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Midcanopy growth following thinning in young-growth conifer forests on the Olympic Peninsula western Washington

Emily J. Comfort[a,*], Scott D. Roberts[a], Constance A. Harrington[b]

[a] Mississippi State University, Department of Forestry, Box 9681, Mississippi State, MS 39762, United States
[b] USDA, Forest Service, Pacific Northwest Research Station, 3625 93rd Ave SW, Olympia, WA 98512, United States

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ABSTRACT

Midcanopy layers are essential structures in "old-growth" forests on the Olympic Peninsula. Little is known about which stand and tree factors influence the ability of midcanopy trees in young-growth forests to respond to release; however, this information is important to managers interested in accelerating development of late-successional structural characteristics. We examined basal area growth response of midcanopy trees following variable-density thinning in an effort to determine the effect of thinning and local environment on the release of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* ex. D. Don) on the Olympic Peninsula in western Washington. Release was measured as the difference between average annual basal area growth over the 5-year prior to thinning and the 3-to-6 year period following thinning. Results indicate that while growth rates were similar prior to thinning (5.4 cm^2 $year^{-1}$in both thinned and unthinned patches) midcanopy trees retained in a uniformly thinned matrix grew significantly more (8.0 cm^2 $year^{-1}$) than those in unthinned patches (5.4 cm^2 $year^{-1}$) for western hemlock and for western redcedar. Crown fullness and crown crowding affected the release of western hemlock in the thinned matrix. Initial tree size, relative age, local crowding and measures of crown size and vigor affected the release of western redcedar in the thinned matrix. Our results indicate that midcanopy western hemlock and western redcedar retain the ability to respond rapidly with increased growth when overstory competition is reduced and the magnitude of response is related to neighborhood variables (intracohort competition, overstory competition, and tree vigor), thus suggest that variable-density thinning can be an effective tool to create variability in the growth of midcanopy trees in young-growth stands. We expect that this rapid response will produce even greater variability over time.

1. Introduction

Forest management practices in the Pacific Northwest for most of the last century have led to the homogenizing of managed, young-growth forest stands and fragmentation of existing old-growth stands (Bolsinger and Waddell, 1993; Tappeiner et al., 1997; Puettmann et al., 2009). Lack of habitat with complex structure similar to old-growth forests is associated with declines in old-growth dependent species, such as the northern spotted owl (*Strix occidentalis caurina* Merriam) (Lamberson et al., 1992; Courtney et al., 2008). Forest managers in the Pacific Northwest are trying to develop management practices to accelerate the transformation of even-aged, young-growth conifer stands into more heterogeneous stands that fill the ecological and aesthetic role of late-successional forests (Franklin et al., 2002; Reutebuch et al., 2004). Although numerous studies have examined the growth of residual canopy trees following thinning (Curtis and Marshall, 1986; Harrington and Reukema, 1983; McComb et al., 1993; Roberts and Harrington, 2008; Swanson and Franklin, 1992), little research has examined the growth of residual midcanopy trees or determined which individual tree and local environmental characteristics influence the ability of these trees to release after thinning treatments. Because the development of midcanopy layers is an important component of old-growth structure (Franklin et al., 1986), a closer examination of the response of midcanopy trees to alternative management practices may offer insight into the longer-term implications and effectiveness of these treatments.

Old-growth forests are typically initiated following catastrophic disturbance events including wildfire and wind storms (Winter et al., 2002; Franklin et al., 2002) by species such as Douglas-fir (*Pseudotsuga Menziesii* (Mirb.) Franco.) often with surviving legacy trees from previous stands. Douglas-fir is a long-lived species (Hermann and Lavender, 1990), so after the onset of canopy closure

* Corresponding author at: Oregon State University, Forest Engineering, Resources, and Management, 265 Richardson Hall, Corvallis, OR 97331, United States. Tel.: +1 541 602 6566.
E-mail address: emily.comfort@oregonstate.edu (E.J. Comfort).

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and initial density-dependent mortality of pioneering trees, the stands can stagnate in the stem-exclusion phase of stand development for long periods of time (Oliver and Larson, 1996).

Small-scale disturbances over time allow shade-tolerant trees such as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* ex. D. Don) to establish and grow in the understory and midcanopy, while larger scale disturbances allow new cohorts of shade-intolerant species to establish. In the absence of small-scale (non-stand-replacing) disturbance, forests would likely remain structurally simple and be more prone to stand-replacing disturbances (fuel overloads) (Zenner, 2005; Bailey and Tappeiner, 1998).

Manipulating forest structure to mimic disturbance can change the competitive environment for remnant trees, thereby allowing a diverse assemblage of trees to thrive and possibly help to achieve goals of creating old-growth structural complexity (Reutebuch et al., 2004; Zenner, 2004). Because succession in western conifer forests commonly begins with structurally simple stands, young-growth stands are ideal for examining the effects of inducing spatial heterogeneity on the development of late-successional characteristics.

Variable-density thinning (VDT) is an ecologically-based treatment option for increasing structural complexity in mature young-growth stands. The general strategy is to selectively thin adjacent areas within a stand at different intensities. This creates a heterogeneous release of light and nutrient resources across the stand. Trees will presumably respond to the level of thinning in their immediate neighborhood, creating variable growth responses, and leading to greater structural diversity. However, because VDT is a relatively new management approach, little is known about the long-term effects of VDT on growth and development of forest stands. Alternatives to VDT, such as variable retention harvests and variable spatial distributions of thinning at various stand ages (e.g. pre-commercial thinning and mid-rotation thinning) are also being examined (Reutebuch et al., 2004; Carey et al., 1999).

The survival and growth of understory and midcanopy trees are necessary to achieve the structural and spatial heterogeneity associated with "old-growth" forests. However, there is very little information available on the response of these subcanopy trees to the increase in resources available following thinning. This retrospective study examined growth release of residual midcanopy trees measured as change in basal area growth from the 5 years prior to thinning to the 3–6 years following thinning. Specific questions that were addressed include: (1) Did VDT increase the growth rate of residual midcanopy trees in thinned patches relative to unthinned patches? We expected that midcanopy trees that were from the same cohort as the canopy trees may not respond to the thinning with increased growth in the short term (3–6 years). (2) Which tree- and stand-level factors were related to the growth response of midcanopy trees? We expected that ability to respond to the thinning would be related to tree size, vigor and age and the intensity of local competition.

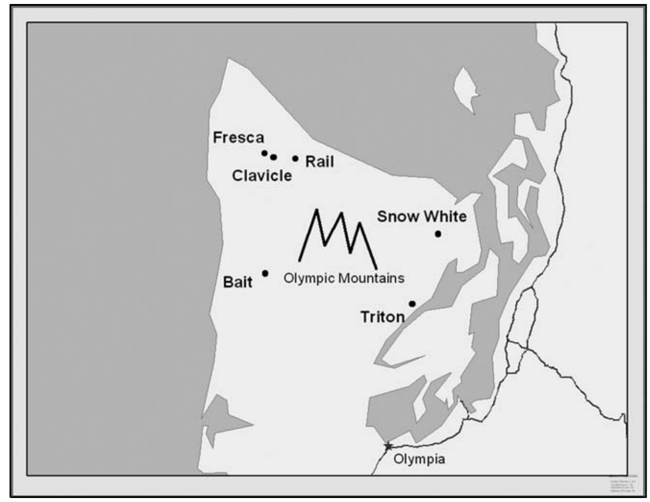

Fig. 1. Locations of the six OHDS blocks used in this study on the Olympic Peninsula in Washington, USA.

2. Methods

2.1. Site description

The Olympic Habitat Development Study (OHDS) is located in the Olympic National Forest on the Olympic Peninsula in western Washington. This joint venture between the Olympic National Forest and the Pacific Northwest Research Station was initiated in 1994 to examine whether management in 35- to 70-year-old even-aged conifer stands could accelerate the development of the compositional and structural characteristics typical of late-successional stands (for more information about the OHDS see Harrington et al., 2005; Roberts and Harrington, 2008).

Eight forest blocks were initially identified on the Olympic Peninsula for use in the larger OHDS study. Six of the blocks (Snow White, Bait, Rail, Fresca, Clavicle, and Triton) had been thinned and were used in this study (Fig. 1). Elevation at the study sites ranges from ca. 150 m to 575 m. Terrain varies from relatively flat to steep. Average annual precipitation ranges from 1950 mm to 3185 mm, occurring mostly during the winter (Harrington et al., 2005) (Table 1). Annual precipitation near Quilcene, WA, located on the east side of the Olympic Peninsula (near Snow White and Triton), averaged 965 mm per year between 1994 and 2005. In contrast, annual precipitation near Forks, WA on the west side of the peninsula (near the other four blocks), averaged 3162 mm per year over the same time interval.

Table 1
Site characteristics by block for OHDS sites used in this study.

Block	Age	Primary tree species	Initial stocking[a]		Elevation	Annual precipitation[b]
			Trees ha^{-1}	$m^2\,ha^{-1}$	m	mm
Rail	56	Douglas-fir, western hemlock	788	50	275	2390
Fresca	56	Sitka spruce, western hemlock	547	72	150	2650
Clavicle	62	Sitka spruce, western hemlock	678	86	475	2100
Bait	46	Douglas-fir, western hemlock	856	69	250	3180
Triton	74	Western hemlock, Douglas-fir, western redcedar	1151	59	400	3050
Snow White	74	Douglas-fir	1592	62	575	1950

[a] Stocking values based on pre-treatment conditions in stem-mapped plots.
[b] Annual precipitation estimates based on the parameter-elevation regressions on independent slopes model (PRISM) (U.S. Department of Agriculture Natural Resources Conservation Service et al., 1999).

Most of the stands used in the study originated from natural regeneration following harvest of the previous old-growth stand. Although Snow White and Bait were also planted with Douglas-fir, both blocks experienced substantial natural regeneration. Bait was pre-commercially thinned around 1970. Snow White was commercially thinned in the early 1970s. Rail had a light salvage thinning in 1986. The stands included in the study were representative of common stand conditions on the Olympic National Forest which were likely to be managed in the next few decades, had large enough trees to support a commercial thinning operation, and had been designated in the Forest's Resource Management Plan as having both economic and ecological objectives.

2.2. Study design and field methods

The study design for OHDS consisted of one uncut control plot and three to four plots that received a VDT treatment installed at each block, but for this project only one VDT plot per block was sampled. Plots were 6–10 ha each. The VDT treatment consisted of a thinning with skips and gaps: uniformly thinning the matrix of the stand (20–25% basal area removal in a uniform thinning from below) while leaving about 10% of the total stand area in 0.1–0.3 ha unthinned patches and 15% of the total stand area in small (0.04–0.05 ha) canopy gaps. Efforts taken to minimize the impact of thinning operations on the unthinned patches included locating canopy gaps at least 20 m away and prohibiting equipment access to those areas. Rail and Fresca were thinned in 1997, Bait, Snow White, and Clavicle after the 1999 growing season, and Triton in 2002.

Prior to thinning, all trees greater than 1.3 m in height were tagged in 1.44 ha plot, stem-mapped, measured for DBH, and identified as either a leave tree or a tree to be harvested. In the first dormant season following treatment, all residual trees were located and re-measured for DBH. A subsample of trees was measured for height, height to live crown and crown width. Five years following thinning, all tagged trees were identified as alive or dead and remeasured for DBH. All trees previously measured for crown dimensions were again measured for height, height to live crown, and crown width.

Residual midcanopy trees at the six study sites were examined in 2006 (3–8 years following VDT). An exploratory analysis identified potential midcanopy trees (e.g. trees that were present below the main canopy at the time of thinning). Midstory status was confirmed in the field. Trees were not included in the study if they had severe and recent damage such as a broken top that would alter measurements such as height and live crown ratio. We determined that such defects would not be representative of midstory response to the thinning treatment.

Each midcanopy tree was measured for diameter at breast height (DBH 1.3 m above the ground), height, and height to live crown. Crown radius was measured in four cardinal directions. Tree and crown health was assessed based on the condition of the leader, condition of the crown, fullness of the crown, and stem condition. Condition of the leader was rated from 1 (no dominant leader—not in good condition for height growth and unlikely to recover) to 4 (single, dominant leader—apparently healthy and in good condition for height growth). Crown condition was rated from 1 (flattened top—suffering from dieback or other damage and not likely to recover) to 4 (conical shape—apparently healthy and in good condition for height growth). To assess crown fullness, the volume of the live crown was divided into four roughly equal-sized quadrants. A point was awarded for each section that was ≥50% full (i.e. no missing branches, foliage). Stem condition was evaluated in terms of damage that might affect crown vigor and rated on a scale of 1 (stem damage that appears likely to eventually kill the tree) to 4 (healthy, straight stem with no visible defects).

Crown crowding was estimated using the method developed by Churchill (2005). An imaginary cylinder with a radius equal to that of the longest branch was envisioned around the live crown of the target tree. The volume of that cylinder occupied by non-target tree crowns was estimated to the nearest 10%.

An increment core was extracted from each midcanopy tree at 1.3 m above ground. The cores were used to estimate tree age and measure the width of individual growth rings for the 5 years prior to thinning and the years following thinning (which varied from 3 years to 8 years post-treatment). Relative age was calculated as the age of an individual tree relative to the oldest measured midcanopy tree in the same block. Additionally, the width of the core from the pith to the inside edge of the bark was measured, as was the total width for the 5 years prior to treatment and the time span that had elapsed following treatment.

Midcanopy crown measurements were used to create a midcanopy crown area layer for each plot in ArcGIS (Environmental Systems Research Institute, ArcMap, version 9.1, Redlands, CA). The subsample of crown width measurements from the canopy trees was used to develop regression models for estimating crown widths of Douglas-fir, western hemlock, western redcedar, and Sitka spruce (*Picea stichensis* (Bong.) Carr.). Estimated crown widths of canopy trees were used to create a canopy crown area layer. Overtopping of each midcanopy tree was estimated as the percent of the tree crown area overlapped by the main canopy.

The local competitive environment for each midcanopy tree was characterized in several ways. The distance from each midcanopy tree to all competitor trees (i.e. other live trees ≥1.3 m in height) within 10 m was calculated. A 10-m radius appeared to capture competitive effects (i.e. including additional trees beyond 10 m did not have a significant impact on growth). This is consistent with Canham et al. (2004), who suggest a distance of 8–12 m was sufficient for capturing competitive effects for western hemlock and western redcedar. Seven standard distance-dependent competition indices were calculated (Table 2). Additionally a 10-m radius was used to calculate distance-independent competition measures for each tree including measures of average competitor tree size and competitor density (trees per hectare, TPH). The average density (TPH) of trees on the entire plot prior to treatment was also calculated.

2.3. Analysis

Western hemlock and western redcedar were analyzed independently because initial analyses showed significant interaction between species and treatment effects. Because we were interested in determining the "release" of midcanopy trees, we chose a response variable that tied growth prior to treatment to growth following treatment: the difference in average annual basal area growth (ΔBA_{inc}) between the 5-year period prior to treatment and growth in the 3- and 6-year periods following treatment. Triton, Clavicle, and Snow White were the only blocks containing

Table 2
List of distance-dependent competition indices calculated for individual midcanopy trees.

Index	Calculation	Competitor size
Ci1	$\sum(DBH_{comp}/DBH_{target})/DIST$	All
Ci1a	$\sum(DBH_{comp}/DBH_{target})/DIST$	Larger only
Ci2	$\sum(DBH_{comp}/DBH_{target})/DIST^2$	All
Ci2a	$\sum(DBH_{comp}/DBH_{target})/DIST^2$	Larger only
Ci3	$\sum(DBH_{comp}/DBH_{target})^2/DIST$	All
Ci3a	$\sum(DBH_{comp}/DBH_{target})^2/DIST$	Larger only
Ci4	$\sum(DBH_{comp}/DBH_{target})/DIST$	Smaller only

Table 3
Sample size, *P*-value for treatment effect, and fit statistics (FI) for mixed model analysis of treatment effects on western hemlock release.

Time period following thinning	*N*	Treatment *P*-value	FI (%)
1–3 years	169	0.068	16
1–6 years	156	0.050[a]	19
3–6 years	156	0.048[a]	19

[a] Significant at $\alpha = 0.05$.

significant numbers of western redcedar. Triton only had data for 3 years following thinning, therefore, the results for western redcedar are only reported for the 3 year period following thinning in order to include multiple blocks.

A mixed model analysis was used to test for treatment effects on ΔBA_{inc}. Mixed models account for random variation from block to block and for unbalanced sample of trees (including blocks with few or no trees in one or the other treatment). Because there is not an easily interpreted fit statistic for comparing mixed models, a fit index (Eq. (1)) was calculated to explain the reduction in error obtained by using the model to predict ΔBA_{inc} rather than using the overall mean ΔBA_{inc}.

$$FI = 100 \times \left[1 - \left(\frac{\sum(\Delta BA_{inc\text{-}i} - \Delta BA_{inc\text{-}pred})^2}{\sum(\Delta BA_{inc\text{-}i} - \Delta BA_{inc\text{-}mean})^2}\right)\right] \quad (1)$$

where:

FI = fit index.

$\Delta BA_{inc\text{-}i}$ = measured change in basal area increment for tree *i*.

$\Delta BA_{inc\text{-}pred\,i}$ = predicted change in basal area increment for tree *i* using the mixed model.

$\Delta BA_{inc\text{-}mean}$ = the overall mean change in basal area increment.

If ΔBA_{inc} was significantly related to treatment over a particular time period, then local environment and individual tree characteristics were examined. A mixed model was used to test for the effect of each local competition index and tree vigor variable on midcanopy tree release in the thinned matrix. Initial tree size, where significant, was included in the model as a covariate. FI values were calculated for all variables significantly related to ΔBA_{inc}.

3. Results

3.1. Western hemlock

There were 169 midstory western hemlock in the OHDS which were suitable for use in this study. Of those, 59 were located in unthinned patches and 110 were located in the thinned matrix. On average, midcanopy trees used in this analysis were 16 years (S.E. = 0.92 years) younger than the overstory trees in their respective blocks, the difference in age did vary by block however. The smallest difference in age was at the youngest block, Bait, and the largest difference in age was in the two oldest blocks, Triton and Snow. The difference in age did not vary by treatment ($P = 0.125$). Midcanopy western hemlock in the unthinned patches had an average DBH 5 years prior to treatment of 17.3 cm (S.E. = 0.63 cm) compared to an average DBH of 14.0 cm (S.E. = 0.35 cm) for trees in the thinned matrix. By the sixth year following VDT (not including Triton), trees in the unthinned patches had increased in DBH by 2.3 cm (S.E. = 0.12 cm) compared to an increase of 2.9 cm (S.E. = 0.16 cm) for trees in the thinned matrix.

Average basal area growth of midcanopy western hemlock in the unthinned patches declined during the first 3 years following treatment ($P = 0.002$) from 5.9 $cm^2\,year^{-1}$ (S.E. = 0.46 $cm^2\,year^{-1}$) to 5.0 $cm^2\,year^{-1}$ (S.E. = 0.38 $cm^2\,year^{-1}$); however, annualized growth over the entire 6 years following treatment was

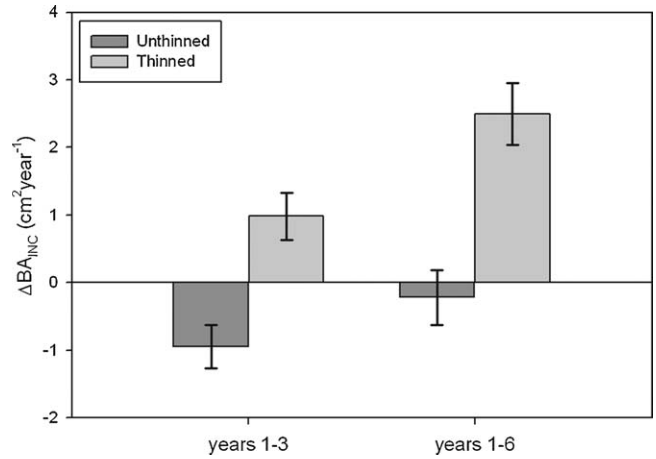

Fig. 2. Mean change in annual basal area increment (and 95% confidence limit interval) for midcanopy western hemlock in unthinned patches and the thinned matrix. Changes in basal area increment were calculated as the difference between annual growth 5 years prior to treatment and growth 1–3, 1–6, and 4–6 years following treatment.

5.6 $cm^2\,year^{-1}$ (S.E. = 0.41 $cm^2\,year^{-1}$), which did not differ from basal area growth prior to treatment ($P = 0.385$). For trees within the thinned matrix, however, ΔBA_{inc} was greater than zero over each time period ($P = 0.003$ and $P < 0.001$, respectively) and basal area growth increased from 4.9 $cm^2\,year^{-1}$ (S.E. = 0.39 $cm^2\,year^{-1}$) prior to treatment to 5.9 $cm^2\,year^{-1}$ (S.E. = 0.45 $cm^2\,year^{-1}$) in the first 3 years following treatment and 7.2 $cm^2\,year^{-1}$ (S.E. = 0.51 $cm^2\,year^{-1}$) in the first 6-year following treatment, indicating significant growth release following thinning (Fig. 2). In the model that accounted for random block effects on basal area growth, ΔBA_{inc} was significantly greater for the trees in the thinned matrix than for those in the unthinned patches for the 6-year post-thinning period. Over years 1–3, ΔBA_{inc} was slightly larger than for thinned trees but the effect was not significant. The FI was slightly less for the 3-year period following thinning (16%), than for the 6-year period (19%) (Table 3).

Several measures of crown crowding and crown vigor were significantly related to ΔBA_{inc} in the thinned matrix (Fig. 3, Table 4). Crown overlap had a negative correlation with ΔBA_{inc}. Crown area and live crown ratio were positively correlated with ΔBA_{inc}. The crown fullness rating was also significantly related to ΔBA_{inc}. A pairwise comparison of least-squared means suggested that crowns with a rating of 4 (75–100% full), had significantly higher mean ΔBA_{inc} than crowns with lower ratings.

3.2. Western redcedar

There were 94 western redcedar present in the midcanopy at three blocks of the OHDS. Sixteen were located in unthinned patches and had an average initial DBH (5 years prior to treatment) of 18.4 cm (S.E. = 1.5 cm). The 78 trees in the thinned matrix had an average initial DBH of 17.9 cm (S.E. = 0.65 cm). On average midcanopy trees were 47 years of age (S.E. = 1.2 years) and 19 years younger than the overstory trees in their respective blocks. There was not a significant difference in the ages of trees between the treatments ($P = 0.488$). By the end of the third year following treatment, average growth of midcanopy western redcedar trees was 1.0 cm (S.E. = 0.12 cm) in the unthinned patches and 1.8 cm (S.E. = 0.12 cm) in the thinned matrix.

When initial tree size was included in the model, thinning treatment has a significant effect on ΔBA_{inc} ($P = 0.033$) in the first 3 years following treatment ($P = 0.012$ for effect of initial size). During that period, mean ΔBA_{inc} was not different than zero

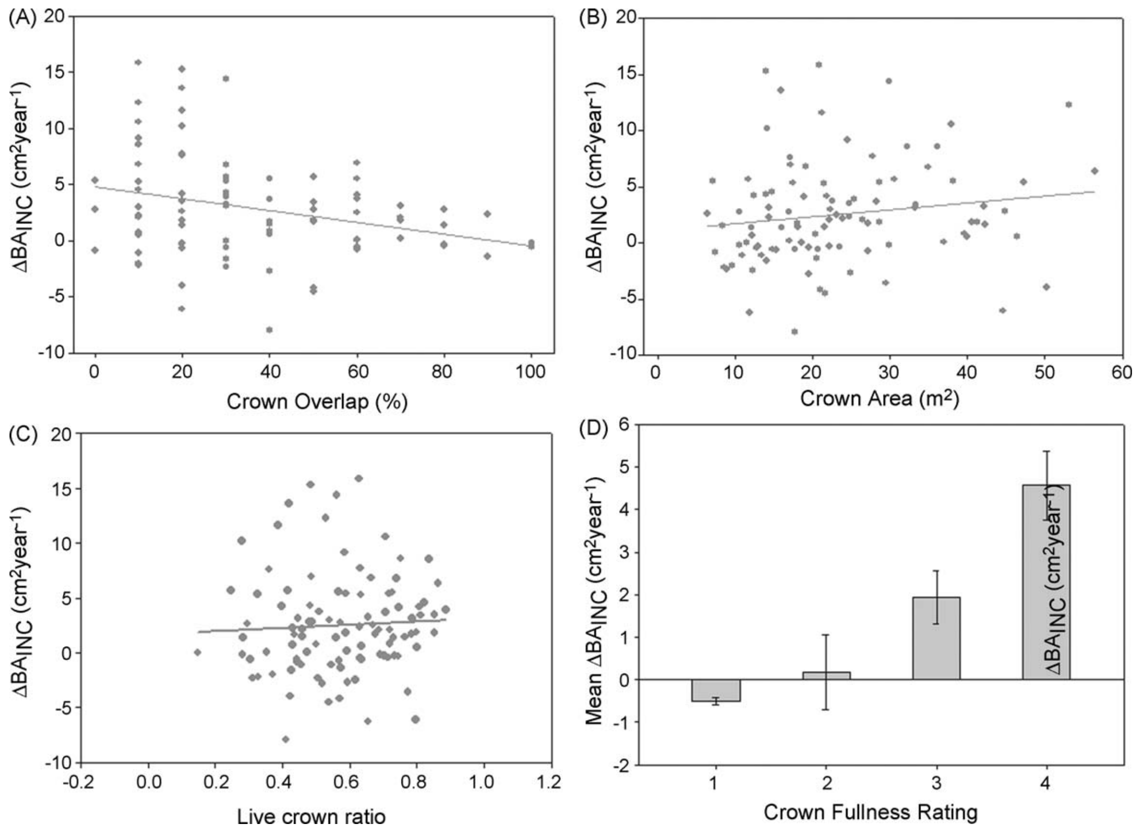

Fig. 3. Local environment and individual tree characteristics were significantly related to ΔBA_{inc} for midcanopy western hemlock in the thinned matrix: (A) ΔBA_{inc} versus crown overlap (%) with neighboring tree crowns for individual midcanopy trees, (B) ΔBA_{inc} versus total crown cross-sectional area at widest point, (C) ΔBA_{inc} versus live crown ratio and (D) mean ΔBA_{inc} by crown fullness rating with standard error bars.

Table 4
Sample size, *P*-value, and fit statistics (FI) for factors significantly related to ΔBA_{inc} during the 6 years following VDT in the thinned matrix using single-factor mixed model analysis for western hemlock.

Factor	*N*	*P*-value	FI (%)
Crown overlap	90	0.004	24
Crown area	99	0.014	27
Live crown ratio	100	0.030	27
Crown fullness	100	0.007	31

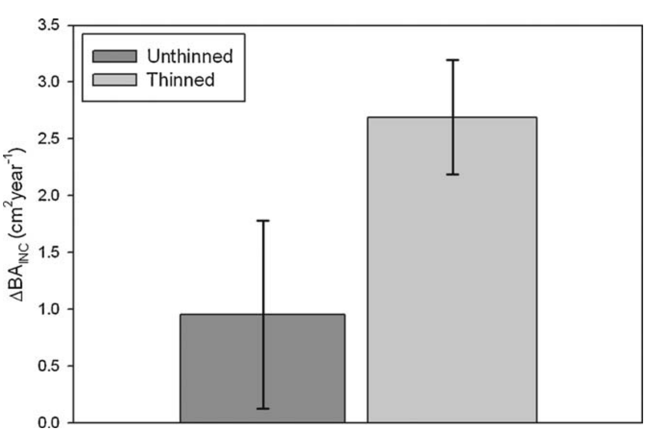

Fig. 4. Mean change (and 95% confidence limit interval) in annual basal area increment for midcanopy western redcedar in unthinned patches and thinned matrix. Changes in basal area increment were calculated as the difference between annual growth 5 years prior to treatment and annual growth for 3 years following treatment.

($P = 0.267$) in the unthinned patches, but was greater than zero in the thinned matrix ($P < 0.001$) (Fig. 4). Basal area increment increase from 3.7 $cm^2\ year^{-1}$ (S.E. = 0.57 $cm^2\ year^{-1}$) in the unthinned patches prior to treatment to 4.6 $cm^2\ year^{-1}$ (S.E. = 1.19 $cm^2\ year^{-1}$) in the first 3 years and 8.74 $cm^2\ year^{-1}$ (S.E. = 0.86 $cm^2\ year^{-1}$) in the first 6 years following treatment. In the thinned matrix, basal area increment increased from 6.1 $cm^2\ year^{-1}$ (S.E. = 0.54 $cm^2\ year^{-1}$) to 8.7 $cm^2\ year^{-1}$ (S.E. = 0.86 $cm^2\ year^{-1}$) in the first 3 years and 9.1 $cm^2\ year^{-1}$ (S.E. = 0.87 $cm^2\ year^{-1}$) in the first 6 years following treatment.

Several factors related to local competition and tree vigor were significant predictors of ΔBA_{inc} for western redcedar within the

Table 5
Sample size (*N*), *P*-value, and fit statistics (FI) for local competition factors that were significantly related to ΔBA_{inc} for western redcedar over the 3 years following VDT in the thinned matrix and in the unthinned patches using single-factor mixed model analysis.

Factor	Thinned			Unthinned		
	N	*P*-value	FI (%)	*N*	*P*-value	FI (%)
AvgCompDBH	53	0.421	12	14	0.041*	30
∑CompBA	53	0.012*	21	14	0.240	32
BAL	53	0.006*	22	14	0.242	32
SDI	53	0.023*	20	14	0.311	35
Pre-treatment TPH	78	<0.001*	19	16	0.106	18
Crown overlap	77	0.584	18	16	0.045*	39

Competition measures that include competition within 10 m of the target tree at the time of treatment are average competitor DBH (AvgCompDBH), the sum of basal area of all trees (∑CompBA), the sum of basal area of trees with a larger DBH than target trees (BAL), and competitor stand density index (SDI). Pre-treatment tree per hectare (pre-treatment TPH) was calculated for the stem-mapped plot. Crown overlap was estimated in 2006 (crown overlap).

* Significant.

thinned matrix. All of the distance-independent measures of local competition at the time of treatment had significant (Table 5) negative correlations with ΔBA_{inc}, although none of the distance-dependent measures of local competition appeared to be related to ΔBA_{inc} for western redcedar in the thinned matrix. Tree factors affecting ΔBA_{inc} in the thinned matrix were those related to initial tree size and crown vigor (Table 6). Initial DBH ($r = 0.253$) and relative age ($r = 0.307$) were both positively correlated with ΔBA_{inc} during the 6 years following treatment (Fig. 5). Measures of crown vigor (i.e. crown area, live crown ratio, and crown condition) were also positively correlated with ΔBA_{inc} (Fig. 6).

Table 6
Sample size (*N*), *P*-value, and fit statistics (FI) for tree factors that were significantly related to ΔBA_{inc} for western redcedar over the 3 years following VDT in the thinned matrix and in the unthinned block using single-factor mixed model analysis.

Factor	Thinned (%)			Unthinned (%)		
	N	*P*-value	FI	*N*	*P*-value	FI
Initial DBH	78	0.023*	25	16	0.063	23
Relative age	78	0.001*	31	16	0.072	34
Total crown area	75	0.006*	28	16	0.025*	31
Live crown ratio	78	<0.001*	35	16	0.117	17
Crown condition	78	0.008*	31	16	0.745	23

* Significant.

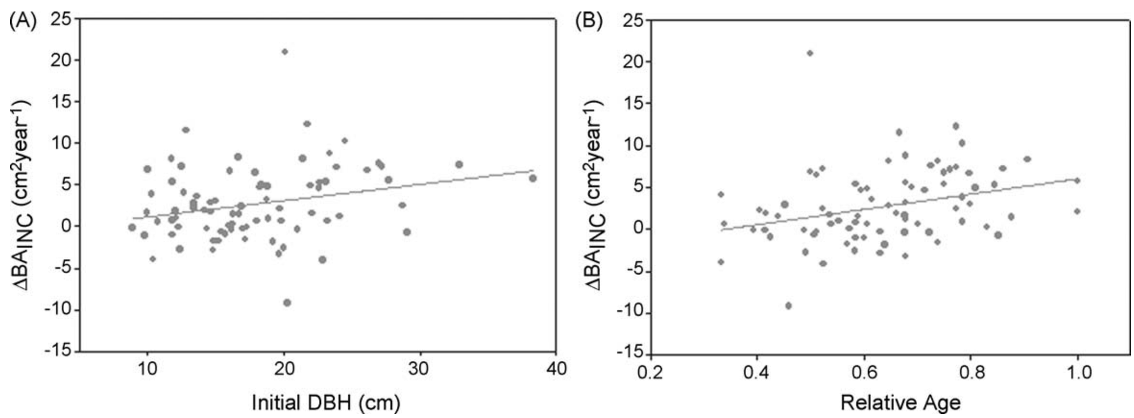

Fig. 5. Responses of Midcanopy western redcedar in the thinned matrix were significantly related to stand variables; shown are ΔBA_{inc} versus (A) initial DBH (5 years prior to treatment) and (B) relative age (age of tree relative to oldest midcanopy tree in block) plotted against ΔBA_{inc} for midcanopy western redcedar in the thinned matrix.

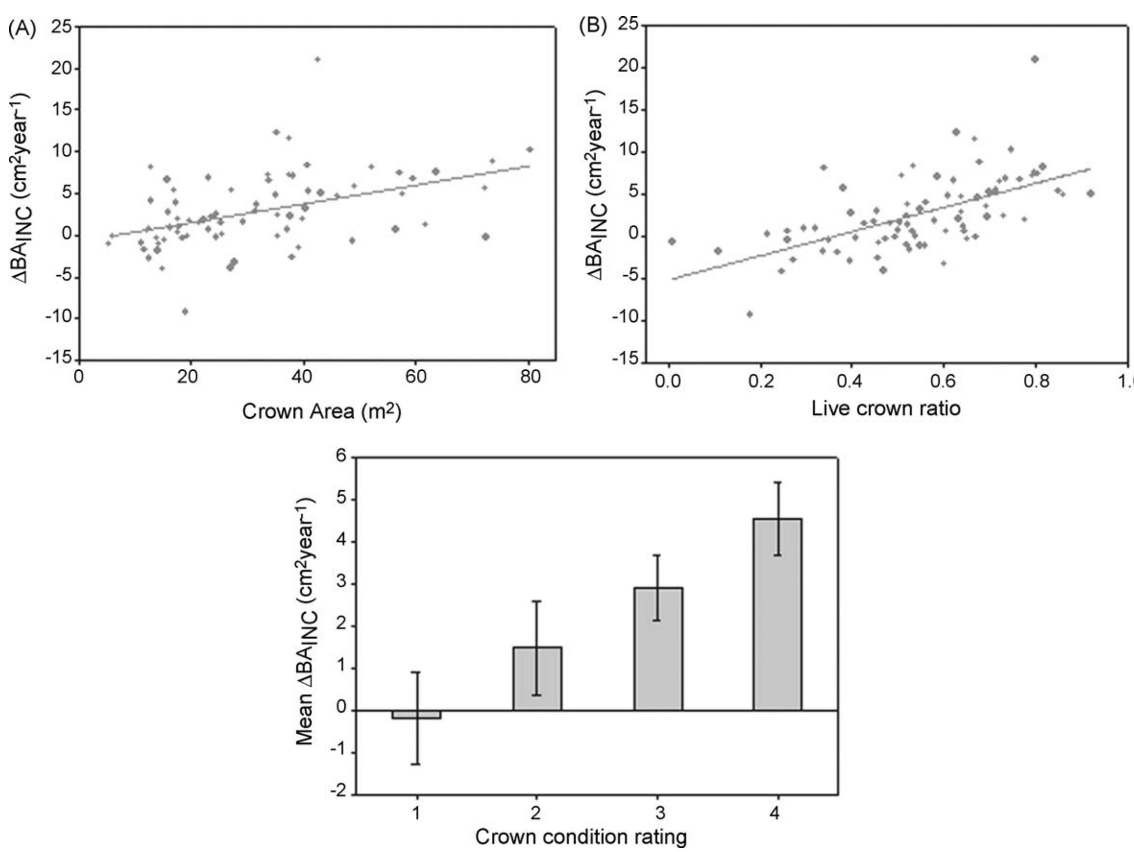

Fig. 6. Crown vigor characteristics were significantly correlated with ΔBA_{inc} for midcanopy western redcedar in the thinned matrix: (A) total crown cross-sectional area at its widest point. (B) Live crown ratio and (C) crown condition rating: a rating of 4 is the highest vigor category.

4. Discussion

4.1. Western hemlock and western redcedar

These results indicate that midcanopy trees of both western hemlock and western redcedar have the ability to increase their growth rates rapidly (within 3–6 years) in response to the increase of resources associated with thinning. Both western hemlock and western redcedar are shade-tolerant species that can persist in heavily shaded conditions for long periods of time (Packee, 1990; Minore, 1990). It is not surprising to find that they are able to respond to the thinning. Information on response of western redcedar to thinning is limited, but positive growth responses have been reported (Harrington and Weirman, 1990). Western hemlock seedlings and saplings have been shown to respond with increases in height growth to multiple thinning entries (Shatford et al., 2009).

Although ΔBA_{inc} was not statistically different for western hemlock in thinned and unthinned patches over the first 3 years when random plot differences are included in the model, differences in the average ΔBA_{inc} suggest that the thinned matrix had started to respond with increased growth rates. Other studies have observed periods of unchanged or reduced growth following retention of advanced regeneration or understory trees (Kneeshaw et al., 2002; Halpern et al., 2005). Kneeshaw et al. (2002) suggested that this period corresponds to a period of increased root growth in which the trees are reallocating resources while adjusting to new site conditions.

Initial tree size and age were important factors related to the ability of western redcedar to release. As expected, larger trees were better able to take advantage of reduced competition pressure and grew better. There was also a correlation between initial size and relative age suggesting that western redcedar had been growing fairly steadily in the understory and midcanopy at these sites. In fact, relative age appeared to be a better indicator of ΔBA_{inc} than initial size (FI = 31% versus 25% for initial size). On average, midcanopy western redcedar were 19 years younger than the main canopy trees in any given block, indicating that they are not suppressed trees from the canopy cohort. Despite the fact that midcanopy western hemlock were generally the same age as their western redcedar counterparts and exhibited the same correlation between initial size and relative age ($P < 0.001$), initial size did not affect ΔBA_{inc} for midcanopy western hemlock. It may be that for this species, other factors such as competition and tree vigor outweighed the effects of initial size and tree age.

The release of both midstory western hemlock and western redcedar appeared to be related to crown vigor. Total crown area and live crown ratio were significantly correlated with ΔBA_{inc} in the thinned matrix for both species. These measures suggest that crown size is a good predictor of growth. Other measures of crown health, such as crown condition or condition of leader were not correlated with ΔBA_{inc}. However, all measures of crown vigor were taken at the end of the study period. Tree condition may have differed between the beginning and the end of the study period; therefore, we cannot draw firm conclusions from relationships observed only at the end of the study. It could be that midcanopy trees with larger crowns were better able to take advantage of improved growing environment and thus grew better after the thinning. Conversely, it could be that trees with greater ability for growth release responded by also developing relatively large crowns. Others have suggested the ability to expand crowns rapidly is generally an indication of vigorous trees (Oliver and Larson, 1996). Waring et al. (1980) found that a tree vigor index based on sapwood basal area (as a predictor of leaf area) was well correlated with basal area growth on a variety of sites. Using the same vigor index as Waring et al. (1980), Larsson et al. (1983) found that low tree vigor was also related to ponderosa pine (*Pinus ponderosa* Laws.) susceptibility to mountain pine beetle (*Dendroctonus ponderosae* Hopk.) attack. Our results support the idea that tree vigor, as indicated by well-developed crowns, is important to tree growth and health, specifically for residual midcanopy trees following a thinning.

For western redcedar, our measure of overall crown condition was also related to ΔBA_{inc}. Crown condition rating was subjectively based on the condition of the crown to put on height growth. This suggests that the ability to put on height growth may also be related to ΔBA_{inc}, not surprising given that height growth is a major way in which trees expand their crowns and increase leaf area.

Tree vigor should also be affected by the competitive pressure experienced by the tree. Crown overlap was the only measure of competition that was a significant predictor of ΔBA_{inc} for midcanopy western hemlock. Crown overlap was also significant for midcanopy western redcedar. Crown overlap is a measure of local crowding among similar sized trees. However, because crown area is reduced for trees in heavy competition environments (Oliver and Larson, 1996), low crown overlap may not necessarily indicate lack of competition. The results of this analysis, however, are consistent with the findings of Canham et al. (2004) suggesting that growth of midcanopy trees is affected by competition with other midcanopy trees.

Measures of inter-strata competition, such as overtopping from canopy trees and basal area of larger diameter trees (BAL), were not significantly related to the ability of midcanopy western hemlock to increase growth following VDT. By contrast, distance-independent measures of local competition (both size and number of competitors) were consistently related to ΔBA_{inc} for western redcedar. Measures of competition for western redcedar in the thinned matrix had lower means and higher variance than in the unthinned patches, indicating that the local competitive environment in the thinned matrix was more variable thus resulting in greater variability in ΔBA_{inc} (Fig. 7).

Local conditions and management history may have played a role in the ability of midcanopy trees to quickly respond to the thinning. At Rail, for instance, ΔBA_{inc} over the 6 years following thinning did not differ between the unthinned patches and the thinned matrix for western hemlock ($P = 0.122$). In contrast, at Bait and Snow White ΔBA_{inc} over the 6 years following thinning was greater in the thinned matrix than in the unthinned patches ($P = 0.005$ and $P = 0.027$). Rail had received a light salvage thinning in 1986 (11 years prior to this study), so it may be that in the 5 years prior to the VDT, trees at Rail were still benefiting from the

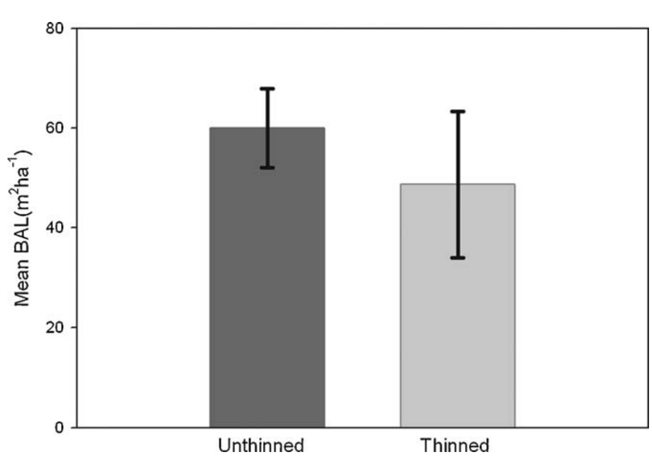

Fig. 7. Mean BAL for western redcedar in the unthinned patches and in the thinned matrix. BAL was calculated as the mean basal area of trees within 10 m of the target tree and having a diameter larger than that of the target tree.

previous thinning operation. Bait and Snow White, on the other hand, had previously been thinned in the 1970s and the beneficial effects of those thinnings would no longer be present by the time the trees were sampled. It appears that in the 5 years prior to VDT, growth was reduced compared to potential at these sites and the VDT provided a competition release for midcanopy trees. Although the difference in ΔBA_{inc} at Rail was not significantly different between thinning treatments due to large variation, the mean ΔBA_{inc} in the thinned matrix was greater than the mean ΔBA_{inc} in the unthinned patches. Given more time, these differences may become significant and the more recent thinning (VDT) may prove to provide release for midcanopy trees.

4.2. Conclusions

Overall the VDT treatment appears to be creating greater spatial heterogeneity in post-thinning growth of midcanopy trees in these stands. On average, midcanopy trees in the thinned matrix had increased basal area growth rates following thinning (approximately 1.7 $cm^2\ year^{-1}$ greater basal area growth in the 3 years and 3.0 $cm^2\ year^{-1}$ greater in the 6 years following thinning compared to the 5 years prior to thinning). Growth rates changed very little over the course of the study for midcanopy trees in the unthinned patches with minor decreases in growth rates in years 1–3 ($-0.5\ cm^2\ year^{-1}$) and a slight increase for the whole 6-year period ($0.2\ cm^2\ year^{-1}$). Historically, management practices were aimed at lowering variation in tree growth, while maximizing the growth of final crop trees. One of the defining characteristics of "old-growth" forests is the gradient of tree size and age classes (Spies and Franklin, 1991; Franklin et al., 1986). Managing for heterogeneity in structure makes it necessary to induce variation in individual tree growth within the stand as well as the spatial arrangement of residual trees. During the 6 years following VDT, there was variation in the growth of midcanopy trees at the OHDS sites based on thinning treatment. Another study at the OHDS examining the effect of VDT on canopy tree growth (Roberts and Harrington, 2008) found similar results. Canopy trees in the thinned matrix are growing better than canopy trees in the unthinned patches. Other studies have found that thinning (commercial or pre-commercial) can increase the survival and growth of small trees, understory regeneration, and shrubs (Bailey and Tappeiner, 1998). Increased variation at the stand level can add adaptability and resistance to future disturbances and threats (Puettmann et al., 2009).

Although developing forest structure is a long-term process, early results support the idea that the process of increasing within stand heterogeneity can be accelerated through management practices that emulate natural disturbance processes. Natural disturbance processes, such as swiss needle cast (Maguire et al., 2002) or dwarf mistletoe (Shaw et al., 2008) reduce individual tree basal area growth. It is important to consider these early responses to management practices because (1) a lack of response would indicate that there is limited management opportunity for emulating the effects of natural disturbance or increasing variability of size classes within stands and (2) monitoring the response can help managers determine if and when future entries are needed to continue promoting the growth of the midcanopy layers.

In this study, there was considerable variation in the results at different blocks. This variability suggests that results will vary with future applications of this technique in terms of length of time required to see a significant response and the particular local variables that affect release. Previous management history and initial conditions of the stand should be considered when prescribing a VDT.

In general, these results suggest that variable-density thinning can result in increased growth of midcanopy trees retained in the thinned matrix as long as conditions are amenable for the development of vigorous crowns. Although various measures of crown vigor have often been correlated with tree health and growth, crown measurements and other quantifications of vigor have low precision (Solberg, 1999). Future studies could look at the ratings used in this study in order to determine how well they correlate with growth under different conditions. Management actions should also consider the importance of crown vigor when attempting to promote the release of midcanopy trees by protecting vigorous crowns or enhancing the ability of midcanopy tree crown to expand following treatments.

The structural diversity in late-successional forests provides critical habitat for many plant and animal species such as the threatened northern spotted owl. The term "old-growth" is also used to refer to late-successional forests; as the term implies, these stands are indeed old, forming over the course of centuries. Over the short period of 6 years it is not possible to assess the success of relatively new treatments, such as VDT for accelerating the development of more complex stand structures. However, early response to treatments can help managers determine if they are on the right track or if other options should be explored. The results of this study support the growing body of evidence that VDT can be a viable management option for creating variation in growth rates of residual trees.

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References

Bailey, J.D., Tappeiner, J.C., 1998. Effects of thinning on structural development in 40- to 100-year-old Douglas-fir stands in western Oregon. Forest Ecology and Management 108, 99–113.

Bolsinger, C.L., Waddell, K.L., 1993. Area of Old-growth Forests in California, Oregon, and Washington. USDA Forest Service, Pacific Northwest Research Station, Portland, OR (Research Bulletin 197).

Canham, C.D., LePage, P.T., Coates, K.D., 2004. A neighborhood analysis of canopy tree competition: effects of shading versus crowding. Canadian Journal of Forest Research 34, 778–787.

Carey, A.B., Thysell, D.R., Brodie, A.W., 1999. The Forest Ecosystem Study: Background, Rationale, Implementation, Baseline Conditions and Silvicultural Assessment. USDA Forest Service, Pacific Northwest Research Station, Portland, OR (General Technical Report 457).

Churchill, D.J., 2005. Factors influencing understory Douglas-fir vigor in multi-cohort prairie colonization stands at Fort Lewis, Washington. MS Thesis. University of Washington, Seattle, WA.

Courtney, S.P., Carey, A.B., Cody, M.L., Engel, K., Fehring, K.E., Franklin, J.F., Fuller, M.R., Gutierrez, R.J., Lehmkuhl, J.F., Hemstrom, M.A., Hessburg, P.F., Stephens, S.L., Sztukowski, L.A., Young, L., 2008. Scientific Review of the Draft Northern Spotted Owl Recovery Plan and Reviewer Comments. Sustainable Ecosystem Institute, Portland, OR, USA.

Curtis, R.O., Marshall, D.D., 1986. Levels-of-growing-stock Cooperative Study in Douglas-fir: Report No. 8—The LOGS Study: Twenty-year Results. USDA Forest Service, Pacific Northwest Forest and Range Station, Portland, OR (General Technical Report 356).

Franklin, J.F., Spies, T.A., Van Pelt, R., Carey, A.B., Thornburgh, D.A., Berg, D.R., Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K., Chen, J.Q., 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management 155, 399–423.

Franklin, J.F., Hall, F., Laudenslayer, W., Maser, C., Nunan, J., Poppino, J., Ralph, C.J., Spies, T., 1986. Interim Definitions for Old-growth Douglas-fir and Mixed-conifer Forests in the Pacific Northwest and California. USDA Forest Service, Pacific Northwest Research Station, Portland, OR (Research Note 447).

Halpern, C.B., McKenzie, D., Evans, S.A., Maguire, D.A., 2005. Initial responses of forest understories to varying levels and patterns of green-tree retention. Ecological Applications 15, 175–195.

Harrington, C.A., Roberts, S.D., Brodie, L.C., 2005. Tree and understory responses to variable-density thinning in Western Washington. In: Peterson, C.E., Maguire, D.A. (Eds.), Balancing Ecosystem Values. USDA Forest Service, Pacific Northwest Research Station, Portland, OR (General Technical Report 635).
Harrington, C.A., Reukema, D.L., 1983. Initial shock and long-term stand development following thinning in a Douglas-fir plantation. Forest Science 29, 33–46.
Hermann, R.K., Lavender, D.P., 1990. Pseudostuga menziesii (Mirb.) Franco. In: Burns, R.M., Honkola, B.H. (Eds.), Silvics of North America, vol. 1, Conifers. USDA Forest Service (Agricultural Handbook 654).
Kneeshaw, D., Williams, H., Nikinmaa, E., Messier, C., 2002. Patterns of above- and below-ground response of understory conifer release 6 years after partial cutting. Canadian Journal of Forest Research 32, 255–265.
Lamberson, R.H., McKelvey, R., Noon, B.R., Voss, C., 1992. A dynamic analysis of northern spotted owl viability in a fragmented forest landscape. Conservation Biology 6, 505–512.
Larsson, S., Oren, R., Waring, R.H., Barrett, J.W., 1983. Attacks of mountain-pine-beetle as related to tree vigor ponderosa pine. Forest Science 29, 395–402.
Maguire, D.A., Kanaskie, A., Voelker, W., Johnson, R., Johnson, G., 2002. Growth of young Douglas-fir plantations across a gradient in swiss needle cast severity. Western Journal of Applied Forestry 17, 86–95.
McComb, W.C., Spies, T.A., Emmingham, W.H., 1993. Douglas-fir forests. Journal of Forestry 91, 31–42.
Minore, D., 1990. *Thuja plicata* Donn ex D. Don. In: Burns, R.M., Honkola, B.H. (Eds.), Silvics of North America, vol. 1, Conifers. USDA Forest Service (Agricultural Handbook 654).
Oliver, C.D., Larson, B.C., 1996. Forest Stand Dynamics. Wiley, New York.
Packee, E.E., 1990. *Tsuga heterophylla* (Raf.) Sarg. In: Burns, R.M., Honkola, B.H. (Eds.), Silvics of North America, vol. 1, Conifers. USDA Forest Service, (Agricultural Handbook), p. 654.
Puettmann, K.J., Coates, K.D., Messier, C.C., 2009. A Critique of Silviculture: Managing for Complexity. Island Press, Washington, DC.
Reutebuch, S.E., Harrington, C.A., Marshall, D.D., Brodie, L.C., 2004. Use of large-scale silvicultural studies to evaluate management options in Pacific Northwest forests of the United States. Forest, Snow and Landscape Research 78, 191–208.
Roberts, S.D., Harrington, C.A., 2008. Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. Forest Ecology and Management 255, 2771–2781.
Shaw, D.C., Huso, M., Bruner, H., 2008. Basal area growth impacts of dwarf mistletoe on western hemlock in an old growth forest. Canadian Journal of Forest Research 38, 576–583.
Shatford, J.P.A., Bailey, J.D., Tappeiner, J.C., 2009. Understory tree development with repeated stand density treatments in coastal Douglas-fir forests of Oregon. Western Journal of Applied Forestry 24, 11–16.
Solberg, S., 1999. Crown condition and growth relationships within stands of Picea abies. Scandinavian Journal of Forest Research 14, 320–327.
Spies, T.A., Franklin, J.F., 1991. The structure of natural young, mature, and old-growth Doulgas-fir forests in Oregon and Washington. (Tech. Cords.) In: Ruggiero, L.F., Aubry, K.B., Carey, A.B., Huff, M.H. (Eds.), Wildlife and Vegetation of Unmanaged Douglas-fir Forests. USDA Forest Service, Pacific Northwest Research Station, Portland, OR (General Technical Report 285).
Swanson, F.J., Franklin, J.F., 1992. New forestry principles from ecosystem analysis of Pacific-Northwest forests. Ecological Applications 2, 262–274.
Tappeiner, J.C., Huffman, D., Marshall, D., Spies, T.A., Bailey, J.D., 1997. Density, ages, and growth rates in old-growth and young-growth forests in coastal Oregon. Canadian Journal of Forest Research 27, 638–648.
Waring, R.H., Thies, W.G., Muscato, D., 1980. Stem growth per unit of leaf-area—a measure of tree vigor. Forest Science 26, 112–117.
Winter, L.E., Brubaker, L.B., Franklin, J.F., Miller, E.A., DeWitt, D.Q., 2002. Initiation of an old-growth Douglas-fir stand in the Pacific Northwest: a reconstruction from tree-ring records. Canadian Journal of Forest Research 32, 1039–1056.
U.S. Department of Agriculture, Natural Resources Conservation Service [NRCS]; National Water and Climate Center; Oregon State University Spatial Climate Analysis Service. 1999. Parameter-elevation regressions on independent slopes model (PRISM). http://www.wcc.nrcs.usda.gov/water/climate/prism/prism.html.[November 14, 2003].
Zenner, E.K., 2004. Does old-growth condition imply high live-tree structural complexity? Forest Ecology and Management 195, 243–258.
Zenner, E.K., 2005. Development of tree size distributions in Douglas-fir forests under differing disturbance regimes. Ecological Applications 15, 701–714.