnings in this study increased variation in overstory cover relative to unthinned stands, especially when gaps were added. Similar to canopy openness, this effect disappeared within three years for the LT treatment, suggesting that traditional thinning may have limited or possibly even undesirable impacts on understory development. Variation in canopy cover following heavier thinnings or thinnings with gaps may prevent homogeneous dominance of a few understory species by ensuring uneven distribution of light (Franklin and Van Pelt 2004). Work currently underway by the authors on the understory vegetation response to the thinning treatments will examine these patterns in more detail.

Thinning treatments differed in their ability to accelerate diameter growth, important to development of the large-tree component of late-successional structure in west-side Douglas-fir forests of the PNW. The influence of residual density on overall tree growth was obvious, as the HT, which resulted in residual densities lower than most conventional thinnings, consistently reduced competition enough to permit residual trees to capitalize on elevated resource availability and increase their diameter growth (Oliver and Murray 1983, Marshall and Curtis 2002). If the difference in growth rates continues, development of large diameter trees will occur faster in heavily thinned stands than unthinned stands. Because these large trees are valuable nest sites for northern spotted owls (Forsman et al. 1984), provide substrate for several epiphytic species (Clement and Shaw 1999), and may eventually become the large snags and downed logs essential to several wildlife species (Hayes et al. 1997), acceleration of their development is key in acceleration of late-successional habitat and structure.

On the other hand, our study indicates that, despite reduction in stand density, competition among the largest trees in the LT (i.e., commonly used thinning regimes), remains too high for these trees to substantially increase their growth (Staebler 1956). However, when this thinning prescription is combined with gap creation, trees bordering gaps seem to benefit from released resources (Gray et al. 2002) and experience slightly elevated growth. Five years may not be sufficient for trees to build up a crown and the increased resource availability may not be expressed in terms of diameter growth. Thus, the trend detectable for the edge trees may strengthen over time (Staebler 1956, Oliver and Murray 1983).

The very largest trees (10 tph) did not experience a release, even in the HT, indicating that they may already have been in a dominant position with minor competition from neighbors (Staebler 1956, Oliver and Murray 1983, D'Amato and Puettmann 2004). While more intense than traditional thinning, the residual density of the HT was still higher than densities at which some old growth stands may have initiated (Tappeiner et al. 1997, Poage and Tappeiner 2002, but see Winter et al. 2002). This seems to suggest that in some instances even more intensive thinnings may be necessary or desirable in order to accelerate growth of the largest trees. Other concerns, such as wind stability, may prohibit very open conditions or heavy thinning operations. In these cases variable density thinnings, which focus on reducing competition to the largest trees, may be more appropriate.

Amplified growth of non-dominant trees and understory vegetation may eventually strain resource availability, especially on drier sites (Messier and Mitchell 1994, Bennett et al. 2003). Other work, however, has shown that dominant trees in young stands tend to contribute the largest proportion of stand production up to the point of stand closure at which time dominance begins to diminish and smaller trees contribute proportionately more to stand growth (Binkley et al. 2003, Binkley 2004). It is hypothesized that when this dominance begins to relax, the trees are so large that their growth no longer balances with their greater control of resources (Binkley 2004). At this point, assuming the largest trees we investigated are dominant in our stands, the trees will be sufficiently large to support a variety of wildlife and other species.

Despite differences in growth and overstory cover, vertical structure was not affected by thinning in the short term. A multi-tiered canopy capable of providing a diversified microhabitat, like that common in old-growth stands (Franklin and Spies 1991a), has not yet begun to develop in these stands. Given the early post-treatment response observed (2 to 4 years after thinning), however, significant changes in crown extension and epicormic branching were unlikely. Maybe more importantly, our results indicate that overstory crown structure in the thinned stands was not simplified, as commonly predicted in low thinnings (Smith et al. 1997). Leaving tree species other than Douglas-fir ensured that the lower layers, which are removed during a conventional low thin, were maintained. Retention of these other species also maintained valuable ecological components, such as hardwoods (Hagar et al. 1996, Rambo and Muir 1998, Rosso 2000). A mixture of overstory species that includes hardwoods can often support several species assemblages better than a forest lacking diversity in overstory composition (Hagar et al. 1996, Hayes et al. 1997, Rosso 2000). Bird species, such as the warbling vireo (*Vireo gilvus*), are related to hardwood presence (Hagar et al. 1996). Hardwoods also generally provide more nutrient rich leachate than conifers, making them important to forest floor bryophyte species that obtain the majority of their nutrients from leachate (Rambo and Muir 1998).

Concerns about loss of tree species other than Douglas-fir due to increased mortality in thinned stands were not warranted. Most mortality was related to competition, as mortality of Douglas-fir, golden chinquapin, and all combined hardwood species was higher in unthinned stands relative to thinned stands. The dense conditions of unthinned stands probably inflicted extreme competition for resources upon suppressed and intermediate trees, resulting in high mortality (Oliver and Larson 1996, Franklin et al. 2002). By removing several intermediate and suppressed trees, thinning likely relaxed resource competition among remaining trees, thereby decreasing mortality (Oliver and Larson 1996, Marshall and Curtis 2002). On the other hand, heavier thinnings did not result in unstable stand conditions over the measurement period.

In summary, thinning of the type implemented in this study can be an effective way of increasing complexity in young, managed stands. However, applying traditional thinning practices are likely not sufficient to accelerate the development of late successional structures. Instead, thinning practices need to be "customized" in terms of the specific structural components (e.g., large trees, diverse understory light conditions) that are desired.

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