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Variable density thinning promotes variable structural responses 14 years after treatment in the Pacific Northwest

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ABSTRACT

Young stands are commonly assumed to require centuries to develop into late-successional forest habitat. This viewpoint reflects the fact that young stands often lack many of the structural features that define late-successional habitat, and that these features derive from complex stand dynamics that are difficult to mimic with forest management. Variable density thinning (VDT) is a silvicultural strategy designed to accelerate development of late-successional habitat by applying a variety of harvest intensities within a stand. Previous reports indicate that VDT has had initial success increasing growth and regeneration. However, few studies have examined the effects of VDT at longer time scales. Here, we report 14-year growth response of residual trees in the thinned and unthinned VDT sub-treatments in five young mixed-conifer stands located on the Olympic Peninsula in western Washington. Our objectives were to investigate whether thinning has accelerated the recruitment of large trees (> 80 cm dbh), recruitment of shade-tolerant species into the mid-story (40–65 cm), or development of longer crowns relative to the unthinned sub-treatment. In addition, we investigated whether the basal area distribution in the combined VDT sub-treatments has become more diverse compared to the unthinned sub-treatment. The response to thinning varied consistently across the diameter size class gradient. Thinning was ineffective at stimulating growth of upper canopy trees (65–80 cm). In this size class neither diameter growth nor crown length increased significantly compared to trees in unthinned patches. Further, only one stand has reached the restoration benchmark for large tree density. In contrast, thinning significantly increased diameter growth and crown length among trees in the mid-story (40–65 cm) and shade-tolerant species in the future mid-story (20–40 cm). Higher rates of recruitment into the mid-story were also observed from shade tolerant species growing in the thinned (34%) compared to unthinned (19%) patches, with two stands reaching the restoration benchmark for shade-tolerant mid-story density. Clear trends in basal area diversity and evenness have yet to develop in either the combined or unthinned sub-treatments. Collectively, our results demonstrate that VDT has partially accomplished its objectives. Although thinning has not yet accelerated recruitment of large trees, it has accelerated the advancement of shade-tolerant species into the mid-story and the development of deeper crowns among trees in smaller size classes. In addition, differing rates of diameter growth among smaller diameter trees in the various VDT sub-treatments suggest that increases in structural diversity may be developing more quickly than in untreated stands.

1. Introduction

Forest restoration has become an increasingly common forest management objective, particularly on public lands. Throughout much of western North America, restoration efforts have focused on reversing forest succession to offset decades of fire suppression (Covington, 2000; Allen et al., 2002; Baker and Shinneman, 2004). One notable exception to this regional trend can be found in the Pacific Northwest (PNW), where accelerating the formation of late-successional structural attributes is a restoration priority (Bolsinger and Waddell, 1993; Franklin and Norman Johnson, 2012).

Interest in restoring late-successional structure on federal land is largely driven by concerns over declining late-successional wildlife habitat and biodiversity (Carey and Harrington, 2001; Spies et al., 2010). Of particular concern is the relative structural simplicity of forests managed for wood production. Late-successional structural attributes often lacking in stands managed for timber production include: large canopy trees (> 80 cm in diameter), diversity of tree size-classes,

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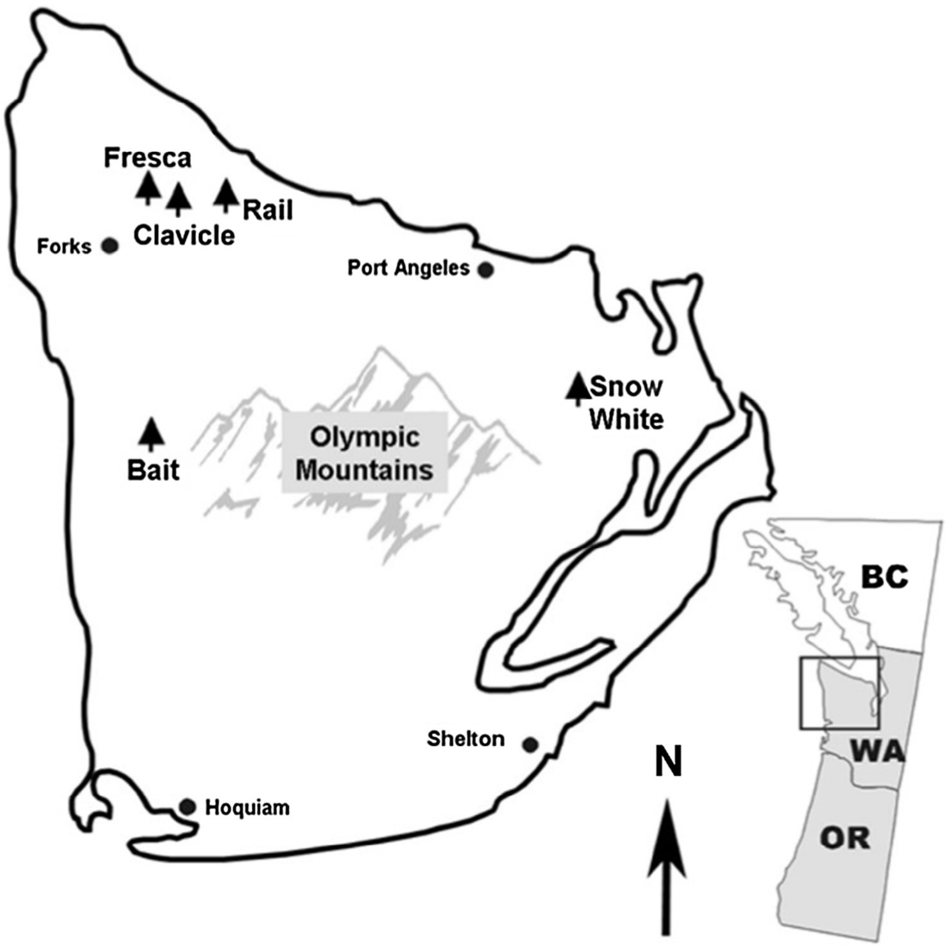

Fig. 1. Area map of the Olympic Peninsula in northwestern Washington showing locations of the five study sites on the Olympic National Forest where wind damage was assessed following variable-density thinning. Circles indicate locations of major towns on the Olympic Peninsula.

coarse woody debris (CWD – down wood and snags), variation in crown structure, and the development of a shade-tolerant mid-story (Franklin and Spies, 1991; Spies, 2004; Zenner, 2004; Bauhus et al., 2009). While all of these attributes typically develop naturally over time, considerable interest has been given to testing management practices which may accelerate the successional process (Curtis and Carey, 1998; Franklin et al., 2002; Reutebuch et al., 2004; Carey, 2006; Curtis et al., 2017).

Thinning has been shown to accelerate tree growth (Mitchell, 2000; Marshall and Curtis, 2002), suggesting that it may be applied to hasten both stand and individual tree growth. Traditional forms of low thinning, however, have been focused on stand growth rather than structural diversity (Nyland, 1996). Natural restoration processes may even be delayed by traditional forms of thinning, particularly low thinning, as these treatments tend to homogenize stand structure, limit CWD input, and remove snags (Nyland, 2003; Larson and Churchill, 2008). Variable density thinning (VDT), on the other hand, is a silvicultural strategy designed to stimulate forest growth while promoting late-successional forest structure (Carey, 2003, 2006). Unlike thinning for wood production, VDT distributes resources unevenly within a stand by creating canopy gaps and gradients of stand density (Carey, 2003; Comfort et al., 2010). The goal of these treatments is to encourage horizontal and vertical heterogeneity within the stand. For example, high resource environments such as thinned areas or canopy gaps are created to encourage rapid tree growth, crown retention and expansion, regeneration, and a more diverse herbaceous vegetation layer (Puettmann et al., 2016). Conversely, unthinned patches are retained resulting in slower individual tree growth, crown contraction, and higher mortality, thus encouraging the creation of snags and greater inputs of CWD to the forest floor. The intended effect of these varying treatments is to produce a more structurally complex stand, consistent with the defining characteristics of late-successional forests in the region (Franklin and Spies, 1991).

Initial reports on the effectiveness of VDT have varied among structural attributes and ecological processes. Diameter growth has been shown to positively respond to VDT at the stand level (Davis et al., 2007; Dodson, 2012), in the mid-story (Comfort et al., 2010), and among individual trees located in proximity to harvest gaps or skid trails (Roberts and Harrington, 2008; O'Hara et al., 2010; Dodson, 2012). Natural regeneration, crown length expansion, and herbaceous layer species richness and diversity have also been shown to increase following gap creation or VDT (Thysell and Carey, 2001; Ares et al., 2010; Dodson, 2012; Curtis et al., 2017). In contrast, growth rates amongst the largest trees have been largely unresponsive to thinning (Dodson, 2012), at least initially, raising questions over whether these trees are experiencing a delayed response or whether more intensive thinning is required to stimulate growth (Maguire et al., 2006; Davis et al., 2007). Similar questions exist surrounding the impact of VDT on forest structure. Dodson (2012) report higher BA variation in plots treated with VDT. However, in a longer-term study, Kuehne et al. (2015) found no significant improvement in structural heterogeneity following VDT. Finally, long-term questions regarding growth dynamics, tree size class diversity, and crown response to VDT remain unanswered, as few studies have reported results beyond the first decade following treatment (Kuehne et al., 2015).

In this report, we examine late-successional structural development in five relatively young second-growth mixed-conifer stands on the Olympic Peninsula in western Washington 14 years following VDT. We focus on the development of main- and mid-canopy structural diversity, and therefore limit our analysis to trees in those canopy strata at the

Table 1
Selected site and stand variables for five stem-mapped plots in the Olympic Habitat Development Study.

Stand	BH age[a] (yrs)	Elevation (m)	Annual precip.[b] (mm)	Avg. temp.[b] (°C)	Primary tree species
Rail	43	275	2376	9.6, 22.6, 1.5	Douglas-fir, western hemlock
Fresca	50	150	2709	10.1, 23.3, 1.9	Western hemlock, Sitka spruce
Clavicle	48	475	2540	9.0, 22.7, 0.7	Western hemlock, Sitka spruce
Bait	38	245	3362	10.1, 24.0, 1.6	Western hemlock, Douglas-fir
Snow White	63	580	1460	8.9, 23.2, 0.9	Douglas-fir, western hemlock, western redcedar

[a] Breast height age is age at beginning of the treatment, based on 6–10 dominant trees.
[b] Average precipitation and temperatures values are 30-year averages over the period from 1981 to 2010. Temperature values provided as mean annual, mean August maximum, and mean January minimum based on PRISM model values (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, retrieved 27 April 2017. Model description in Daly et al., 1994).

onset of the study. Our objectives were to evaluate whether VDT has accelerated: (1) growth of upper canopy trees (65–80 cm) and recruitment of large trees (> 80 cm); (2) growth of shade-tolerant trees likely to constitute the future mid-story (20–40 cm) and recruitment of these shade-tolerant trees into the defined mid-story size class (40–65 cm); (3) live-crown expansion across diameter size classes, as well as with location within the stand; and (4) basal area diversity and evenness among tree size classes.

2. Methods

2.1. Site description

We utilized data from five stands located on the Olympic National Forest on the Olympic Peninsula in western Washington (Fig. 1). Elevations range from approximately 150 m to nearly 600 m ASL. Soils at all sites are deep loams with good drainage. Average annual precipitation ranges from 1955 mm to 3175 mm and falls mostly as winter rain, with comparatively dry summers. Winters are cool and summers warm, with mean annual temperatures of approximately 8–10 °C (Table 1).

Differences in stand management history, local topography, site quality, and floral composition exist among sites. The Fresca and Rail sites regenerated naturally following clearcutting and broadcast burning around 1930. Both still appear as recently cutover in 1939 aerial photography suggesting an extended stand initiation phase (Peter and Harrington, 2010). Fresca and Rail are situated on terraces of the Solduc River with generally flat topography. The dominant plant association at Fresca is *Picea sitchensis/Oxalis oregana* (Henderson et al., 1989). At time of treatment, Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) were the dominant tree species. Site index for both western hemlock and Sitka spruce is ca. 37 m at 50 years (Wiley, 1978; Farr, 1984). Fresca had received no known silvicultural treatments prior to this study. The dominant plant association at Rail is *Tsuga heterophylla/Gaultheria shallon-Polystichum munitum* (Henderson et al., 1989). At time of treatment, western hemlock and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) were the dominant tree species. Site indices at 50 years for western hemlock and Douglas-fir are ca. 41 m and 38 m, respectively (Wiley, 1978; King, 1966). A light thinning to salvage trees killed by bark beetles was conducted at Rail in 1986, removing less than 15% of the stocking.

Clavicle is shown on forest inventories as recently cutover in the early 1930s. Management records from that time are not known to exist; however, typical post logging management in that area was to burn the slash and let the stand regenerate naturally. Breast-height age in 1994 was only 48 years, which suggests the area endured an extended or delayed period of stand establishment. The area of the stand examined in this study sits on a flat ridge with slopes generally less than 5%. The dominant plant association at Clavicle is *Picea sitchensis/Polystichum munitum/Oxalis oregana*. At time of treatment, western hemlock and Sitka spruce were the dominant tree species. Site index at 50 years for western hemlock is ca. 35 m, and for Sitka spruce is ca. 39 m.

Bait was clearcut in the early 1950s, and likely burned prior to being planted with Douglas-fir. Substantial amounts of western hemlock has established naturally. Slopes range from 0% (hilltops) to 35%. The dominant plant associations are *Tsuga heterophylla/Polystichum munitum-Oxalis oregana* and *Tsuga heterophylla/Gaultheria shallon-Oxalis oregana*. At time of treatment, Douglas-fir and western hemlock were the major tree species. Site index at 50 years for both species is ca. 40 m. Bait received a light pre-commercial thinning in the late 1960s and early 1970s. There are no records of the stand receiving any other cultural treatments.

Snow White is the only site located on the east side of the Olympic Peninsula. The site was clearcut around 1928, burned, and planted with Douglas-fir in the early 1930s. Slopes at Snow White generally vary from 10 to 25%. Common plant associations include *Tsuga heterophylla/Mahonia repens/Oxalis oregana*, *Tsuga heterophylla/Gaultheria shallon/Polystichum munitum*, and *Tsuga heterophylla/Gaultheria shallon*. At time of treatment, Douglas-fir was the dominant tree species, but western hemlock and western redcedar (*Thuja plicata* Donn ex D. Don) were also well-represented. Site index at 50 years for Douglas-fir is ca. 35 m. The site was commercially thinned in the early 1970s.

2.2. Treatments

A variable-density thinning was implemented at Fresca and Rail in 1997 and at Bait, Snow White, and Clavicle in 1999. The prescription called for a series of gaps and untreated patches to be embedded within a thinned matrix. Creation of 0.04–0.05 ha gaps on 15% of the treatment area involved removal of all merchantable stems (ca. > 20 cm dbh) with the exception of species of low local abundance (e.g., hardwoods, western redcedar). Unthinned patches were 0.1–0.3 ha in size and covered 10% of the treatment area. No harvest or entry of equipment was allowed in the unthinned areas. The thinned matrix, covering the remaining 75% of the treatment area, called for 25% basal area removal, primarily from the lower crown classes. All trees were hand felled. Ground-based yarding equipment was used to remove trees at all sites except Bait, which used a skyline yarding system.

Treatment areas at each site were approximately 6–10 ha in size, and replicated three or four times. Within one of the treatment areas at each site, a single plot of 1.44 ha (1.53 ha at Fresca) was established prior to treatment for complete stem mapping (Fig. 2). Each stem-mapped plot contained two complete gaps, one complete unthinned patch, and a portion of a third gap and second unthinned patch. Within the plot, all trees with heights greater than 1.3 m were tagged and their locations mapped and coordinates stored in a GIS database. A summary of stand conditions prior to, immediately following, and 14-years after variable-density thinning is provided in Table 2.

The analysis presented here utilizes data from the stem mapped plots. One caveat of our design is that the stem-mapped plots did not have a true control. Therefore, for the purposes of this analysis, we assumed that the characteristics of the unthinned patches approximated how the stand would have developed had the VDT treatment not been

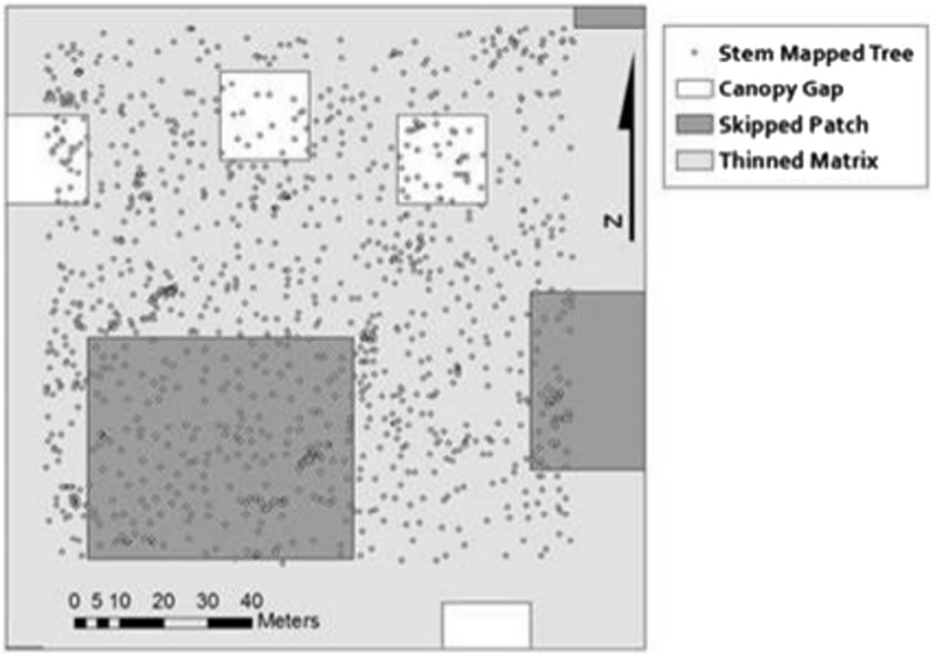

Fig. 2. An example of a stem-mapped plot (Rail) at the OHDS, showing the sub-treatments associated with the variable-density thinning.

implemented.

2.3. Field measurements and data analysis

Detailed measurements were taken within each stem-mapped plot prior to and immediately following the VDT, and 14 years following treatment. For all tagged trees, dbh was measured, and species and crown class were recorded. Total height and height to base of the live crown were taken on a sub-sample of between 75 and 143 trees per stem-mapped plot representing the range of tree species and sizes found on the plot. Crown length was calculated as the difference between total height and height to the base of the live crown.

Diameter growth was taken as the difference between dbh measured immediately following thinning and dbh at the 14-year re-measurement. Basal area (BA) of each tagged tree was calculated from the diameter measurements and a 14-year BA increment was calculated for each tree as the difference between the two post-treatment measurements.

The main goal of the OHDS is to test whether VDT accelerates late-successional habitat development. The analysis presented here focuses primarily on whether the VDT sub-treatments were successful in accomplishing objectives related to canopy structure. The few trees retained within gaps were excluded from analyses due to low representation. We also did not address regeneration dynamics in this

Table 2
Stand conditions for all trees ≥20 cm dbh prior to, immediately following, and 14-years following application of the variable-density thinning treatment at five sites (blocks) in the Olympic Habitat Development Study. Data do not include understory trees. Post-harvest data include trees that grew into the ≥20 cm dbh class since the previous measurement.

Stand	Pre-harvest			Immediately Post-harvest[a]			14-year Post-harvest		
	Density (tph)	Dq (cm)	BA ($m^2 ha^{-1}$)	Density[b] (tph)	Dq (cm)	BA ($m^2 ha^{-1}$)	Density[b] (tph)	Dq (cm)	BA ($m^2 ha^{-1}$)
Rail									
Total	288	42.5	41.0	308	43.4	45.6	293	50.7	59.3
Unthinned				426	41.1	56.6	397	47.5	70.4
Thinned				268	44.6	41.8	258	52.3	55.5
Fresca									
Total	314	47.6	55.8	298	48.7	55.5	263	57.2	67.5
Unthinned				475	45.4	76.9	412	53.1	91.1
Thinned				262	49.9	51.2	233	58.6	62.8
Clavicle									
Total	409	45.2	65.6	401	46.6	68.4	373	53.5	83.8
Unthinned				648	40.9	85.0	565	46.4	95.7
Thinned				350	48.6	64.9	333	55.7	81.3
Bait									
Total	467	36.9	50.0	458	37.7	51.1	449	43.2	65.8
Unthinned				678	35.6	67.4	625	40.4	80.0
Thinned				379	38.9	45.2	386	44.7	60.6
Snow White									
Total	269	44.9	50.0	264	46.1	44.2	282	50.2	55.7
Unthinned				364	44.5	56.6	360	48.9	67.5
Thinned				242	46.6	41.5	265	50.5	53.2

[a] Post-harvest stand measurements taken 1–2 growing seasons following pre-harvest measurements.
[b] Density measurements include ingrowth into the ≥20 cm dbh class.

analysis as that is the subject of a future report. We were also interested in how individual species, stand conditions, and initial tree size influenced progress towards our four objectives. Analyses were performed using JMP 9.0 and SAS 9.4 (SAS Institute, Cary, NC). A description of the analyses used for each objective is provided below.

Objective One – A shortage of existing large trees (> 80 cm) (n = 13) limited the analysis of growth in this size class to descriptive statistics. Consequently, our analysis of the recruitment of large trees focused primarily on the 14-year growth and survival of trees initially in the upper canopy (65–80 cm) size class. These trees were targeted because their initial size made them the most likely candidates to become large trees (Franklin and Spies, 1991). Due to small existing populations, upper canopy trees at Bait and Rail were excluded from the analysis. Trees that died over the time period examined were also excluded from the growth analysis. This resulted in a sample population of 105 upper canopy trees distributed across Clavicle, Snow White, and Fresca.

In addition to the existing upper canopy trees, we examined the diameter growth of all trees initially in the defined mid-story size class (dbh 40–65 cm) (Franklin et al., 1986). Although the growth response of these mid-story trees were unlikely to contribute to large tree recruitment within the time frame of this study, we were interested in whether their growth differed from that of trees in the upper canopy size class. Trees from all five stands were included in this growth analysis, resulting in a sample size of 1148 trees. Due to the younger stand age of Bait, trees whose initial size fell within the designated mid-story diameter range occupied upper canopy as well as mid-story canopy positions; while at the other sites, designated mid-story trees were primarily found in mid-story canopy positions.

To identify factors affecting the diameter growth of residual trees, we constructed general linear, least squares models assuming a normal error distribution. Limitations associated with uneven replication among factors prevented us from analyzing a full model of main effects and higher-order interactions. Instead, our analysis included the main effects of treatment (thinned matrix vs. unthinned patches), species, initial tree size (dbh), stand, and the interaction between treatment and stand. The treatment x stand interaction was included in the model because we considered the response of stands to VDT to be the most meaningful interaction for applied restoration, and because it had the most robust sample population among the two-way interactions. Preliminary analysis indicated that growth responses among species differed significantly. Thus, a separate analysis was conducted for each species' response to treatment, initial size, stand, and the interaction of treatment and stand. Prior to analysis, residuals of each model were explored to confirm the assumptions of linear modeling, and a square root transformation of diameter growth was required to meet the assumption of equal variance. To account for the fact that all species were more abundant in the thinned compared to unthinned treatments, a weighted ANOVA was used to quantify average growth by the total number of trees of each species in each treatment (Quinn and Keough, 2002). Model selection was accomplished through backwards elimination. Preliminary model runs indicating an interaction exceeding the suggested threshold for pooling ($P > .25$) resulted in the removal of the highest-order interaction term with the highest P-value (Bancroft, 1964). Pooling at the suggested threshold was done to avoid distorting the power of the final model. This procedure was repeated iteratively until the P-value of all interactions fell below the suggested pooling threshold. A critical threshold value of $\alpha = 0.05$, used to determine significance in the final model. Significant main effects of stand and species were further examined for differences with Tukey's multiple comparison tests ($\alpha = 0.05$). Average survival rates and large canopy tree recruitment were calculated, but not compared statistically. Restoration progress was assessed through post hoc comparisons of large tree density (new recruits + existing canopy trees) in each of the three stands.

Objective Two – At the beginning of the study, every stand but Snow White contained the desired density of trees in the defined mid-story size class (> 30 trees ha^{-1} > 40 cm) (Franklin et al., 1986). However, given the relatively young age of our stands at the time of treatment (38–63 years), some of these trees are currently occupying positions within the main canopy and will not function as the future mid-story in these stands, making this size class designation somewhat arbitrary. Consequently, we examined the growth of shade-tolerant species whose initial diameter was between 20 and 40 cm. Douglas-fir was excluded from this analysis, due to its intermediate shade tolerance (Burns and Honkala, 1990). Trees which died during the 14-year period were also removed from consideration, leaving a population of 625 trees in this size class located across all five sites.

Potential factors affecting 14-year diameter growth of the future mid-story trees were examined following the same protocol described under Objective One. The initial model contained the main effects of treatment, initial tree size, species, stand (all five sites), and two-way interactions between stand, species, and treatment. Two-way interactions involving initial size were not included in the full model because these relationships offer little applicable information. Low replication compelled us to exclude the species x site interaction. Models involving treatment were weighted to adjust for the higher number of trees in the thinned treatment. A square root transformation was once again required to meet the assumptions of normality. All other steps in the growth and survival analyses remained consistent with the above-described procedures. Restoration progress was assessed through post hoc comparisons of shade-tolerant species recruitment into the defined mid-story size class relative to the previously stated restoration target (> 30 trees ha^{-1} > 40 cm) (Franklin et al., 1986).

Objective Three – The development of deep canopies characteristic of late successional forests involves not only the development of a mid-story of shade-tolerant species, but also the enlargement of crowns on upper canopy, midstory and future mid-story trees. We, therefore, examined the change in live crown length over the 14-year post-VDT period within the diameter size classes. Similar to the previously described objectives, a general linear modeling approach was used to examine treatment effects on crown length while including stand, species, crown class, and initial crown length in the model as covariates. The analysis included all trees greater than 20 cm dbh at the time of treatment that had heights and crown measurements taken at both the initial post-treatment measurement and the 14-year re-measurement. Since we were looking at the development of different components of the canopy, we separately examined existing upper canopy and large trees (≥65 cm), trees in the defined mid-story category (40–65 cm), and future mid-story trees (20–40 cm).

An anticipated benefit of the VDT treatment was the spatially variable developmental processes acting on trees due to the incorporation of the gaps and unthinned patches. Thus, we examined the effect of proximity to internal stand edges on crown development of trees within both the thinned matrix and the unthinned patches. Trees were classified into five different locations representing a gradient in competitive environments. The locations were: GE – trees in the thinned matrix and within 10 m of a gap edge, MAT – trees in the thinned matrix and not within 10 m of any internal edge, MUE – trees in the thinned matrix and within 10 m of the 'soft' edge between the thinned matrix and an unthinned patch, UE – trees in an unthinned patch and within 10 m of the thinned matrix, and UT – trees in an unthinned patch and not within 10 m of the thinned matrix. We tested whether the proximity of trees to these internal edges resulted in differential changes in crown length over the 14-year post-VDT period.

Objective Four – To assess changes in structural diversity we compared the distribution of tree sizes, as measured by individual tree basal area, for the entire stem-mapped plot (thinned matrix and unthinned patches) to the distribution of tree sizes in the unthinned patches only. This was examined both immediately following the VDT treatment and again 14-years post-VDT. BA data for all live trees greater than 20 cm dbh immediate post-treatment and 14-year post-treatment were sorted by BA, and placed into 5 cm^2 classes. Trees < 20 cm dbh at the beginning of the experiment were omitted from the baseline diversity calculations, as we wanted to isolate the effects of VDT on previously established future mid-story trees. However, trees that grew into the future mid-story size class were accounted for in the final diversity calculations. A Shannon-Wiener diversity index was calculated to track changes in size class diversity, while a Gini coefficient was utilized to quantify changes in basal area evenness. These indices were selected for their discriminant ability and relatively low sensitivity to sample size (Lexerød and Eid, 2006). Size class richness was calculated by summing the number of size classes present in the population.

3. Results

3.1. Large tree recruitment (> 80 cm) and growth of smaller diameter size classes

The existing large tree (dbh > 80 cm) population consisted entirely of Sitka spruce, and was found only at Clavicle and Fresca. For these trees, total diameter growth (14-year interval) averaged 12.3 cm, and survival was 100%. Total diameter growth for existing upper canopy trees (dbh 65–80 cm) averaged 10.5 cm. Over the 14-year period, 59% (n = 62) of the upper canopy trees advanced into the large tree size class. Upper canopy trees in the thinned matrix (10.9 cm) did not grow significantly faster than upper canopy trees in unthinned patches (10.1 cm) (Table 3), and a slightly lower percentage of trees from the thinned treatment (58%) advanced into the large canopy tree size class relative to the unthinned patches (65%). Neither stand nor initial tree size had a significant influence on upper canopy tree diameter growth (Table 3). Significant species differences were observed in the growth of trees in the upper canopy size class, as Sitka spruce grew more in diameter (11.3 cm) than Douglas fir (6.5 cm) (Table 3). This trend, however, was not significantly related to any examined factor. Mortality of existing upper canopy trees was low, with 98% survival through the final measurement. At 14 years post-VDT, only Clavicle with 24 trees ha^{-1} had reached the restoration target for large canopy tree density.

Diameter growth among trees in the existing mid-story size class (dbh 40–65 cm) followed a different trend. In contrast to the upper-canopy trees, diameter growth in existing mid-story was significantly increased by the thinning ($P < .0001$) (Data not shown). On average, trees in the thinned matrix (n = 874) added 7.4 cm of total diameter growth, while trees in the unthinned patches (n = 274) gained 5.9 cm over the 14-year interval. Overall, 16% of existing mid-story trees in the thinned matrix grew into the upper canopy size class compared to 13% of the trees in the unthinned patches. No mid-story trees (40–65 cm dbh) grew into the large tree size class (> 80 cm dbh) regardless of treatment. Mortality equaled 3% in both the thinned and unthinned sub-treatments over the 14-year period.

Table 3
Results of a general linear model for the main effects of treatment (thinned vs. unthinned), species, initial diameter, stand (Clavicle, Fresca, Snow White), and the interaction between treatment and stand on diameter growth over 14 years for existing upper canopy trees (dbh 65–80 cm). Factors were considered significant at α = 0.05 (N = 105 trees).

Factor	Sum of squares	F ratio	Prob > F
Treatment	0.32	1.33	0.2516
Species	4.94	10.15	< 0.0001
Initial size	0.35	1.42	0.2356
Stand	0.14	0.28	0.7571
Treatment × Stand	0.98	2.01	0.14
Adj. R^2 = 0.19			
Prob > F = 0.0004			

Table 4
Results of a general linear model for the main effects of treatment (thinned vs. unthinned), species, initial diameter, stand, and two-way interactions treatment x species and treatment x stand on diameter growth over 14 years for shade-tolerant future mid-story trees (20–40 cm diameter). Interactions with P > .25 were pooled into the error term (Bancroft, 1964). Factors were considered significant at α = 0.05) (N = 625 trees).

Factor	Sum of squares	F ratio	Prob > F
Treatment	44.57	160.17	< 0.0001
Species	0.31	0.56	0.5742
Initial size	30.22	108.60	< 0.0001
Stand	128.57	115.51	< 0.0001
Adj. R^2 = 0.52			
Prob > F < 0.0001			

3.2. Future mid-story growth and mid-story recruitment

Shade-tolerant species in the future mid-story size class (dbh 20–40 cm) (i.e., excluding Douglas-fir) averaged 4.5 cm of total diameter growth. Thinning significantly accelerated total diameter growth of future mid-story trees (Table 4). Accordingly, recruitment into the defined mid-story size range mirrored the growth response and was higher in the thinned matrix (34%) than in unthinned patches (19%). Significant differences in diameter growth were also detected between stands (Table 4). On average, future shade-tolerant mid-story trees exhibited the greatest increase in total diameter growth at Bait (6.6 cm), while trees at Clavicle (3.1 cm) and Fresca (3.0 cm) grew the least (Fig. 3). Bait (48 trees ha^{-1}) and Clavicle (49 trees ha^{-1}) were also the only stands that reached the restoration target density for recruitment into the defined mid-story size class. Initial tree size also significantly influenced future mid-story development (Table 4), as larger diameter trees had higher average growth rates. Overall, mortality averaged 11% over the 14-year period, being only slightly lower in the thinned matrix (10%) than in the unthinned patches (12%).

3.3. Crown development

A total of 276 trees located in the thinned matrix (n = 183) and unthinned patches (n = 93) had crown measurements taken immediately post-treatment and again after 14 years, and were therefore included in the analysis of crown development. Across all 276 trees, the average increase in crown length over the 14-year post-treatment period was 1.1 m. Western hemlock showed the greatest increase at 1.7 m, Sitka spruce increased 1.3 m, and Douglas-fir crowns remained

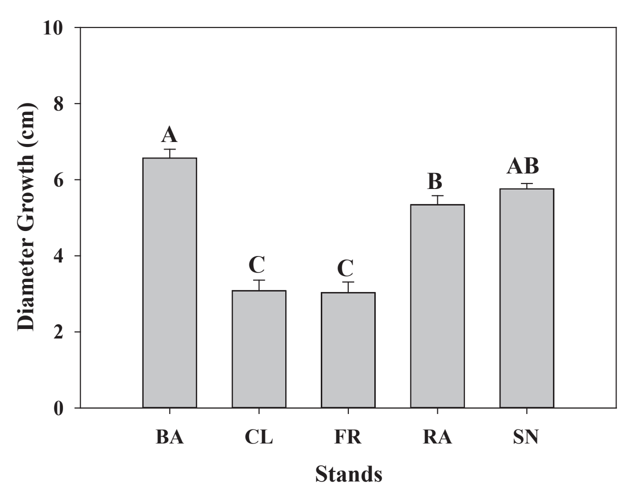

Fig. 3. Average diameter growth (cm) of shade tolerant future mid-story trees (20 < 40 cm dbh) over 14 years at Bait (BA), Clavicle (CL), Fresca, (FR), Rail (RA), and Snow White (SN). Stands with differing letters were found to be significantly different (Tukey's HSD post hoc comparisons, α = 0.05). Error bars represent 1 SE.

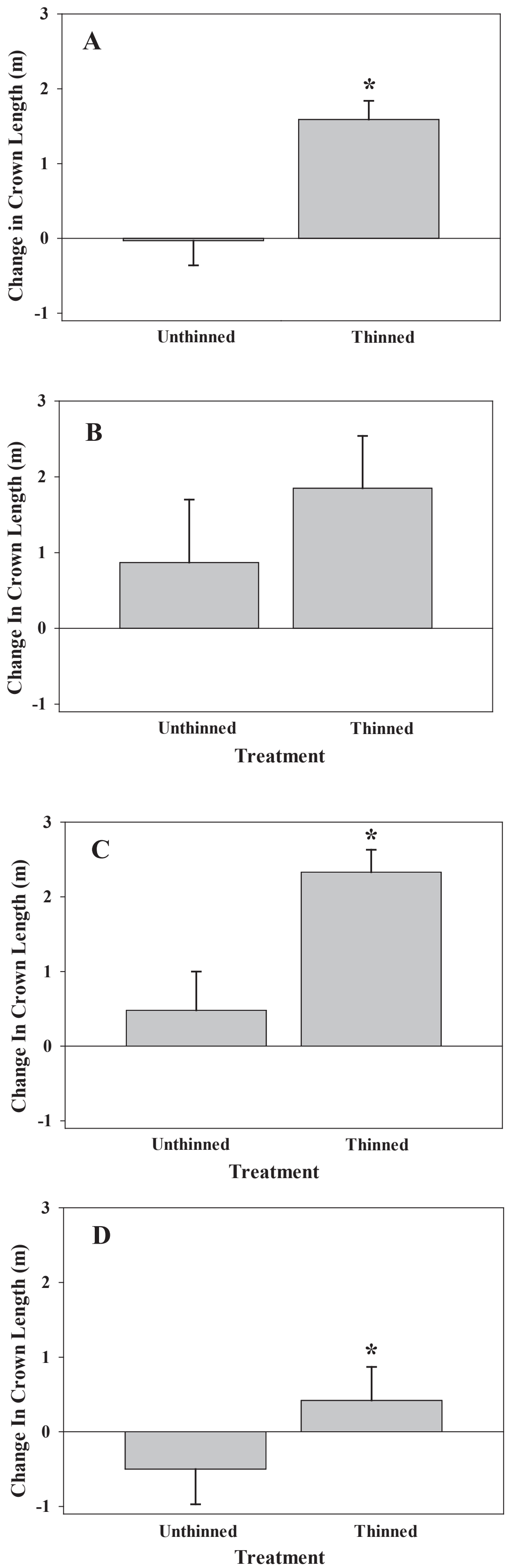

Fig. 4. Changes in the average length of the live crowns in the thinned matrix and in unthinned patches. Individual panels show A – All trees ≥ 20 cm dbh, B – trees > 65 cm dbh, C – trees 40–65 cm dbh, and D – trees 20–40 cm dbh. Asterisks represent a significant difference between treatments (paired *t*-test, α = 0.05). Error bars represent 1 SE.

nearly unchanged, increasing on average by only 0.2 m. Larger diameter trees generally showed greater increases in crown length. For trees greater than 40 cm dbh, the average crown length increased 1.8 m, with hemlock (2.5 m) again showing greater increases than Sitka spruce (1.9 m) or Douglas-fir (1.1 m). Trees less than 40 cm dbh on average had no change in crown length. Smaller hemlock (< 40 cm dbh) showed only a slight increase in crown length (1.0 m) while smaller Sitka spruce (−1.9 m) and Douglas-fir (−1.1 m) exhibited reductions in crown length. In almost all cases, changes in crown length for species differed significantly by treatment, with greater increases (or smaller decreases) occurring in the thinned matrix than in the unthinned patches.

When all trees were examined together, treatment had a significant effect on the change in crown length (P < .0001, Fig. 4A). Crown lengths of trees in the unthinned patches remained, on average, unchanged over the 14-year post-treatment period, while trees in the thinned matrix increased by an average of 1.6 m. The change in crown length did not differ significantly between treatments when only trees greater than 65 cm dbh were examined (P = .268, n = 30, Fig. 4B). When trees in the defined mid-story size class (dbh 40–65 cm) were examined (n = 129), treatment had a significant effect on change in crown length (P = .006, Fig. 4C). Trees in the unthinned patches increased an average of 0.5 m in crown length, while trees in the thinned matrix increased on average by 2.3 m. Treatment was also significant (P = .025) among future mid-story trees (dbh 20–40 cm, n = 117, Fig. 4D). Future mid-story trees in the unthinned patches decreased in average crown length by 0.5 m while trees in the thinned matrix increased in crown length by 0.4 m.

When location of trees relative to internal edges was inserted in the model in place of treatment, location was a significant predictor of change in crown length. This was true when all trees were examined together (n = 276, P < .001), and where size classes were examined separately, e.g., upper canopy (n = 30, P = .019), mid-story (n = 129, P = .024), and future mid-story (n = 117, P = .047). While change in crown length was quite variable due in part to differences in stand, species, crown class, and initial crown length, a consistent trend emerged across all tree size classes. Increases in crown lengths were, on average, greater for trees in the thinned matrix that were closest to canopy gaps (Fig. 5A–D). Average change in crown length decreased in the thinned matrix for trees located closer to the unthinned patches. With a few exceptions, average crown length changes were smallest within the unthinned patches.

3.4. Forest structure

Although thinning had an overall positive impact on diameter growth, evidence demonstrating accelerated structural development by VDT (whole stem-mapped plot) was less conclusive. Higher basal area diversity was observed following VDT at Rail and Bait (Table 5). Basal area evenness was also higher following VDT in every stand except Fresca (Table 6). In contrast, VDT resulted in lower basal area diversity at Snow White, Clavicle, and Fresca, and lower size class richness at Rail, Snow White, and Clavicle compared to the unthinned patches (Table 7). The contrasting responses observed across stands were not clearly related to tree species composition, as stands with similar species assemblages (e.g. Rail and Snow White or Clavicle and Fresca) responded differently to VDT.

4. Discussion

4.1. Large tree recruitment (> 80 cm) and growth of smaller diameter size classes

Large trees are renowned for their biological and aesthetic contributions to late successional forests (Franklin and Spies, 1991; Lutz et al., 2012). As such, accelerating their recruitment is an important

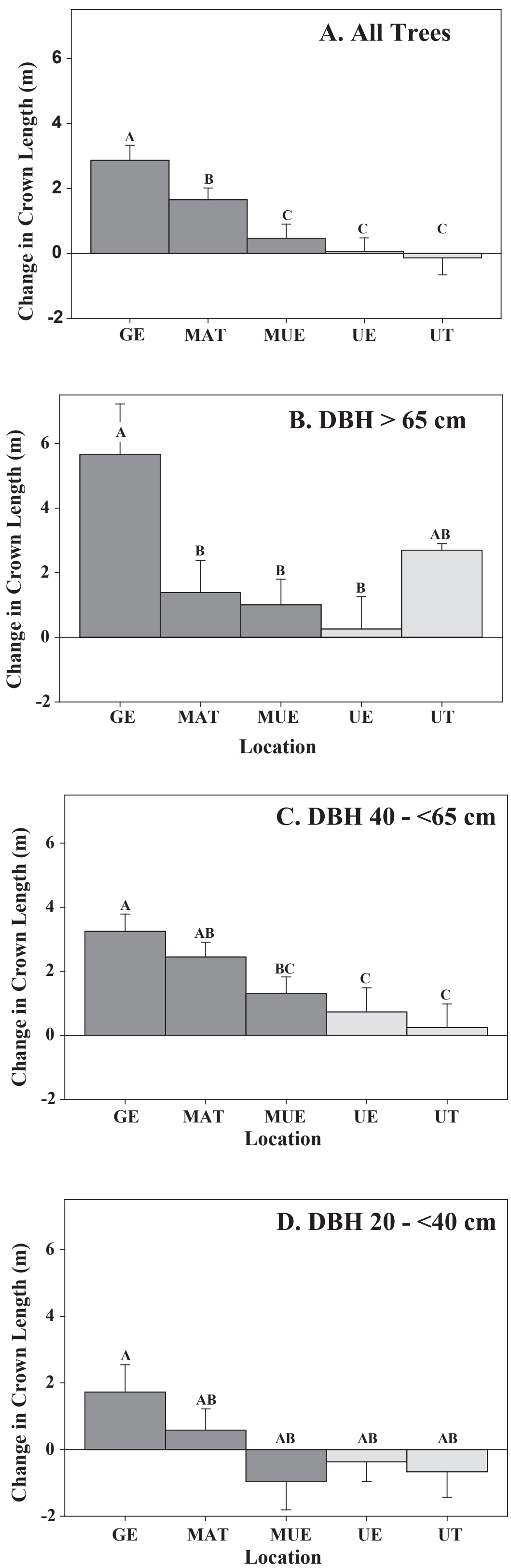

Fig. 5. Changes in the average length of the live crowns as a function of a tree's location within the stand. Dark colored bars represent trees within the thinned matrix. Light colored bars represent trees within the unthinned patches. Location GE includes trees in the thinned matrix within 10 m of a gap edge. Location MAT includes trees in the thinned matrix further than 10 m from any internal edge. Location MUE includes trees in the thinned matrix within 10 m of an unthinned patch. Location UE includes trees in unthinned patches within 10 m of the thinned matrix. Location UT includes trees in an unthinned patch further than 10 m from any internal edge.

Table 5
Changes in basal area diversity from the initial measurement through the 14th growing season in sections treated with variable density thinning (VDT) (thinned matrix + unthinned patches) compared to unthinned patches in each experimental stand. Basal area diversity was quantified with a Shannon-Wiener diversity index using 5 cm size classes as surrogates for individual "species." Increases in index values represent an increase in basal area diversity, while a decreases indicate a less diverse distribution.

Stand	Unthinned initial	Unthinned final	VDT initial	VDT final	VDT impact
Rail	2.06	2.18	2.00	2.19	+0.07
Fresca	2.41	2.61	2.49	2.56	−0.13
Clavicle	2.47	2.58	2.56	2.57	−0.10
Bait	2.02	2.17	2.00	2.16	+0.01
Snow White	2.24	2.47	2.31	2.5	−0.04

Table 6
Changes in basal area evenness from the initial measurement through the 14th growing season in sections treated with variable density thinning (VDT) (thinned matrix + unthinned patches) compared to unthinned patches in each experimental stand. Basal area evenness was assessed with a Gini coefficient using 5-cm size classes as surrogates for individual "species." Negative changes in coefficient values represent a more even distribution of basal area, while positive changes indicate a more imbalanced distribution.

Stand	Unthinned initial	Unthinned final	VDT initial	VDT final	VDT impact
Rail	0.5	0.51	0.55	0.53	−0.03
Fresca	0.45	0.43	0.48	0.5	+0.04
Clavicle	0.37	0.33	0.42	0.37	−0.01
Bait	0.46	0.5	0.52	0.54	−0.02
Snow White	0.43	0.43	0.52	0.45	−0.07

Table 7
Changes in size class richness from the initial measurement through the 14th growing season in sections treated with variable density thinning (VDT) (thinned matrix + unthinned patches) compared to unthinned patches in each experimental stand. Richness was quantified as the number of 5-cm size classes containing at least one tree.

Stand	Unthinned initial	Unthinned final	VDT initial	VDT final	VDT impact
Rail	12	15	13	15	−1
Fresca	16	18	18	21	+1
Clavicle	15	16	18	17	−2
Bait	11	14	12	15	+0
Snow White	13	16	15	17	−1

consideration in accelerating the development of late-successional structures in younger stands (Bauhus et al., 2009). Fourteen years following treatment, only Clavicle has reached the suggested standard for density of large (> 80 cm dbh) canopy trees (20 ha^{-1}) (Franklin and Spies, 1991). This outcome was driven primarily by the baseline diameter distributions of our stands. Only Clavicle and Fresca began the study with any existing canopy trees in the 65–80 cm size class, and in all stands the initial mean diameter fell well below the designated large canopy tree range (Roberts and Harrington, 2008). Thus, reaching the large canopy tree restoration benchmark was going to be a long-term process in the majority of our stands regardless of the growth response. Further evidence emphasizing the importance of baseline conditions comes from the fact that Clavicle reached the established restoration benchmark without demonstrating significantly higher diameter growth among upper canopy trees (dbh 65–80 cm) in response to the thinning. Consequently, our results demonstrate that baseline conditions may impact the restoration timeframe as much as, if not more than, any manipulative treatment. This is perhaps especially germane to physiological processes like stem diameter growth, which naturally slow in larger and older trees, and sometimes demonstrate a delayed response to manipulation (Latham and Tappeiner, 2002).

Species composition also aided the recruitment of large canopy trees at Clavicle, and to a lesser extent at Fresca. Consistent with the findings of Deal et al. (2013), existing upper canopy Sitka spruce significantly outgrew other species of similar size. At Clavicle, the existing population of large trees was nearly pure Sitka spruce. Thus, stand growth at Clavicle benefited more from spruce's growth advantage than the stands at Fresca (87% Sitka spruce) or Snow White (0% spruce). Therefore, not only did the existing upper canopy trees at Clavicle require less growth to reach the target size class (80 cm dbh), but Clavicle also had a population of trees that demonstrated the greatest growth response.

Thinning did produce a modest, though statistically insignificant, increase in canopy tree growth. Changing resource allocation patterns are sometimes thought to constrain growth potential in older, larger trees (Weiner and Thomas, 2001). However, for the existing upper canopy tree population (dbh 65–80 cm) in this study, age-related physiological shifts were most likely negligible, as conifers have been found to grow vigorously well-beyond the average age (75 years) of our existing stands (Tappeiner et al., 1997; Poage and Tappeiner, 2002). Instead, we attribute the modest growth response, at least in part, to the conservative nature of the thinning treatment. Due to concerns over potential wind damage, stands were thinned lightly from below (25% basal area removal) (Roberts and Harrington, 2008), resulting in a residual stem density (303–496 trees ha^{-1}) roughly triple the density reported by Tappeiner et al. (1997) for old growth forests (100–120 trees ha^{-1}). The relatively modest reduction of sub-dominant trees likely had little effect on resource availability for the existing upper canopy trees, as most were already in dominant or co-dominant canopy positions and likely not under strong competitive stress from trees in the sub-canopy (Weldon and Slauson, 1986; D'Amato and Puettmann, 2004). Moreover, with the exception of locations adjacent to harvest gaps, the relatively low levels of canopy disturbance associated with the low-intensity thinning likely had little effect on belowground resource availability (Gray et al., 2002; Jerabkova et al., 2011). While our experimental design prevented us from isolating the impact of thinning intensity, other studies examining this aspect reported similarly modest responses of larger trees to low-intensity thinnings (Marqus and Ernst, 1991; Walter and Maguire, 2004; Davis et al., 2007; O'Hara et al., 2010; Dodson, 2012).

Alternatively, pre-existing structural conditions may account for the modest upper canopy (65–80 cm dbh) response to thinning. Given the relatively young age of the stands and high pre-harvest stem densities, many of the residual upper canopy trees may have had relatively small crowns and root systems at the time of thinning compared to upper canopy trees formed under initially lower density conditions. Thus, even though resource availability may have increased following the thinning treatment, the upper canopy trees in this study may have been constrained in their ability to capture sufficient resources to result in higher growth rates. (Niinemets, 2010). Residual trees with relatively small crowns might also be expected to allocate a larger proportion of their fixed carbon towards structures, such as leaves and branches that would enhance their ability to intercept available light (Thornley, 1972; Bloom et al., 1985). Thus, at least some of our residual upper canopy trees may have responded to thinning by expanding their crowns and root systems rather than immediately adding stem growth.

Another potential explanation for the lack of large tree response may come from our experimental design. Due the proximity of the subtreatments, and the relatively small size of the stem-mapped plots, we cannot rule out the possibility that trees in proximity to neighboring sub-treatments may have experienced modestly different growth environments compared to trees in the interior of any individual subtreatment. In order to minimize this potential source of variability, and still maintain an adequate sample size, future studies should strive to sample from larger plots or from greater number of stands than were available for sampling in this study.

4.2. Future mid-story growth and mid-story recruitment

The presence of a shade-tolerant mid-story is a defining structural feature of late-successional habitat and is a preferred structural attribute for spotted owl nesting in the PNW (Solis and Gutiérrez, 1990; Thomas et al., 1990). Unlike the existing upper canopy tree response, thinning significantly increased diameter growth among the future mid-story trees. This result supports the findings of Comfort et al. (2010), who also reported accelerated basal area development from residual mid-canopy trees at our sites, and other investigators examining VDT in the PNW (Davis et al., 2007; Dodson, 2012). Many of the theories presented as explanation of the modest response to thinning of existing upper canopy trees, can also be used to explain the significant growth response of trees in the existing and future mid-story size classes (dbh 40–65 cm and 20–40 cm, respectively). Perhaps the most logical argument that can be applied is the impact of thinning on resource availability. However, thinning likely had a much larger impact on resource competition among trees in the existing and future mid-story, as the residual trees were likely released from some of their strongest competition. This, in turn, would have allowed many of the residual mid-story and future mid-story trees to expand their crowns and capture a larger percentage of incoming light; likely contributing to the prolonged growth response and lower mortality rates observed in the thinned matrix.

Diameter growth of future mid-story trees (dbh 20–40 cm) varied among stands, with trees at Bait showing the greatest increase. Favorable environmental conditions combined with a slightly younger stand may explain part of this pattern, as Bait, on average, receives the highest amount of annual precipitation and moderate annual temperatures (Roberts and Harrington, 2008). Future mid-story growth at Bait may also have been enhanced by a combination of previous disturbances. Following planting of Douglas fir in the 1950s, Bait was precommercially thinned in the late 1960s, opening up growing space for a large cohort of shade-tolerant western hemlock that had become established at the time of stand initiation. This cohort likely experienced additional partial release from windstorms that struck several of the stands in the OHDS study in the late 1990s (Roberts et al., 2007). Thus, at the start of the study, many of the shade-tolerant species whose diameters fell within our arbitrary future mid-story diameter range, were actually in co-dominant growing positions in this stand. Therefore, the enhanced growth response recorded at Bait may have been facilitated not only by the favorable environmental conditions, but also by greater access to light, resulting from a more favorable initial canopy position. Nevertheless, it should be pointed out that Bait also had the highest post-thinning density; potentially indicating that competition with larger trees may have been more important than overall stand density.

4.3. Crown development

A structural feature characteristic of late-successional forests is the development of a deep canopy (Franklin and Spies, 1991). Canopy depth is enhanced not only by the development of a shade-tolerant mid-story, but also by the development of longer tree crowns in the main canopy. Foresters have long been aware of the relationship between stand density and crown size, whereby greater self-pruning limits crown length in higher density stands. In fact, foresters have often used the reduction in live crown ratio (i.e., the shortening of crowns) as an indicator of the need for thinning a stand (Daniel et al., 1979; Smith et al., 1997). Our results showing that VDT increased crown lengths within the thinned matrix was therefore consistent with our expectations.

Variable-density thinning approaches are designed to create a range of conditions throughout the stand that differentially influence stand development. Internal edges created by this approach resulted in differences in light environments and local tree competitive environments, which in turn affected crown development. Consistent with our understanding of photosynthate allocation patterns and crown length (Muhairwe, 1994), and the relationship between crown size and stand density (Pape, 1999; Gort, 2010) trees in close proximity to gaps took advantage of the increased growing space and displayed greater crown elongation, while trees close to the unthinned patches showed reduced elongation. Trees within the unthinned patches exhibited little crown elongation, and in many cases crown length was reduced on average as the competitive environment for these trees continued to intensify. Collectively, these results confirm the findings of other investigators examining the influence of VDT on crown growth dynamics (Davis et al., 2007; Puettmann et al., 2016). Species composition also affected crown growth responses to the VDT treatment. As might be expected due to its greater shade-tolerance (Burns and Honkala, 1990), western hemlock was able to increase in crown length significantly more than either Sitka spruce or Douglas-fir. Worth noting, however, is that for trees in the mid-story size classes and above (dbh > 40 cm), Douglas-fir did demonstrate substantial crown elongation in the thinned matrix, suggesting that over time larger overstory Douglas-fir can continue to enlarge their crowns and contribute to enhanced canopy depth.

Overall, the changes in crown lengths observed in our study were relatively modest. Density reductions in the thinned matrix resulted in average crown lengths increasing by roughly 1.5–2 m over that of crowns in the unthinned patches. The low intensity thinning employed in the OHDS likely contributed to the modest response, as thinning intensity has been shown to positively influence crown length (Mäkinen and Isomäki, 2004). Consequently, we believe that a more intensive thinning, or perhaps a thinning strategy that targeted larger trees for removal, may have stimulated a greater crown response.

4.4. Forest structure

Size class variation is another old-growth structural attribute often lacking in forests managed for production (Franklin and Spies, 1991; Spies, 2004). Like all late-successional attributes, size class variation will develop naturally (Oliver and Larson, 1996). However, in even-aged stands in the PNW, given the long-lived nature of many of the tree species, stands can often take centuries to develop substantial size variation. Variable-density thinning is designed to hasten this process by creating differential growing environments within a stand. In our study, VDT generally reduced the dominance of the most prominent size class. In the majority of our stands, however, size class diversity and richness have not been promoted by VDT, supporting the previous findings of Kuehne et al. (2015). While many of these findings can be explained by the differing growth patterns observed within the different size classes, this result may partially be related to the way in which we quantified changes in stand structure.

Part of the mixed structural response likely reflects the fact that we adapted traditional diversity indices (e.g., Shannon-Weiner diversity index) to measure structural changes among mature trees. Although diversity indices have been used previously to quantify changes in structural diversity (Lexerød and Eid, 2006), this methodology requires the investigator to treat tree size classes as surrogates for individual species. One issue with this approach is the question of how large a size class should be. This relatively arbitrary interpretation of what defines a “species” directly influences the calculation of the diversity metric. Thus, we urge caution when interpreting the results presented here and in future reports where diversity indices are applied in a non-traditional manner.

A second issue that complicates the use of traditional indices is that tree diameter growth is a relatively slow process. Unlike relatively short-lived plants or animals, forests do not rapidly ‘create’ new size classes through migration or increased reproductive output. New size classes can only be obtained through growth into previously unoccupied size classes. Even with the relatively narrow range of our size class groups (5 cm), developing significant numbers of new size classes through growth was going to require many years regardless of silvicultural manipulation.

We also acknowledge that our assessment of structural diversity is somewhat limited that it did not consider spatial components of diversity, nor did we consider trees less than 20 cm in diameter at the beginning of the experiment (Zenner and Hibbs, 2000). As such, we did not consider changes in structural diversity that are occurring as a result of regeneration within harvest gaps that were nested within our sampling blocks. Without question, the gaps are increasing the spatial structural variability within our stands. However, we chose not to incorporate new recruits into our calculation of diversity, as our original sampling protocols were not designed to measure these components of diversity, and because we were primarily interested in the response of existing canopy and sub-canopy trees to the VDT treatment.

Perhaps the biggest factor hindering structural development was the lack of growth differentiation amongst existing upper canopy trees (dbh 65–80 cm). Within all stands, size class richness and, to some extent diversity, depended on adding size classes at the upper-end of the diameter range. The thinning sub-treatment was intended to accelerate growth amongst the largest trees, thereby increasing size class richness and diversity. While growth of the upper canopy trees in the thinned matrix did appear to be increased slightly, the growth rates remained relatively similar to those of upper canopy trees in the unthinned patches, and thus, tree size classes were being added at essentially the same rate. Therefore, our approach to quantifying changes in size class diversity was generally unable to detect any significant changes in this size class over the 14-year observation period.

Ironically, the ineffectiveness of thinning to stimulate growth of existing upper canopy trees appears to have contributed to the increase in basal area evenness in the majority of our stands. This occurred because basal area was allowed to accumulate in the larger size classes, which were previously underrepresented compared to the rest of the distribution. Had new size classes been added at the upper end of the diameter distribution, they would have been severely underrepresented, leading to a decrease in basal area evenness. An example of this measurement effect can be found in the structural characteristics of Fresca, which increased in size class richness while decreasing in evenness. Another factor that contributed to increased evenness was the significant thinning response of trees in the existing mid-story (dbh 40–65 cm) and future mid-story (dbh 20–40 cm) size classes. Stimulating growth of these trees shifted more basal area into larger size classes which, with the exception of Fresca and Clavicle, had previously been underrepresented.

Thinning more intensively might have accelerated the development of structural diversity (Davis et al., 2007; Dodson, 2012). Presumably, a more intense thinning would have accelerated upper canopy tree growth, which, in turn, would have increased size class richness and possibly diversity. The resulting shift in basal area distribution among the various size classes may have led to a temporary reduction in basal area evenness among size classes. However, to our knowledge, there is no restoration value put on size class evenness. If size class diversity is to be a goal of late succession habitat restoration, then quantitative expressions that represent this goal should be developed, as the Shannon-Weiner Index “rewards” evenness as contributing to greater diversity.

5. Conclusion

The main goal of the OHDS has been to examine whether VDT can accelerate the development of late-successional habitat characteristics. Our results demonstrate that the sub treatments of this VDT approach have succeeded in producing differing rates of diameter growth among residual trees beneath the upper canopy 14 years following implementation. This response is encouraging, as it indicates that VDT is hastening the recruitment of shade-tolerant species into mid-story. This was especially evident at Bait and Clavicle, which have exceeded the restoration benchmark for shade-tolerant species in the mid-story size class. The VDT sub-treatments are also resulting in differing rates of crown expansion/contraction, suggesting that the main canopy layer is becoming deeper and more heterogeneous at the stand level. Our attempts at quantifying structural diversity using techniques typically employed to assess species diversity were unable to detect stand-level structural changes. However, structural diversity 'targets' have not been well-articulated for late successional stands, and therefore attempts at quantifying attainment of structural objectives can be challenging.

Fourteen years following VDT, the majority of stands in the OHDS study have not developed the desired number of large trees needed to meet the restoration benchmark for large tree density on western hemlock sites. In our view, rather than being an indication of VDT ineffectiveness, these results largely reflect the existing structural conditions of the OHDS stands prior to the experiment and the relatively short timeframe since the treatments were initiated. Expecting relatively young, even-aged stands to develop structural diversity and/or sizeable populations of large trees within 14 years of treatment is unrealistic (Peter and Harrington, 2010). Only at Clavicle, which had a sizeable population of existing large Sitka spruce prior to the initiation of this study, was the restoration target achieved. Despite this shortcoming, we contend that VDT has largely been successful in accelerating these stands towards providing late-successional habitat conditions given the limitations of what could realistically be attained over a 14-year period. Of future interest will be seeing whether a single VDT treatment will adequately improve structural diversity and large tree recruitment in those stands that started the experiment furthest from the late successional target structure, or whether a second VDT treatment will be needed to accelerate stand development.

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