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Subcanopy response to variable-density thinning in second growth forests of the Pacific Northwest

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SUBCANOPY RESPONSE TO VARIABLE-DENSITY THINNING IN SECOND GROWTH FORESTS OF THE PACIFIC NORTHWEST

By

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Variable-density thinning (VDT) is a management option designed to increase structural heterogeneity in second-growth conifer stands. This study examined subcanopy tree growth response to two variations of VDT.

At the Forest Ecosystem Study in western Washington, thinning intensity was found to have a significant effect on height growth of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings which established following the thinning. At the Olympic Habitat Development Study in western Washington, basal area growth response was examined for residual midcanopy western hemlock (Tsuga heterophylla (Raf.) Sarg.) and western redcedar (Thuja plicata ex. D. Don). Both species retained the ability to respond to thinning.

The results of this study suggest that non-uniform thinning practices, like VDT, can lead to variation in growth response of residual subcanopy trees and new regeneration. This may accelerate the development of more structurally diverse forests than traditional management practices.

Key words: variable-density thinning, forest structure, subcanopy

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CHAPTER 1

INTRODUCTION

Forest managers in the Pacific Northwest are trying to develop management practices to accelerate the transformation of even-aged, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands into more heterogeneous stands that fill the ecological, aesthetic, and production role of late-successional forests. Variable-density thinning (VDT) is a treatment option for increasing spatial heterogeneity in mid-rotation stands. Because it is relatively new, little is known about the long-term effects of the treatment. As the name implies, "old-growth" forests consist of long-lived trees and the effects of management techniques are hard to quantify in the short time span of years or even decades. A closer examination of the response of trees under the main canopy may offer insight into the longer-term implications and effectiveness of VDT.

This study examines the response of 30- to 70-year-old second-growth conifer forests to two different variations of VDT. These forests are generally in the stem-exclusion stage (Oliver and Larson, 1996) of stand development which is the period of lowest biological diversity. Due to the long lifespan of Douglas-fir, stands can remain in this stage of development for decades or centuries. 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, 1997). VDT attempts to mimic the small scale disturbances that can add structural diversity to second-growth stands.

The successful development and growth of subcanopy trees and younger cohorts is essential to creating the multi-canopied structure and the species diversity desired for wildlife and native plant habitat. Established trees that are under the main canopy (subcanopy) are in the best position for rapidly filling the vertical space under the canopy after thinning. The subcanopy will generally be dominated by shade tolerant species (Oliver and Larson, 1996; Franklin et.al., 2002). Younger cohorts of trees that develop from regeneration after a thinning may include more shade intolerant species like Douglas-fir (Caccia and Ballare, 1998) if the thinning creates large enough canopy gaps. Douglas-fir is thought to require canopy gaps greater than 700-1,000m^2 in order to successfully establish a new canopy tree (Spies and Franklin, 1989; Franklin and Dyrness, 1973). Even shade-tolerant species require smaller canopy gaps in order to survive and grow into canopy trees. Achieving the structural and spatial heterogeneity coveted in “old-growth” forests requires the success of a diverse assemblage of residual subcanopy trees and regeneration.

There are different variations of the VDT treatment, but the general strategy is to selectively thin spatially adjacent areas within a stand at different intensities. This creates a heterogeneous release of resources like light and nutrients across the stand. In theory, trees will respond to the level of thinning in their immediate neighborhood, and hence have variable growth following the treatment. As some subcanopy trees grow into larger size classes and others fall behind, the stand becomes more structurally diverse. The Olympic Habitat Development Study, which is examined in this study, used a VDT that created a thinned matrix with patches of unthinned trees and small canopy gaps. The Forest Ecosystem Study, also examined in this study, used a grid of 40mX 40m cells that were heavily thinned, lightly thinned, or mostly cleared with only a few retained trees. Other similar treatments can be applied at different stages of stand development. A variation being examined in a younger forest (Clearwater Creek) includes thinning and creating variable-sized canopy gaps (Reutebuch et. al., 2004). Variable retention harvests, such as group selection, small patch, and retained overstory (two-age), are another option being examined (the Capitol Forest Study) for creating structural and species diversity in mature forests (Curtis et. al., 2004).

Because VDT is a relatively new treatment, little is known about the long-term effects of the treatment on growth and development of forest stands. This study will examine whether the residual subcanopy trees and post-thinning cohort of trees are responding positively in terms of growth rates and recruitment to VDT three to 13 years following treatment. The study will also examine species composition and attempt to correlate species success with local environmental conditions following VDT.

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CHAPTER 2

FACTORS AFFECTING UNDERSTORY COMPOSTITION AND HEIGHT GROWTH 13 YEARS FOLLOWING VARIABLE-DENSITY THINNING OF A CONIFER FOREST IN NORTHWEST WASHINGTON

Abstract

Variable-density thinning (VDT) is a management option aimed at accelerating the development of late-successional structure in second-growth conifer stands. The response of the understory is paramount to the success of the treatment. This study examined the species composition, density, and height growth of post-VDT regeneration 13 years following thinning. Thinning intensity had a significant effect on the number of species found in subplots. Height growth from 2002 to 2005 was assessed for 2,535 Douglas-fir, 43 grand fir, and 39 western white pine in the post- variable-density thinning cohort of second-growth Douglas-fir stands. Thinning intensity was not significantly related to height growth for grand fir or for western white pine. Thinning intensity was significantly related to height growth for Douglas-fir, but the effect varied with initial height. Factors correlated with Douglas-fir height growth in gap-thinned subplots were measures of crown size, measures of intra-cohort crowding, strata

and type of overtopping vegetation, and overstory crown coverage. Smaller regeneration (less than 1.3m tall) was also examined. The stocking of the smaller regeneration was significantly greater in the light thinning intensity than in the heavier thinning. The results of this study indicate that variable-density thinning can induce variation in the abundance and growth of Douglas-fir in post-VDT cohorts.

Introduction

Forest managers in the Pacific Northwest are trying to develop management practices for accelerating the transformation of even-aged, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands into more heterogeneous stands that fill the ecological and aesthetic role of late-successional forests. Variable-density thinning (VDT) is a treatment option for increasing spatial heterogeneity in mid-rotation stands. A closer examination of the response of post-thinning regeneration following VDT may offer insight into the longer-term implications and effectiveness of the treatment.

Traditional timber management strategies in the Pacific Northwest have consisted of clear-cutting mature and old-growth forest stands and replanting with fast-growing species such as Douglas-fir (Curtis et al., 1998). Managers take measures to reduce competition and maximize growth during short rotations before the next harvest (Reutebuch et al., 2004). These plantations of even-aged, monocultures simplify forest ecosystems, creating homogeneous stands that do not support the diversity of species found in natural, old-growth forests (Carey, 2003; Franklin and Spies, 1991; Franklin, 1993).

Composition and structure of canopy trees affects the composition and structure of subcanopy trees. The overstory tree density and distribution determine the light, water, and nutrient availability on the forest floor, creating an understory assemblage that is driven by competitive processes. Poage and Tappeiner (2004) found that the presence of certain species in small and medium size classes is indicative of different disturbance regimes. Manipulating forest structure can mimic disturbance, changing the competitive environment for the residual trees thereby allowing a diverse assemblage of trees to thrive.

Douglas-fir will often regenerate naturally and prolifically (more than 2,500 stems per hectare), in areas that have been burned or clearcut, however the stocking of the new stand is generally patchy and not evenly spread out. On the other hand, regeneration in closed canopy forests can be a challenge due to seedling competition from herbaceous competitors and increasing shade intolerance as seedlings grow (initially seedlings can establish in low light conditions). The site conditions will affect the quantity of regeneration and its ability to survive and grow (Hermann and Lavender, 1990).

Juvenile trees (up to 5 years) grow slowly compared to herbaceous competitor species. Height growth rates tend to increase with age peaking around 20 to 30 years in age. Douglas-fir has been known to maintain height growth for up to 200 years (Hermann and Lavender, 1990).

Halpern et al. (2005) examined the response of the understory to different retention levels and spatial patterns of retention at harvest. Their initial findings (1-2 years post treatment) show decreases in the growth of residual trees and increases in tree species composition and abundance at small-scales. Some explanations for this trend are the variable impact of harvesting or thinning operations and the variability of pre-harvest conditions at the site (Halpern et al. 2005).

Studies of alternative silvicultural treatments such as VDT and variable-retention harvest will help guide future forest management on both public and private lands. Because "old-growth" forests are so long-lived and complex, trying to improve the accuracy with which we can predict the future growth and development of second-growth forests for aesthetic and conservation goals will depend on continued examination of their short-term responses to these treatments.

Understory trees are the canopy trees of the future. In order to achieve the structural heterogeneity coveted in "old-growth" forests, the success of new generations of understory cohorts is paramount. Variable-density thinning is a treatment option for increasing structural complexity. There are different variations of the treatment, but the general strategy is to thin spatially adjacent areas within a stand at different intensities, from light or no thinning to complete removal of canopy trees. This creates a heterogeneous release of growth resources across the stand. In theory, retained trees will respond to the level of thinning in their immediate neighborhood, and hence have variable growth response, leading to greater structural diversity. The creation of canopy gaps will promote the establishment of regeneration cohorts that would not be present or viable in lightly thinned or unthinned areas. Because VDT is a relatively new treatment, little is known about the long-term effects of the treatment on growth and development of forest stands.

The Forest Ecosystem Study was initiated in 1991 to address the issue of creating new Northern Spotted Owl (*Strix occidentalis caurina* Merriam) habitat, as well as habitat for other animals from second-growth Douglas-fir stands. The objective of the overall FES is to determine the success of management practices on accelerating the creation of late-successional characteristics in second-growth conifers stands. Using data collected by the US Forest Service, this study examined how the understory trees responded in terms of growth rates and recruitment to VDT over the 13 years following treatment. This study also examined species composition and attempted to correlate species abundance with local environmental conditions following VDT. Specific questions that were addressed include:

1. Did VDT subtreatments affect the composition and growth rates of the post-VDT cohort?
2. What tree and stand factors were related to the growth response of the post- VDT cohort?

Methods

Study sites

The Forest Ecosystem Study is located at the Rainier Training Area of the Fort Lewis Military Reservation in northwest Washington State. Elevations on the study sites range from 120 to 165m. The terrain is generally rolling hills with occasional steeper areas. Soils at the study sites are coarse-textured gravel and gravelly- sandy loams that are classified as somewhat excessively drained. Average annual rainfall at Fort Lewis is 800-900mm, with most occurring between October and May. There is no year- round standing water. The climate and soil conditions create a somewhat droughty environment (Carey et al., 1999).

Four forest stands (blocks) dominated by 50-70 year old (at the time of treatment) Douglas-fir were used in this study. The stands are located within a few miles of each other in the 60,000 acres of managed forests at Fort Lewis. Two stands (Farley and Hill) were clearcut in 1925 and allowed to regenerate naturally. Two commercial thinnings were applied to each stand, one in 1972 and another in the 1979-80. The other two stands (Star and Stellar) were harvested in 1937 (with some legacy retention) and allowed to regenerate without further intervention (Table 2.1).

Study design and analysis

As part of the larger Forest Ecosystem Study, four 13 ha blocks were established in each stand (a control and 3 treatment blocks). This study only utilized blocks treated with a variable-density thinning. In each block, an 8 X 8 grid of adjacent 40m X 40m cells was established (total grid area = 7.84ha). Grid cells were randomly treated (except for some gap thinnings) with a heavy thinning (target of 185 residual trees per hectare- none of these plots were used in this study), light thinning (target of 310 residual trees per hectare), or a gap thinning (target of 40 residual trees per hectare). The gap thinning included removal of all low vigor trees and was applied specifically to cells with pockets of trees infected with laminated root rot (*Phellinus weiri*) as well as randomly selected and apparently uninfected cells (Figure 2.1). The gap thinning effectively created canopy gaps (~0.16 ha) with a few residual trees per subplot.

The VDT was applied prior to the growing season in 1993. Table 2.2 describes the average post-thinning conditions at the blocks that had received prior commercial thinnings (Farley and Hill) versus the unthinned blocks (Star and Stellar). Additionally the gap thinned plots were supposed to receive underplanting of 27 grand-fir (*Abies grandis* (Dougl. ex D. Don) Lindl), 27 western redcedar (*Thuja plicata* ex D. Don), 27 western white pine (*Pinus monticola* Dougl. ex D. Don), and 20 red alder (*Alnus rubra* Bong.) in 1994; However, some seedlings were mistakenly planted in light thinning cells. The planted conifer species were chosen because of their relatively high shade tolerance.

Red alder was chosen because of its ability to resist laminated root rot. The underplanted trees were not tagged and so are not separated from natural regeneration in this analysis.

In 1999, seven growing seasons following treatment, four 20m X 40m plots were established in each stand (16 in all). The plots were set up such that half of the 40m length was located in a gap thinned cell and half in a lightly thinned cell (subplot = ½ plot). They were placed strategically to orient two plots in each stand with the gap thinning treatment to the south or southwest and the other two with the gap thinning treatment to the north or northeast. All trees taller than 1.3 meters were tagged, stem-mapped, and measured for DBH. This included 30 grand fir (all under 10cm DBH), 8 western white pine (all 3cm or less in DBH), and 206 Douglas-fir (0.3 to 93.8cm DBH) that were alive and suitable for growth studies (i.e.- no forked or broken tops). Additionally bigleaf maple (*Acer macrophyllum* Pursh), red alder, black cottonwood (*Populus trichocarpa* Torr. And Gray), cascara (*Frangula purshiana* (D.C) Cooper), western redcedar, and western hemlock (a total 505 trees that were alive and suitable for growth studies) were recorded in the plots.

The plots were remeasured in the summer of 2005. All previously tagged canopy and understory trees were identified as alive or dead and measured for DBH. All trees suitable for including in height:diameter analyses (i.e., trees with no forks, broken tops, or other crown damage) were also measured for height (HT05), height to live crown (HLC05), and crown width (CW05) (a total of 398 trees). On a subset of these trees (234 trees), crown overlap (CO05) was also determined by visualizing a cylinder around the live crown of each tree with a radius equal to the longest branch and estimating to the nearest 10% the amount of overlap of neighboring tree crowns in that cylinder (Churchill, 2005). Overtopping strata (OT05, i.e. overstory, midstory, etc) and type (OTS05, i.e. evergreen or deciduous) and damage were noted. On a subset of 50 Douglas-fir (all under 22m in height in 2005), 5 western white pine, and 21 grand fir (all species with distinct annual whorls), 2002 height (HT02) was estimated by counting back annual whorls and measuring the height. To adequately describe the neighborhood of trees at the edges of the plots, trees outside the plot but within the limiting distance of a basal area factor 30 prism (metric) were measured for DBH and included in the stem-map.

In 2005, trees not previously mapped that had grown into the greater-than-1.3m height class were tagged and measured for DBH, height, height in 2002 (for appropriate species), height to base of live crown, crown width, crown overtopping, and crown overlap. This group included 19 grand fir, 31 western white pine, and 1,995 Douglas-fir. Other species in this group included bigleaf maple, red alder, Pacific madrone (*Arbutus menziesii* Pursh), Pacific dogwood (*Cornus nuttallii* Pursh), black cottonwood, cascara, Pacific yew (*Taxus brevifolia* Nutt), western redcedar, and western hemlock (255 trees in total).

To get a more complete picture of regeneration, the number and species of trees less than 1.3 meters tall in 2005 were recorded at five 1.5m radius circular regeneration subplots per treatment subplot. Additionally, the tallest seedling in each regeneration subplot was tagged and measured for DBH, height, 2002 height (where easily determined), source of overtopping, and crown overlap. If the tallest seedling was damaged, then the next tallest, undamaged seedling was measured. If the tallest seedling was not Douglas-fir, then the tallest Douglas-fir seedling was also measured. A regeneration subplot was considered "stocked" if there was at least one seedling present. The percent stocking for a treatment subplot was the percent of regeneration subplots that had at least one seedling.

Very few trees existed in the understory at the time of treatment in 1993, therefore trees less than 3cm DBH in 1999 as well as all trees first measured in 2005 are assumed to have established following thinning and are considered to be the post-VDT cohort. For analysis purposes, the post-VDT cohort is considered only regeneration greater than 1.3m in height in 2005. Regeneration less than 1.3m in 2005 is referred to as "smaller regeneration".

A mixed model was used to test for differences in the number of species observed in each thinning intensity (gap thinning vs. light thinning). The model accounted for random variation between blocks and subplots, uneven sample sizes, and missing observations (e.g. there were no post-VDT cohort trees located at two of the lightly thinned subplots).

Height growth of understory trees was assumed to be related to species and thinning treatment. Variation due to more localized competition factors (at the subplot level and within 2m of the target tree) and individual tree factors was also expected. A Geographic Information System (Environmental Research Systems Institute, ArcMAP, version 9.1, Redwoods, CA) was used to characterize the local environment for each tree using distance-dependent local competition indices and distance-independent competition measures (stem densities, local competition indices, and canopy coverage).

A mixed model analysis (SAS/STAT software, version 9.1, Cary, NC) was used to determine if thinning intensity was significantly related to height-growth of the post-VDT cohort after adjusting for initial height (2002) for Douglas-fir, grand fir, and western white pine. The mixed model accounted for random block, plot, and subplot variation, uneven sample sizes, and missing observations. If thinning intensity was significant, a mixed model analysis was used to determine which independent measures of local variation and tree vigor were related to height growth. Because there is not an easily interpreted fit statistic for comparing mixed models, a rough estimate for explaining the improvement in fit (FI, Equation 1) obtained by using the model rather than the mean to predict height growth from 2002 to 2005 was calculated. A significance level of 0.05 was used for all analyses.

$$FI = 100^* \left[1- \left(\frac{\Sigma\,(Ht_{inc\text{-}i} - Ht_{inc\text{-}pred\,i})^2}{\Sigma\,(Ht_{inc\text{-}i} - Ht_{inc\text{-}mean})^2} \right) \right] \qquad (1)$$

Where:

$Ht_{inc\text{-}i}$ is the measured height increment for tree i

$Ht_{inc\text{-}pred\,i}$ is the predicted height increment for tree i

$Ht_{inc\text{-}mean}$ is the mean height increment

Results

The number of trees in the post-VDT cohort (regeneration 1.3m in height or taller) increased dramatically between 1999 and 2005. In 1999 (seven growing seasons following VDT), there were a total of 285 trees in the post-VDT cohort, 37 in the light thinning and 248 in the gap thinning. Ten different species were found with Douglas-fir being the most common (65 trees). Fifty-two of these trees died between 1999 and 2005 (including 36 red alder). By 2005 (13 growing seasons following the VDT), there were a total of 3,075 live regeneration trees that had grown above 1.3m in height. Of that total, 381 trees were located in lightly thinned subplots and the remaining 2,694 trees were located in gap thinned subplots. A total of 13 species were found in the post-VDT cohort in 2005, however, 84% of the trees were Douglas-fir (N= 2,573).

There was an overall average of 4.5 different species in the post-VDT cohort at each subplot. Thinning intensity had a significant effect on the number of species found in subplots (P = 0.0064). The average number of species per gap thinned subplot was 6.3 compared to an average of 2.8 species per light thinned subplot. The gap thinning had a larger number of species than the light thinning in all blocks, except Hill (Figure 2.2), which had an average of 3.0 species per subplot in both the gap thinned subplots and the lightly thinned subplots.

Douglas-fir dominated the post-VDT cohort. The number of live Douglas-fir in the post-VDT cohort in 2005 varied by thinning treatment (P = 0.0070). The gap thin had an average of 173 live Douglas-fir in the post-VDT cohort per subplot (3,550 Trees per hectare). This was significantly greater than the light thinning which had an average of 19 live Douglas-fir per subplot (475 trees per hectare). The average number of live Douglas-fir was greatest in the gap thinning at Star (339 trees per subplot or 8,475 trees per hectare) followed by Stellar (196 trees per subplot or 4,900 trees per hectare). The average number of Douglas-fir at Farley and Hill per subplot in either treatment did not differ significantly from the lightly thinned subplots at Star and Stellar, but the average number of Douglas-fir was still greater in the gap thinning than in the light thinning at both blocks (Figure 2.3).

Height growth

Height growth was assessed on 43 grand fir from the post-VDT cohort: 6 from three blocks in the light thinning treatment and 37 from all four blocks in the gap thinning treatment (Table 2.3). The average initial height (in 2002) of trees in the gap thinned subplots was 2.6m (ranging from 1.0m to 4.6m) and in the light thinned plots was 1.7m (ranging from 1.2m to 2.8m). Grand fir in the gap thinnings grew 1.1m between 2002 and 2005 (ranging from 0.2m to 2.2m). Trees in the light thinning grew, on average, 0.9m during that period (ranging from 0.4m to 1.7m). Thinning intensity was not significantly related to initial height in 2002 (P= 0.1107) or height growth (P = 0.7316). Height growth was significantly related to initial height (P = 0.0023) (Figure 2.4).

38 western white pine in the post-VDT cohort were measured for height growth: 5 in the light thinning at two blocks and 33 in the gap thinning at all four blocks (Table 2.3). On average, the initial height (in 2002) of western white pine in the gap thinning was 1.6m (ranging from 1.0m to 7.5m) and in the light thinning was 1.4m (ranging from 1.1m to 1.7m). Western white pine grew on average 0.7m in the gap thinned subplots between 2002 and 2005 (ranging from 0.2m to 2.0m) and 0.5m in lightly thinned subplots (ranging from 0.4m to 0.8m). Thinning intensity did not significantly affect initial height (P = 0.2043) or height growth (P = 0.1204). There was a significant relationship between initial height and height growth (P = 0.0002) (Figure 2.5).

Height growth was measured for 2,536 Douglas-fir in the post-VDT cohort: 261 in the light thinning and 2,275 in the gap thinning spread out over all four blocks. The average initial height (in 2002) in the gap thinning was 1.3m (ranging from 0.3m to 4.9m) (Table 2.3). In the light thinning, the average initial height was 1.0m (ranging from 0.3m to 5.9m), which was significantly less ($P < 0.0$) than the gap thinning. The mean height growth in the gap thinning between 2002 and 2005 was 0.9m (ranging from 0.0m to 5.5m) which was significantly greater ($P < 0.0001$) than the mean height growth in the light thinning of 0.8m (ranging from 0.1m to 2.2m) (Table 2.4). However, the effect of thinning intensity had an interaction with the effect of initial height (2002) of the tree ($P < 0.0001$). When the effect of initial height on height growth was analyzed separately by thinning intensity, initial height had a significant relationship with height growth in the gap thinning ($P < 0.0001$), but not in the light thinning ($P = 0.3742$) (Figure 2.6).

Because only a small fraction of the regeneration is expected to survive and eventually become canopy trees, the best growers (largest 20% of height increment from 2002 to 2005) and the tallest regeneration (tallest 20% in 2002) in each thinning intensity were also examined. The best growers in the gap thinning were those that grew 1.2m or more between 2002 and 2005. In the light thinning treatment, the top 20% grew 1.0m or more. Treatment was significantly related to both initial size in 2002 ($P < 0.0001$) and height growth from 2002 to 2005 ($P = 0.0002$) for the best growers. The initial height of the top 20% of Douglas-fir (515 trees) ranged from 0.4m to 4.9m, with a mean initial height of

1.8m in the gap thinning. On average, these trees grew 1.5m between 2002 and 2005 and the height growth ranged from 1.2m to 5.5m. In the light thinning, the initial height of the top 20% (56 trees) averaged 0.9m and ranged from 0.3m to 2.5m. The top 20% grew 1.2m, on average, ranging from 1.0m to 2.2m in the light thinning. The tallest 20% of regeneration in 2002 were taller than 1.6m in the gap thinning (511 trees) and 1.0m in the light thinning (60 trees). The tallest 20% in the gap thinning grew significantly better than the tallest 20% in the light thinning ($p < 0.0001$). The tallest 20% in the light thinning did not grow significantly different than the shortest 80% of trees in either thinning intensity (Figure 2.7)

The trend remains the same at individual blocks, in that at the block level, the relationship between initial height and height growth is consistently significant in the gap thinning and not significant in the light thinning (Table 2.4).

Local stand conditions and tree factors

Initial height (in 2002) was significantly related to height growth in the gap thinning. The mixed model that evaluated the fixed effect of initial height and random block and subplot effects on height growth had a FI of 34% (Table 2.5).

Measures of crown size (e.g. crown width and live crown ratio) in 2005 were significantly related to height growth in both the gap thinning and the light thinning (Figure 2.8). They also had relatively high FI's and were significantly correlated with initial height ($P<0.0001$ for both variables). When combined, a mixed model that included significant effects for both initial height ($P<0.0001$) and live crown ratio ($P<0.0001$) had a FI of 54%, compared to 43% for live crown ratio alone or 34% for initial height alone (Table 2.5).

Crown overlap (%) with other tree crowns (CO05) was not significantly related to height growth on its own ($P= 0.9307$) in the gap thinning, but , when adjusted for initial height, crown overlap was significantly related to height growth ($P = 0.0443$, FI = 34%). However, adding crown overlap to the model did not increase the %RE compared to a model with initial height alone (Table 2.6).

The source of overtopping was significantly related to height growth ($P <0.0001$, FI = 27%). Douglas-fir in the post-VDT cohort that had no overtopping had the highest height growth between 2002 and 2005, followed by those that were overtopped by overstory or midstory trees. Trees that were overtopped by other understory trees or shrubs had the lowest height growth (Figure 2.8). Source of overtopping remained significant when initial height was added to the mixed model and the FI increased to 43%; however, there was interaction between the two effects ($P = 0.0007$). At initial heights of less than 1m, there was not a significant difference in height growth between trees that are not overtopped and those that were overtopped by overstory or midstory trees. If the overtopping tree was evergreen, the height growth was significantly less than if the overtopping tree was deciduous ($P <0.0001$).

The number of trees less than 5cm DBH within 2m of the target tree and a competition index (AGHt which sums the difference in height between the target tree and taller regeneration trees within 2m were significantly related to height growth from 2002 to 2005 ($P<0.0001$ for both measures and FI = 12% and 30% respectively) (Table 2.5). However, if just the best growing (top 20%) or the tallest (20% in 2002) regeneration are examined only the AGHt index continues to be significantly related to height growth ($P<0.0001$ and FI = 13%, $P<0.0001$ and FI=0.33, respectively). Measures of overstory competition alone were not significantly related to height growth in the gap thinning for all regeneration. However, if just the tallest (20% in 2002) regeneration are examined, overstory competition is significantly related to height growth in the gap thinning ($P=0.0330$, FI=0.17). For all Douglas-fir regeneration, when competition with overstory trees is combined in a model that also includes the fixed effect of initial height, it is significantly related to height growth ($P<0.0001$) as well as the distance to the nearest competitor tree ($P= 0.0042$) (Table 2.6). Models that included these measures had FI values of 32%, so they actually decrease the fit value of the model compared to a model with initial height alone. In the gap thinning, the percent canopy coverage on the subplot was significantly related to height growth ($P = 0.0059$, FI = 11%), but it explained very little of the variation in height growth (Figure 2.8). Canopy coverage was not significantly related to height growth for the best growers.

In the lightly thinned subplot, tree variables that were significantly related to height growth were crown size measurements (crown width and live crown ratio, $P<0.0001$ for both). The competition index AGHt was the only other variable significantly related to height growth in the light thinning ($P<0.0001$) (Figure 2.9). AGHt was also significant for the top 20% ($P = 0.251$ and FI = 25%) in the light thinning.

Smaller regeneration

There were 703 trees under 1.3m tall in 2005 (small regeneration) counted in the regeneration subplots. They were mostly Douglas-fir (688 Douglas-fir, 13 western redcedar, and 2 western hemlock). Fifty of the total 160 regeneration subplots had Douglas-fir only, one had Douglas-fir and western hemlock, three had western redcedar only, and one had western hemlock only. The remaining 105 regeneration subplots had no small regeneration. Thinning intensity was significantly related to percent stocking ($P = 0.0364$). The light thinning had an average stocking of 40% and the gap thinning had an average stocking of 28% (Figure 2.10).

Density of overstory trees (TPH) was the only local factor that was significantly related to the percent stocking of small regeneration ($P = 0.0235$). TPH of overstory trees was positively correlated with stocking in the lightly thinned supbplots (Figure 2.11). Height growth of the small regeneration was not significantly related to thinning intensity, block, or any of the measured local or individual tree variables.

Discussion

Understory composition

The results of this study indicate that thinning intensity affected both the quantity and composition of the post-VDT cohort. The gap thinning contained very few residual overstory trees and opened up resources for a large number of species and individual trees to establish. The light thinning had very little regeneration as would be expected from a conventional thinning.

By thirteen years following VDT, Douglas-fir was the dominant post-VDT cohort species (82% of the post-VDT cohort) which is not surprising given the droughty site conditions (Carey et.al., 1999) and the limited seed source for species other than Douglas-fir. It is difficult to make inferences about the number of other species present because of the underplanting activities. Overall, Star and Stellar had higher numbers of species and trees and the only occurrence of shade-tolerant Pacific yew was in the light thinning at Star. However, Farley and Hill had the highest occurrence of two shade tolerant species, bigleaf maple and western hemlock, and the only occurrence of bitter cherry (at Hill). These local variations indicate that the combination of site characteristics (possibly due to the prior commercial thinnings) and VDT intensity, overall, is creating a diversity of understory conditions which promote survival and growth for a variety of species. Seiwa (2007) found that early-successional species grew faster under all forest conditions. While growth was not measured for all species over this time period, Douglas-fir, an early-successional species, was most abundant under all conditions.

After canopy closure, Pacific Northwest conifer systems can remain in the stem exclusion stage of stand development (Oliver and Larson, 1996) for long periods of time due to the long lifespan of Douglas-fir. Biological diversity is lowest at this stage of development (Franklin and Spies, 1991). The overstory at the FES was dominated by Douglas-fir at the time of VDT (92-99% stocking of Douglas-fir) and there were very few trees in the understory (Carey et.al., 1999). In 1999, seven growing seasons after VDT, there were few individuals other than Douglas-fir from a limited number of species in the larger (>= 10cm DBH) tree size classes (black cottonwood, western hemlock and red alder), but the number of species and individuals in the understory was growing. By 13 growing seasons following VDT, there were a variety of species in the understory. If these trees survive and continue to grow, the future stand condition should contribute to the goal of creating a diverse and multicanopied forest.

Height growth and thinning intensity

Grand fir was uncommon at the FES study sites, and western white pine was only rarely present, if at all, prior to the VDT and underplanting. It can be assumed that most, if not all of the post-VDT cohort of these species were underplanted. Because the underplanted seedlings were specifically placed in the gap thinning subplot (with some accidental plantings in light thinning subplots) and therefore have a skewed distribution, it is impossible to make any inference regarding the effect of thinning intensity on height growth or distribution.

The effect of thinning intensity on height growth for Douglas-fir seems to be the ability of larger trees to put on more height growth than smaller trees in the gap thinning and the larger range of initial height and height growth in the gap thinning. Height growth of Douglas-fir in the post-VDT cohort increased significantly with initial (2002) height in the gap thinning. Initial height is not significantly related to height growth in the light thinning. This indicates that when growing space is opened up by the gap thinning, the seedlings that are better able to take advantage of the release in resources and quickly put on height growth continue to grow better than other individuals in their cohort. In the light thinning, even the trees that are able to get ahead (the tallest 20% from 2002) are unable to take advantage of the competitive edge on the other members of their cohort because of heavy competition with overstory trees. This supports the findings of Bailey and Tappeiner (1997), who suggest that more intense thinnings promote height growth of small trees and consequently allow more trees to grow into larger size classes. Other studies have also connected increased growth of Douglas-fir to increasing overstory removal (Brandeis et. al., 2001). Due to the larger number of post-VDT cohort trees and the better ability for taller trees to grow, the gap thinning has a larger range of height growth response than the light thinning.

Local stand condition and tree factors

Crown width and live crown ratio explained the greatest amount of variation in height growth for both thinning intensities. Because crown measurements were taken at the end of the growth period, it cannot be determined if the post-VDT cohort trees with large crowns grew more or if trees that grew more also developed larger crowns. However, Douglas-fir is relatively shade intolerant, so we would expect the ability to quickly build crown area would be important to growth and survival in nearly open conditions like the gap thinning. In the light thinning, it is more likely that crown expansion requires a longer time period than three years and that the crown measurements at the end of the period were well correlated with the crown dimensions in 2002 (Canham, 1988; Bond et.al., 1999). This result does, however, emphasize the importance of crown size and vigor for growth of small Douglas-fir.

In the gap thinning, measures of intra-cohort competition (number of understory trees within 2m and AGHt index) affected height growth, but did not explain much of the variation. The only other measure of the local competitive environment that was significant in the gap thinning was crown coverage which also did not account for any more variation than initial height alone. Additionally, the result was counterintuitive, in that there was an increase in height growth with increasing crown coverage. The level of canopy coverage was fairly high even in the gap thinning due to edge effects from adjacent cells. Seiwa (2007) found that seedlings of various broadleaved species (early, mid, and late successional) had better growth rates as the amount of light increased in a temperate forest when planted at the same density. There was a negative relationship between crown coverage and density of understory trees (P <0.0001) which may help explain the positive relationship between crown coverage and height growth. Larger canopy gaps (hence lower canopy coverage) resulted in larger understory tree density. The nature of western conifer forests, with narrow-crowned dominants and long-lived suppressed trees in the subcanopy suggests that light availability in the understory may be influenced more by the vertical and horizontal distribution of overstory trees than by gaps in the canopy (Van Pelt and Franklin, 2000). In this study, the height growth of post-VDT Douglas-fir in the gap thinning was affected more by the negative influence of competition with other understory trees than it was by the presumed positive influence of increased light at the canopy level. For this reason, canopy coverage did not significantly decrease the growth of the best growers (top 20%) that were less influenced by the intra-cohort competition.

In the gap thinning, overtopping strata (overstory, midstory, etc) and whether the overtopper was deciduous or evergreen had a significant influence on the ability of young Douglas-fir to put on height growth. Again, these measures were taken at the end of the study period, so it is difficult to draw strong conclusions based on these results. However, they support the finding that intra-cohort and intra-strata (shrubs) competition had a large influence on height growth in the absence of many overstory trees.

In the light thinnings, the only measure of local competition that was significantly related to height growth was the AGHt competition index. The relationship does not explain much of the variation in height growth (RE= 30% compared to 27% for initial height, which was not significantly related to height growth).

Smaller regeneration

Thirteen years following VDT, there was greater stocking of trees less than 1.3m in height in the light thinning. This may be an indication of longer term versus short term effects of thinning on regeneration. Caccia and Ballare (1998) suggest that higher light levels are not required for seedling germination implying that in the short term, small regeneration benefits from the moderated environmental conditions in the lighter thinning intensity (e.g. less extreme microclimate conditions due to the large trees providing a buffer for the understory) and the lack of intra-strata competition. In the longer term, these trees are only able to grow larger and moved up a size class when growth resources are available, as in the gap thinning. In the gap thinned plots, the large number of regeneration trees that had already grown over 1.3m in height created a competitive environment that excluded any new regeneration. Van Pelt and Franklin (1999) similarly found that the rapid change in temperature and moisture that gaps create initially reduced the growth of residual Pacific silver fir trees closer to the center of canopy gaps; however, after three years, the trees in the middle of gaps exhibited higher growth rates than those in the more sheltered environment near the edges. It is not likely that regeneration in the light thinning will be able to survive and grow into larger size classes, as we see by the sharp difference in the number of regeneration trees greater than 1.3m in height between the two thinning intensities. This conclusion about longer term survival is supported by Bailey and Tappeiner (1997). They found that the frequency of plots with regeneration (greater than 2.5cm DBH and 15cm height) was greater in second-growth stands that had been thinned 10 to 25 years prior than in second- growth stands of the same age that had not been thinned or in old-growth stands.

The only local factor that affected stocking of small regeneration was overstory density (TPH in 1999 of trees greater than 5cm DBH). As overstory density increased, the percent stocking increased in the light thinning and decreased in the gap thinning (Figure 2.10). The increasing stocking in the light thinning may be explained by the fact that with increasing shade, the microclimate is probably cooler and more moist and there is less understory vegetation which provides a better environment for seedlings to emerge. The stocking in the light thinning is unlikely to equate to future stocking levels, as it is common to get germination from seed in closed canopy situations, but the regeneration is unlikely to grow and survive, unless the canopy opens up (Hermann and Lavender, 1990). In the gap thinning, the intense competition from larger regeneration likely prevents the establishment of smaller regeneration.

Height growth of the small regeneration was not well correlated with any measure of individual tree or local environment variability. Below-ground expansion may be more important in this early stage of development, and as such a better indicator of what will survive and make it to the larger size classes, where (as we discussed earlier with the larger post-VDT cohort trees) competition for light and other resources is significantly related to height growth.

Conclusions

The similarity of physiographical site conditions at the different blocks at the FES limits the inferential power of the results to other second-growth conifer forests in the Pacific Northwest, however we would expect results to correspond at other stands of second-growth Douglas-fir located on comparably droughty sites. At the FES, the VDT treatment appears to be achieving the goals of increasing woody plant diversity and spatial heterogeneity as set out in the FES study plan. A variety of species have established in the understory and the different forest blocks and thinning intensities support slightly different assemblages of species.

Additionally the results suggest that the treatment will produce a new cohort of Douglas-fir, as opposed to supporting only more shade-tolerant regeneration. This may also be due to the physiographic conditions of the study sites. The different initial block stand conditions combined with VDT intensities tend to favor the development of different “generations” (or size classes) of Douglas-fir regeneration which may be an indication of the short-term and the long-term impact of the treatment. The gap thinning in Star and Stellar resulted in a large number of post-VDT cohort trees that are now above 1.3m in height, whereas the light thinning in Farley and Hill seemed to provide a good environment for smaller regeneration 13 growing seasons after thinning. Mature forests are formed by both within-system processes (competition, resource availability, etc) and the lingering effects of historical disturbances (Woods, 2000). The VDT treatment is creating heterogeneity in the within-system processes and the previous commercial thinnings, as well as other natural site differences, provide a range of lingering effects. So, the VDT treatment, by Woods’ measure, seems to be accelerating the maturation of the forest.

The Douglas-fir in the post-VDT cohort vary in height growth according to treatment and other local conditions, so the VDT is successful in creating spatial heterogeneity in the understory. This supports the results from other studies that are looking at alternative management options, such as similar VDT treatments and variable-retention harvests, for accelerating the development of late-successional structure in second-growth forest (Halpern et al., 2005; Reutebuch et al., 2004; Harrington et al., 2005).

Because intra-cohort competition and individual crown vigor are important to height growth of the post-VDT cohort, managers may want to look into thinning out some of the regeneration in this stratum to help ensure the survival and accelerate the growth of the highest vigor trees. The more vigorous understory trees in the gap thinning will have the best chance for creating the multilayered canopy that is an important structural component of the “old- growth” forests (Old-growth definition task group, 1986) that managers are trying to develop.

The FES study sites are located on droughty sites, adjacent to oak savannas. The natural cycle at these sites may be driven by more frequent fire intervals than is typical in the kind of “old-growth” forests which northern spotted owls prefer and for which the stands are currently being managed. It may be that the VDT treatment is succeeding in establishing a structure and composition at these sites that may never have previously existed. It also may be that the shade tolerant regeneration in the gap thinnings will not survive and the stand will continue to be dominated by multiple cohorts of Douglas-fir. Future research at these sites could include analyzing the risk that this management system poses towards increasing the intensity of an eventual forest fire.

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Tables

Table 2.1 History and stand conditions at the FES sites measured from prism plots prior to study initiation (From Carey et.al., 1999).

Block name	Year of origin	Harvest activities	Basal area	Douglas-fir	Other tree species
			$m^2 ha^{-1}$	***percent***	
Star	1937	Unthinned since 1937 harvest	42.2	98	Western redcedar, western hemlock, Pacific yew
Stellar	1937	Unthinned since 1937 harvest	50	99	Western hemlock, big-leaf maple
Farley	1925	Clearcut 1925. Thinned twice: 1972, 1979-80	45	97	Red alder, black cottonwood, big-leaf maple, western hemlock
Hill	1925	Clearcut 1925. Thinned twice: 1972, 1979-80	43.6	92	Red alder, black cottonwood

Table 2.2 Comparison of stand conditions prior to and following the VDT at the FES study sites. Blocks are grouped by management history. Farley/ Hill received commercial thinnings prior to the VDT. Star/Stellar had no management operations since regeneration (From Carey et. al., 1999).

			Pre-thinning				**Post-VDT**			
Forest	**Treatment**	**N**	**Basal area**		**Tree density**		**Basal area**		**Tree density**	
			m^2ha^{-1}	***(S.E.)***	***ha^{-1}***	***(S.E)***	***m^2ha^{-1}***	***(S.E.)***	***Ha^{-1}***	***(S.E.)***
Star/ Stellar	Gap thin	36	31.5	(2.2)	351.1	(26.3)	11.4	(0.9)	108.9	(9.6)
	Light thin	66	49.1	(1.0)	503.2	(13.5)	35.9	(0.5)	353.6	(6.3)
Farley/ Hill	Gap thin	42	43.2	(3.1)	199.4	(15.9)	14.7	(0.9)	59.1	(4.8)
	Light thin	77	52.8	(1.1)	216.9	(5.6)	44.1	(0.6)	178.4	(3.4)

Table 2.3 Number of trees (N), mean initial height (2002), mean DBH (2005), and mean height increment from 2002 to 2005 (standard error in parentheses) for trees from the post- VDT cohort that were measured for height growth in 2005 at the FES in the light thinning (LT) and the gap thinning (GT) and overall.

Species	Block	Treatment	N	Mean Ht 2002	Mean DBH 2005	Mean Ht_{inc} 2002-2005	
				m	*cm*	*m*	*(S.E.)*
All	All	All	2617	1.3	1.2	0.9	(0.01)
All	All	LT	272	1.0	0.8	0.8	(0.02)
grand fir	All	LT	6	1.7	2.8	0.9	(0.20)
	Star	LT	1	1.3	2.0	1.2	
	Stellar	LT	1	1.9	3.6	1.7	
	Hill	LT	4	1.8	2.9	0.6	(0.09)
western wt pine	All	LT	5	1.4	1.3	0.5	(0.08)
	Star	LT	3	1.4	1.2	0.4	(0.00)
	Stellar	LT	2	1.5	1.6	0.6	(0.20)
Douglas-fir	All	LT	261	1.0	0.7	0.8	(0.02)
	Star	LT	95	0.8	0.6	0.9	(0.03)
	Stellar	LT	98	0.8	0.5	0.8	(0.02)
	Farley	LT	55	1.0	0.8	0.7	(0.04)
	Hill	LT	13	3.0	2.6	0.5	(0.08)
All	All	GT	2345	1.4	1.2	0.9	(0.01)
grand fir	All	GT	37	2.6	3.7	1.1	(0.09)
	Star	GT	10	2.7	4.2	1.3	(0.14)
	Stellar	GT	18	3.0	4.1	1.2	(0.13)
	Farley	GT	6	1.7	2.0	0.6	(0.12)
	Hill	GT	3	2.0	2.8	0.8	(0.10)
western wt pine	All	GT	33	2.0	2.6	0.9	(0.08)
	Star	GT	14	2.4	3.4	1.1	(0.13)
	Stellar	GT	8	2.1	2.5	0.9	(0.19)
	Farley	GT	8	1.4	1.5	0.6	(0.10)
	Hill	GT	3	1.5	2.0	0.5	(0.06)
Douglas-fir	All	GT	2275	1.3	1.1	0.9	(0.01)
	Star	GT	1341	1.3	1.0	0.9	(0.01)
	Stellar	GT	768	1.4	1.4	1.0	(0.02)
	Farley	GT	139	1.6	1.5	0.8	(0.03)
	Hill	GT	27	1.3	1.5	1.0	(0.07)

Table 2.4 P-values for fixed effects in mixed model analysis of height increment as a function of initial height (Ht02), thinning intensity (Trt), and the interaction effect of initial height and thinning intensity (Ht02*Trt). The mixed model accounts for random effects due to block, plot, and/or subplot depending on the scale of the data subset.

Data Subset		Fixed Effects Ht02 P-value	Trt P-value	Ht02*Trt P-value
All Blocks	All trees	<0.0001	0.0003	<0.0001
	*GT only	<0.0001		
	LT only	0.2942		
Star	All trees	0.0007	0.3454	0.5596
	All trees	<0.0001	0.0693	
	GT only	<0.0001		
	LT only	0.0927		
Stellar	All trees	0.0607	0.0427	0.0336
	GT only	<0.0001		
	LT only	0.61		
Farley	All trees	0.0001	0.0817	0.0746
	All trees	<0.0001	0.731	
	GT only	<0.0001		
	LT only	0.2352		
Hill	All trees	0.0919	0.8752	0.1062
	All trees	0.0024	0.0295	
	GT only	0.0005		
	LT only	0.9394		

* GT = Gap thinned, LT = Lightly thinned

Table 2.5 Sample size (N), P-value, and fit statistics (FI) for mixed model including single factor and random block and subplot effects in the gap thinning (GT) and light thinning (LT).

	GT			LT		
Variable	N	P-value	FI	N	P-value	FI
			%			%
Ht02	2274	<0.0001	34	261	0.3742	27
Ht05	2273	<0.0001	70	261	<0.0001	62
DBH05	2274	<0.0001	62	261	<0.0001	61
CW05	2273	<0.0001	54	261	<0.0001	47
LCR05	2274	<0.0001	43	261	<0.0001	39
CO05	2274	0.9307	11	261	0.9312	26
OT05	2272	<0.0001	27	261	0.1590	28
OTS05	1298	<0.0001	24	170	0.6789	25
over count	2236	0.4888	10	252	0.2420	23
Undercount	2236	<0.0001	12	252	0.6446	23
Aght2	2236	<0.0001	30	252	<0.0001	30
nearest DBH	2236	0.9017	10	252	0.1577	24
nearest distance	2236	0.4232	10	252	0.1450	24
Crown cover	2274	0.0059	11	261	0.8975	26
TPH99	2236	0.5197	10	252	0.4576	23
BA99	2236	0.2669	10	252	0.8704	23
SDI99	2236	0.3247	10	252	0.2298	23

Individual tree variables are height in 2002 (HT02) and height (HT05), DBH (DBH05), crown width (CW05), live crown ratio (LCR05), crown overlap (CO05), overtopping strata (OT05), and source of overtoppting (i.e.- evergreen or deciduous, OTS05) in 2005. Distance-dependent competition measures are number of overstory trees (over count) and understory trees (under count) within 2m, the sum of height differences between target tree and larger understory trees within 2m (Aght2), DBH in 1999 of nearest overstory tree (nearest DBH), and distance to nearest overstory tree (nearest distance). Distance-independent competition measures at the subplot level are percent crown coverage (crown cover) in 2005 and trees per hectare (TPH99), total basal area of trees greater than 5cm DBH (BA99), and stand density index (SDI99) in 1999.

Table 2.6 Sample size, P-value, and fit statistic (FI) for mixed model including individual variables and initial height (Ht02) and random block and subplot effects in the gap thinning.

Variable	N	P-value variable	P-value Ht02	FI
				%
CW05	2273	<0.0001	0.2638	53
LCR05	2274	<0.0001	<0.0001	54
CO05	2274	0.0443	<0.0001	34
OT05	2272	<0.0001	<0.0001	43
OTS05	1298	0.0122	<0.0001	35
Over count	2236	<0.0001	<0.0001	32
undercount	2236	<0.0001	<0.0001	32
Aght2	2236	<0.0001	<0.0001	42
nearest DBH	2236	0.0760	<0.0001	31
nearest Distance	2236	0.0042	<0.0001	31
Crown cover	2274	0.0018	<0.0001	34
TPH99	2236	0.7080	<0.0001	31
BA99	2236	0.0630	<0.0001	31
SDI99	2236	0.0930	<0.0001	31

Individual tree variables are height in crown width (CW05), live crown ratio (LCR05), crown overlap (CO05), overtopping strata (OT05), and source of overtoppting (i.e.- evergreen or deciduous, OTS05) in 2005. Distance-dependent competition measures are number of overstory trees (over count) and understory trees (under count) within 2m, the sum of height differences between target tree and larger understory trees within 2m (Aght2), DBH in 1999 of nearest overstory tree (nearest DBH), and distance to nearest overstory tree (nearest distance). Distance-independent competition measures at the subplot level are percent crown coverage (crown cover) in 2005 and trees per hectare (TPH99), total basal area of trees greater than 5cm DBH (BA99), and stand density index (SDI99) in 1999.

Figures

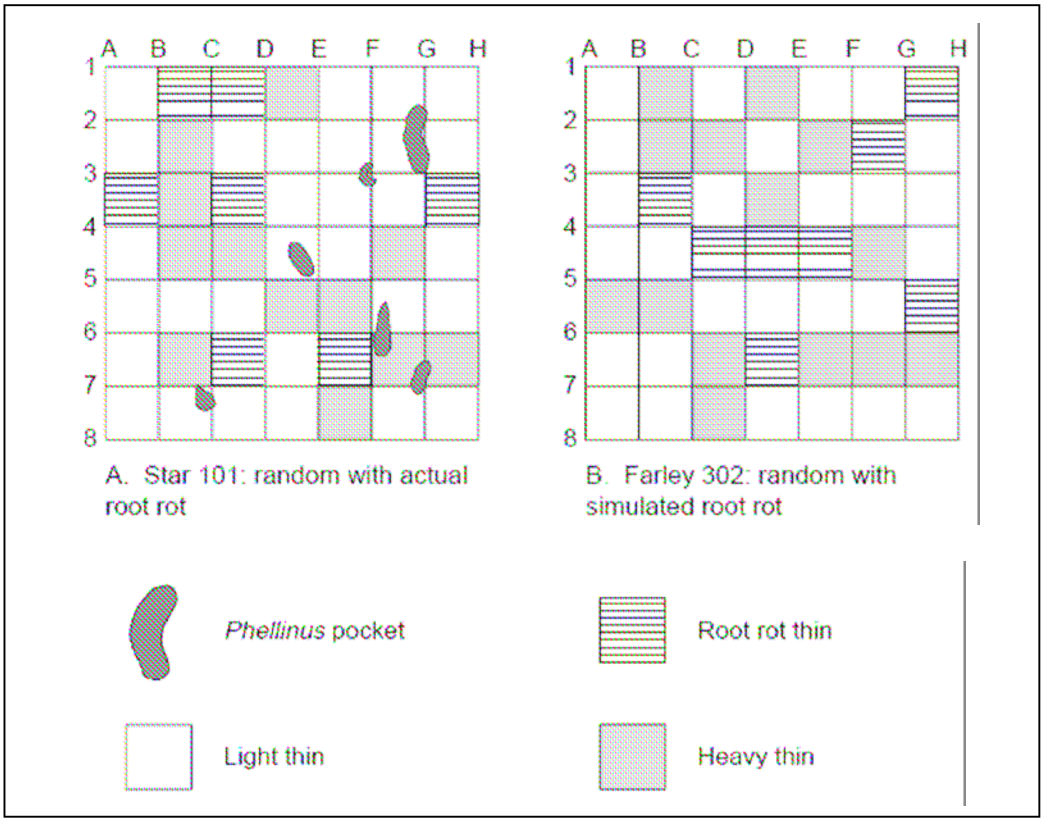

Figure 2.1 Actual and potential applications of variable-density thinning. Star 101 (A) shows random assignment of thinning intensities with actual root rot pockets. Farley 302 (B) shows random assignment of subtreatments with simulated root rot pockets (Carey and others, 1999).

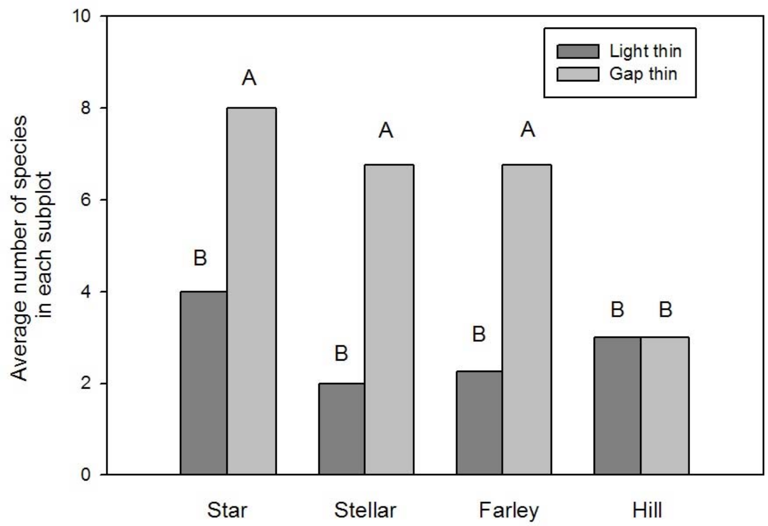

Figure 2.2 The average number of species per subplot in the post-VDT cohort on each block at the FES. Averages with different letters are significantly different.

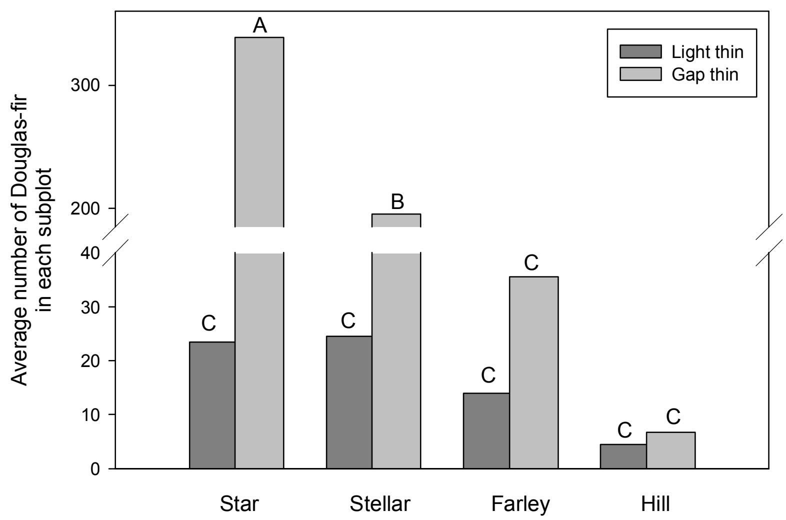

Figure 2.3 The average number of live Douglas-fir per subplot in the post-VDT cohort by block and VDT intensity at the FES. Averages with different letters are significantly different.

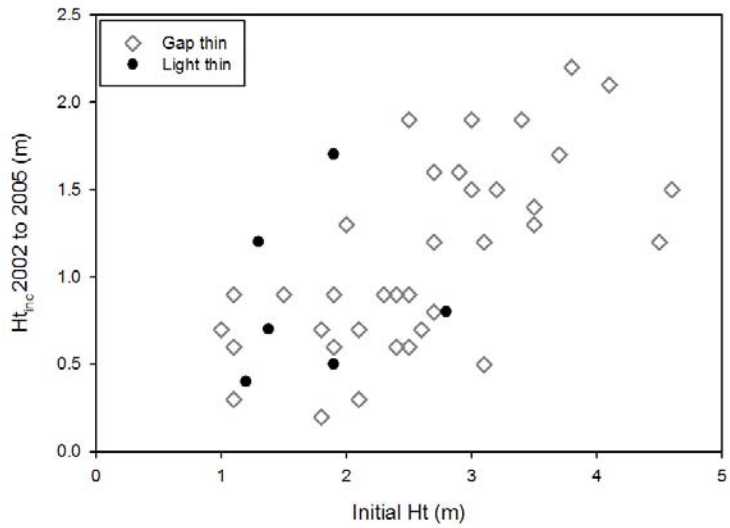

Figure 2.4 Height increment from 2002 to 2005 (m) plotted against initial height (m) in the gap thinning and light thinning for grand fir in the post-VDT cohort at the FES.

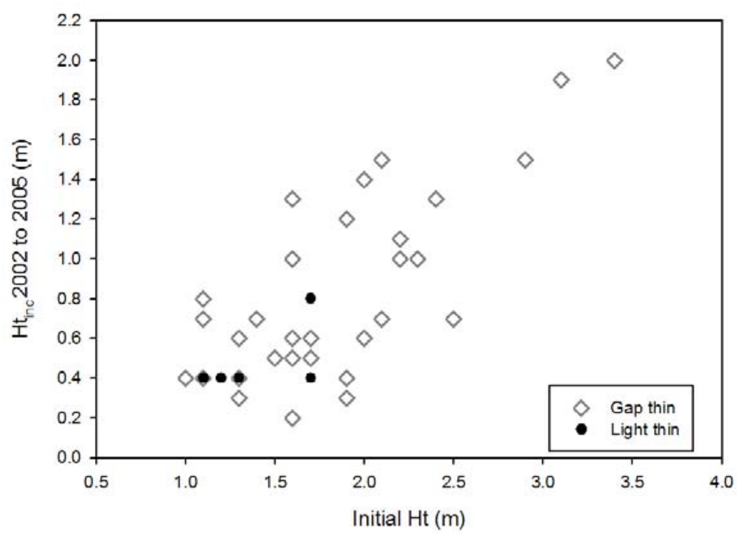

Figure 2.5 Height increment from 2002 to 2005 (m) plotted against initial height (m) in the gap thinning and light thinning for western white pine in the post-VDT cohort at the FES.

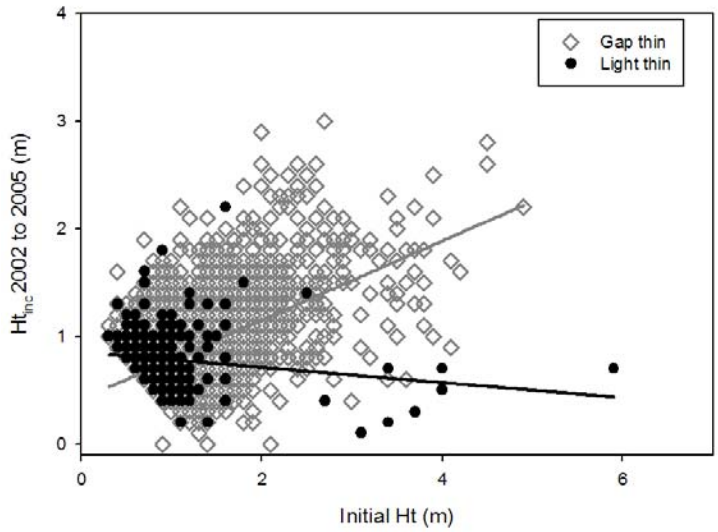

Figure 2.6 Height increment from 2002 to 2005 (m) plotted against initial height (m) in the gap thin and light thin with superimposed linear regression lines for Douglas-fir in the post-VDT cohort at the FES.

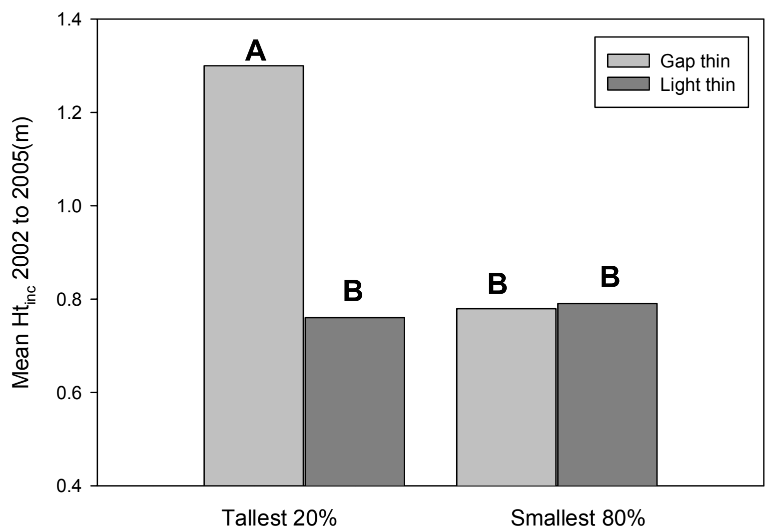

Figure 2.7 Mean height increment from 2002 to 2005 (m) for the tallest 20% of Douglas-fir seedlings in each thinning treatment and the remaining 80% of Douglas-fir seedlings from the post-VDT cohort at the FES. Means with different letters are significantly different.

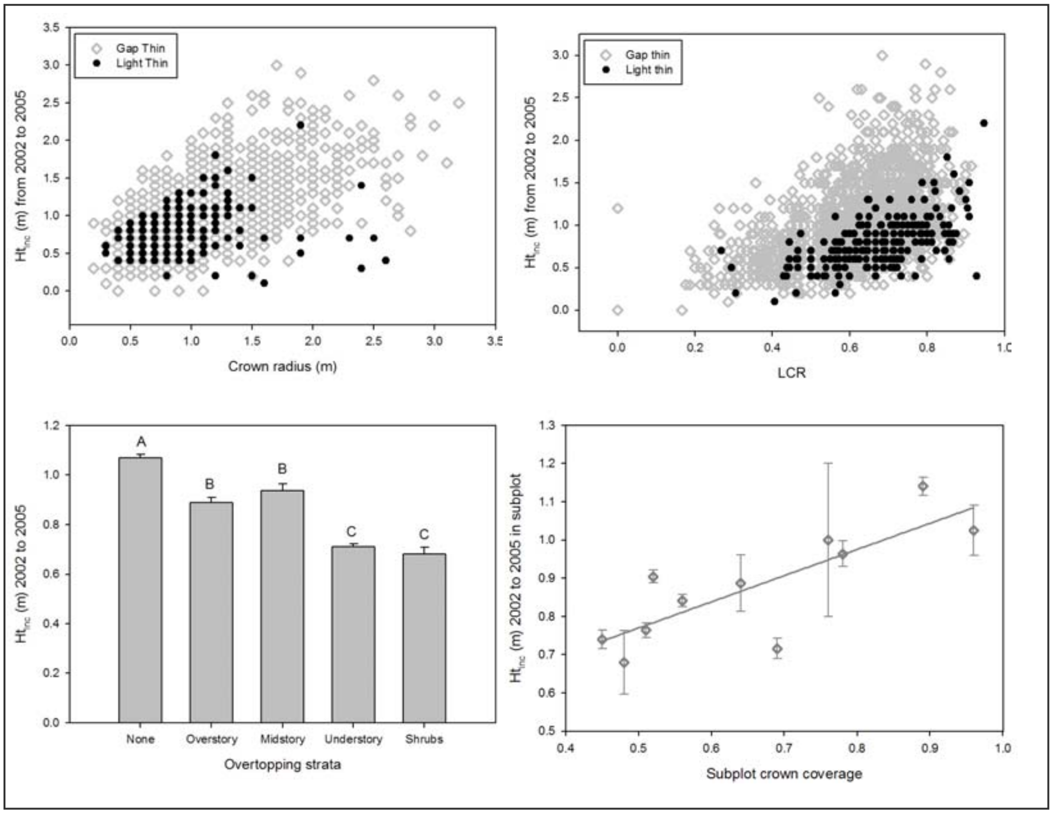

Figure 2.8 Height growth (Ht_{inc}) from 2002 to 2005 plotted against A) crown radius and B) live crown ratio (LCR) in the gap thin and light thin and C) strata of overtopping and D) proportion of subplot crown coverage in the gap thin only for the post-VDT cohort at the FES.

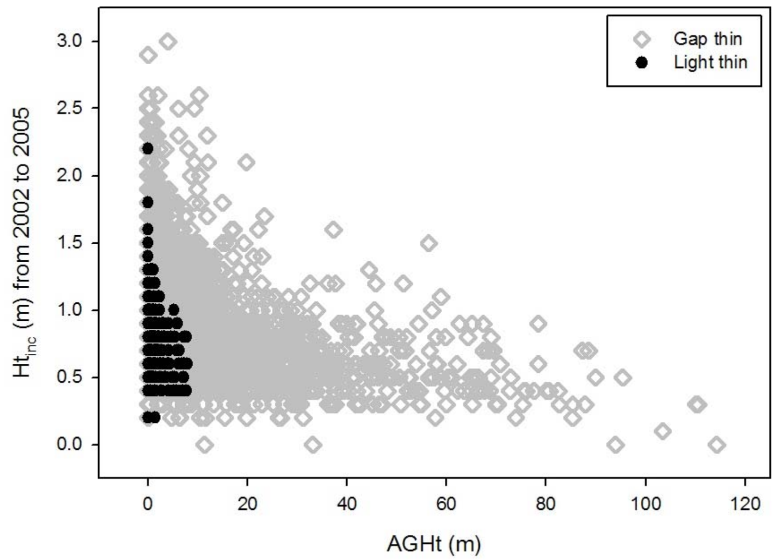

Figure 2.9 Height increment (m) from 2002 to 2005 plotted against AGHt competition index value in the gap thin and light thin for the post-VDT cohort at the FES.

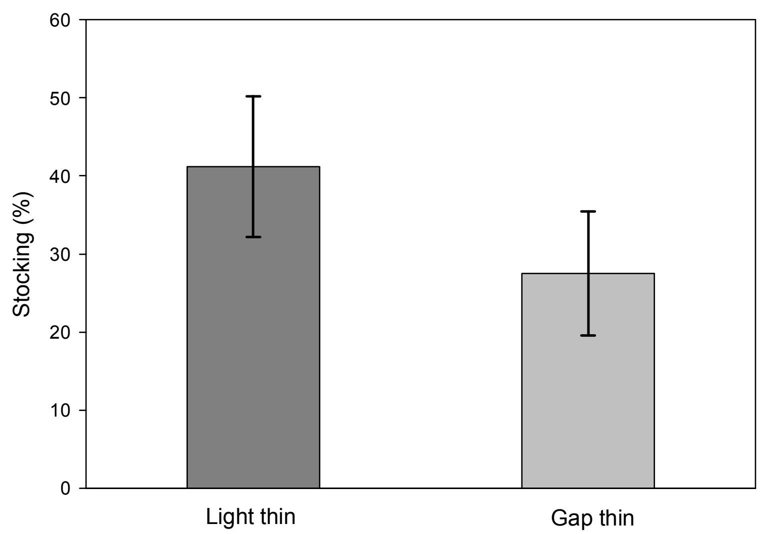

Figure 2.10 Stocking (% of regeneration subplots with one or more seedling) of smaller regeneration at the FES.

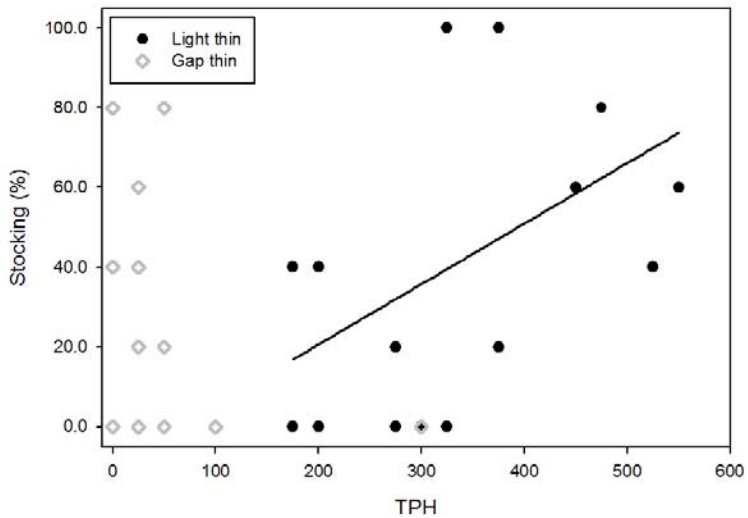

Figure 2.11 Stocking (% of regeneration subplots with one or more seedling) plotted against number of overstory trees (trees per hectare less than or equal to 5cm DBH) in the gap thin and light thin for the post-VDT cohort at the FES.

CHAPTER 3

FACTORS AFFECTING SUBCANOPY GROWTH FOLLOWING VARIABLE-DENSITY THINNING IN SECOND-GROWTH CONIFER FORESTS ON THE OLYMPIC PENINSULA IN WESTERN WASHINGTON

Abstract

Little is known about which stand and tree factors influence the ability of subcanopy trees to respond to release; however, this information is important to managers interested in accelerating development of late-successional structural characteristics in second-growth forests We examined basal area growth response of subcanopy 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-years prior to thinning and the 3-to-6 years following thinning. Results indicate that subcanopy trees retained in a uniformly thinned matrix grew significantly better than those in unthinned patches for western hemlock in the six years following treatment and for western redcedar in the first three years following

treatment . Factors related to the ability of western hemlock in the thinned matrix to increase growth include measures of crown fullness and crown crowding. Western redcedar release was influenced by initial tree dbh, relative age, local crowding and measures of crown size and vigor. Our results indicate that subcanopy western hemlock and western redcedar retain the ability to respond rapidly when overstory competition is reduced and thus suggest that thinning can be an effective tool to accelerate growth of subcanopy trees.

Introduction

Forest managers in the Pacific Northwest are trying to develop management practices to accelerate the transformation of even-aged conifer stands into more heterogeneous stands that fill the ecological and aesthetic role of old-growth forests. Variable-density thinning (VDT) is a treatment option for increasing spatial heterogeneity in mid-rotation stands. As the term implies, "old-growth" forests consist of long-lived trees and the effects of management techniques are hard to quantify in the short time span of years or even decades. Although numerous studies have examined the growth of residual canopy trees following thinning (Harrington and Reukema, 1983; McComb et. al., 1993; Curtis and Marshall, 1986), little research has been done to examine the growth of residual subcanopy trees or to determine which individual tree and local environmental characteristics influence the ability of subcanopy trees to release after thinning treatments. A closer examination of the response of subcanopy trees to VDT may offer insight into the longer-term implications and effectiveness of these treatments.

Old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests are typically remnant even-aged Douglas-fir stands that were formed after stand replacing disturbances hundreds of years ago. Douglas-fir is a relatively shade intolerant species, so succession is initially driven by intraspecific competition. Self-thinning creates a uniform distribution of Douglas-fir in middle-aged forests. Further along in the succession process, shade tolerant species, such as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* ex. D. Don) establish in gaps created by dead Douglas-fir (He and Duncan, 2000). Over the course of time, interspecific competition and small-scale disturbance lead to diversification of age and height classes allowing a variety of subcanopy trees to establish. The structural gradient created by the remnant tall, large-diameter Douglas-fir with the stratified midstory perpetuates varied understory light conditions. This heterogeneity in light condition allows a diverse assemblage of species with varying tolerances to remain in the understory (Zenner, 2004).

Composition and structure of canopy trees has a major influence on the composition and structure of subcanopy trees. The overstory trees control the light, water, and nutrient environment of the forest floor, creating an understory assemblage that is driven by competitive processes. Poage and Tappeiner (2004) found that the presence of certain species in the small and medium size classes are indicative of particular disturbance regimes. Manipulating forest structure can mimic disturbance by changing the competitive environment for the remnant trees and thereby allowing a diverse assemblage of trees to thrive.

Mature forests are formed by both within-system processes (competition, resource availability, etc) and the lingering effects of historical disturbances (Woods, 2000). Management practices can be patterned after these processes in order to achieve goals of creating old-growth structural complexity. Because succession in Douglas-fir forests generally begins with monocultures, second-growth stands are ideal for examining the effects of inducing spatial heterogeneity on the development of late-successional characteristics.

Disturbance plays a large role in the composition and success of the subcanopy. Small-scale disturbances allow shade tolerant subcanopy trees to establish and grow, 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, 1997). Second-growth conifer stands in the Pacific Northwest can maintain a long period of stem exclusion (Oliver and Larson, 1996) if disturbances do not occur.

Variable-density thinning is a treatment option for increasing structural complexity in mature second-growth stands. Similar treatments are being examined to quantify the effects of variable retention and spatial distribution of pre-commercial thinning, mid-rotation thinning and harvesting (Reutebuch et al., 2004; Carey et al., 1999). The general strategy is to selectively thin spatially adjacent areas within a stand at different intensities. This creates a heterogeneous release of resources like light and nutrients across the stand. In theory, trees will respond to the level of thinning in their immediate neighborhood, and hence have variable growth response, leading to greater structural diversity. Because VDT is a relatively new treatment, little is known about the long-term effects of the treatment on growth and development of forest stands.

The understory and midstory trees are the canopy trees of the future. In order to achieve the structural and spatial heterogeneity coveted in "old-growth" forests, the survival and growth of subcanopy trees is paramount. This study examined the midstory trees for signs of release in terms of basal area growth three to six years following VDT. Specific questions that were addressed include:

1. Did VDT effectively increase the growth rate of residual subcanopy trees in thinned versus unthinned areas?
2. What tree and stand factors were related to subcanopy growth response?

Methods

Site description

The Olympic Habitat Development Study (OHDS) is located in the Olympic National Forest in northwest Washington. The study, a joint venture between the Olympic National Forest and the Pacific Northwest Research Station, was initiated in 1994 to evaluate if management in 35-70-year-old even-aged conifer stands could accelerate the development of species composition and structural characteristics similar to late-successional stands.

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) were used in this study (Figure 3.1). The terrain of the study sites varies from low elevation (150m) and flat to higher elevation (580m) and steep. Historic average annual rainfall ranges from 1150 to 3175mm and occurs mostly during the winter (Harrington et al., 2005) (Table 3.1). The town of Quilcene, located on the east side of the Olympic peninsula (near Snow White and Triton), received on average 965mm of precipitation per year between 1994 and 2005. In contrast, the town of Forks on the west side of the peninsula (near the remaining blocks), received on average 3162mm per year over the same time interval. Most blocks regenerated naturally after original harvest (Snow White and Bait were planted with Douglas-fir, but also had a large amount of natural regeneration). Bait was pre-commercially thinned around 1970. Snow

White was commercially thinned in the early 1970's. Rail had a light commercial thinning in 1986. The blocks were chosen specifically to represent a range of initial conditions that are typical of second-growth conifer forests in the region.

Field methods

Each block consists of one uncut control plot and three to four VDT plots. The plots are 6-10 ha each. The VDT treatment consisted of thinning the matrix of the stand (removal of about 25% of basal area in a uniform thinning from below) while leaving about 10% of the total stand area unthinned in blocks of 0.1-0.3 ha and 15% of the total stand area in small canopy gaps of 0.04 to 0.05 ha. Measures were taken to minimize the impact of the thinning operations on the unthinned patches, such as locating the canopy gaps at least 20m away from and preventing equipment access to the unthinned patches. Rail and Fresca were thinned in 1997, Bait in 1999, Snow White and Clavicle in 2000 (before the growing season), and Triton in 2002.

Prior to thinning, a 1.44 ha stem-mapped plot was established in one of the VDT plots in each block. The stem-mapped plots included at least 2 full canopy gaps and 1 full unthinned patch (Figure 3.2). Prior to thinning, all trees greater than 1.3m in height were tagged, stem-mapped, measured for DBH, and identified as a harvest tree or a leave tree. In the 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. The locations of the subtreatment (unthinned patch and canopy gap) boundaries within the plots were mapped. Five years after 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.

In the spring of 2006, subcanopy trees at the six study sites were examined (Table 3.2). Potential subcanopy trees were identified using a scatterplot of height to diameter of all trees from the post-treatment measurements at each block (Figure 3.3). In the field, midstory status was confirmed and trees were added or deleted from the dataset if their height was outside of the range determined by the scatterplot. Trees were also deleted if they had severe and recent damage such as a broken top.

The diameter at breast height of each identified subcanopy tree was measured, along with height and height to the base of the live crown. If the base of the live crown was unequal, the base was measured at the mid-point between the lowest live branch and the first whorl with three live branches to account for the unevenness of the crown. All subsequent measures of crown characteristics only include branches that were considered in the live crown (as determined above). Crown width was measured in four cardinal directions. Crown health was assessed based on the following characteristics: condition of the leader, condition of the crown, fullness of the crown, and stem condition. Condition of the leader was rated on a scale ranging from four (single, dominant leader-apparently healthy and in good condition for height growth) to one (no dominant leader- not in good condition for height growth and unlikely to recover in the near future). Crown condition was assessed on a scale from four (conical shape- apparently healthy and in good condition for height growth) to one (flattened top- suffering from dieback or other damage and not likely to recover). To assign the rating for crown fullness, the tree was divided into four quadrants and given a point for each quadrant that was 50% or more full. Stem condition was evaluated in terms of damage that might affect crown vigor and rated on a scale of four (healthy, straight stem with no visible defects) to one (stem damage that appears likely to eventually kill the tree).

The degree of 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 target tree. The amount of that cylinder that was occupied by non-target tree crowns was estimated to the nearest 10%.

A core was taken at breast height for each subcanopy tree. The cores were placed in plastic straws and stored in a freezer to prevent molding. Later, the cores were measured to estimate age and the width (in millimeters) of individual growth rings from five years before treatment to current year (varied from 3 years post- treatment to eight years post-treatment). Relative age was calculated as the age of an individual tree relative to the oldest measured tree in the same block. Additionally, the width of the core from the center to inside edge of the bark was measured, the widths of the annual rings for the entire five years span both before and after treatment was measured.

Midstory crown measurements were used to create a GIS layer (Environmental Systems Research Institute, ArcMap, version 9.1, Redlands, CA). The crown width measured on a subsample of canopy trees was used to estimate a crown width regression model by species for Douglas-fir, western hemlock, western redcedar, and sitka spruce (*Picea stichensis* (Bong.) Carr.). Estimated crown widths were used to create a canopy layer in ArcMap. The percent of the subcanopy tree crown area that was overlapped by the canopy was recorded as overtopping of the subcanopy tree.

ArcMap was used to calculate the distance from each subcanopy tree to all competitor trees within ten meters and from each tree to the stem-mapped plot boundary. A 10m radius was found, through statistical analyses, to be sufficient to capture competition effects. Canham et al. (2004) suggest a distance of 8 to 12m sufficient for capturing competition effects for western hemlock and western redcedar. Seven distance-dependent competition indices were calculated (Table 3.3). Additionally a 10m radius was used to calculate distance-independent competition measures for each tree including measures of average competitor tree size and competitor stocking. The stocking of trees at the plot-level prior to treatment was also calculated.

Analysis

The response variable used to quantify release was the difference in average annual basal area growth (ΔBA_{inc}) between the five-year period prior to treatment to the periods from one-to-three years, one-to-six years, and four-to-six years following treatment. Because Triton only had data up to three years following thinning and all the subcanopy western redcedar at Clavicle were located in thinned matrix, the results for western redcedar are only reported for the three year period following thinning. A mixed model was used to test for treatment effects in order to account for random variation from block to block and for the unbalanced sample of trees (including blocks with few or no trees in one or the other treatment). Species were expected to respond uniquely to the thinning so were analyzed separately. Because there is not an easily interpreted fit statistic for comparing mixed models, a fit index was calculated (FI) to explain the reduction in error obtained by using the model rather than the mean to predict ΔBA_{inc}. Least-squared means were compared or T-tests were performed to directly compare any two means. A significance level of 0.05 was used for all analyses.

$$FI = 100^{*} \left[1- \left(\frac{\Sigma(\Delta BA_{inc-i} - \Delta BA_{inc-pred i})^2}{\Sigma(\Delta BA_{inc-i} - \Delta BA_{inc-mean})^2} \right) \right] \qquad (1)$$

Where:

ΔBA_{inc-i} is the measured change in basal area increment for tree i

$\Delta BA_{inc-pred i}$ is the predicted change in basal area increment for tree i

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

If treatment was determined to be significantly related to release in a particular time period, local environment and individual tree characteristics were examined closer. A mixed model was used to test for the effect of each of the local measures of competition and tree vigor for trees in the thinned matrix. For any variable that was significantly related to ΔBA_{inc}, we calculated a FI. If initial size was significant, it was also used as a covariate with other measures.

Results

Western hemlock

There were 170 western hemlock at the OHDS suitable for use in this study. Of those, 59 were located in unthinned patches and 110 were located in the thinned matrix (Table 3.2). Subcanopy western hemlock in the unthinned patches had an average initial DBH (five years prior to treatment) of 17.3cm (s.e.= 0.6), which was significantly different from the trees in the thinned matrix which averaged 14.0cm initial DBH (s.e.= 0.3, $P < 0.0001$). By the end of the sixth year following VDT (not including Triton), trees in the unthinned patches had increased in DBH on average by 2.3cm (s.e.= 0.1) which was significantly less than trees in the thinned matrix where trees had increased in DBH by 2.9cm (s.e.= 0.2, $P = 0.0008$).

The average change in basal area increment in the unthinned patches was significantly less than zero after first three years ($P = 0.0022$). If the basal area increment following treatment is calculated for the six years or the four-to-six years following treatment, the mean change was not significantly different from zero ($P = 0.5959$ and $P = 0.3847$). Within the thinned matrix, the mean was significantly greater than zero ($P = 0.0027$, $P < 0.0001$, and $P < 0.0001$ respectively) in each time period (Figure 3.4). ΔBA_{inc} was significantly related to thinning treatment when post-treatment basal area increment was average over six years or four-to-six years following treatment. Over the three-year period following treatment, thinning treatment was not significantly related to ΔBA_{inc} (Table 3.4). The FI for the mixed model that accounts for random block and subplot variation and fixed thinning effects was slightly less for the period from one-to-three years following thinning than for the six-year period or the four-to-six year period following VDT (16%, 19%, 19% respectively).

Factors that were related to the ΔBA_{inc} over the entire six-year period and the four-to-six years following thinning were examined for western hemlock. The results were similar, so only the results from the six-year period are presented. Triton was not included in the analysis because only three years had passed since VDT.

Measures of crown crowding and crown vigor were significantly related to ΔBA_{inc} (Figure 3.5) in the thinned matrix (Table 3.5). Crown overlap had a significant negative correlation with ΔBA_{inc} (r = -0.3490). Crown area and live crown ratio were positively correlated with ΔBA_{inc} (r = 0.1424 and r = 0.1419 respectively). The rating of crown fullness was significantly related to ΔBA_{inc}. A pairwise comparison of least-squared means suggests that a rating of four (approximately 75- 100% full), had a significantly higher mean ΔBA_{inc} than any other rating.

Western redcedar

Overall, thinning was significantly related to ΔBA_{inc} (P= 0.0333) in the first three years after VDT (Table 3.6) if initial size was added as a covariate (P = 0.0120 for effect of initial size). During that period, the mean ΔBA_{inc} was not significantly different than zero (P = 0.2673) in the unthinned patches and was significantly greater than zero in the thinned matrix (P < 0.0001). (Figure 3.6).

There were 94 western redcedar present in the subcanopy at three blocks of the OHDS (Table 3.2). 16 were in the unthinned patches and had an average initial DBH (five years prior to treatment) of 18.4cm (s.e.= 1.5). The remaining 78 were in the thinned matrix and had an average initial DBH of 17.9cm (s.e.= 0.7). These means were not significantly different (P = 0.7770). By the end of the third year following treatment, subcanopy western redcedar in the unthinned patches had grown on average 1.0cm (s.e.= 0.1) and trees in the thinned matrix had grown 1.8cm (s.e.= 0.1) which was significantly greater (P = 0.0046).

Factors significantly related to the ΔBA_{inc} for western redcedar in the thinned matrix over the three-year period following treatment included measures of local competition and tree vigor. All of the distance-independent measures of local competition within 10meters of the subject tree at the time of treatment were significant in the thinned matrix (Table 3.7): sum of competitor basal area (ΣCompBA), total basal area in competitors larger than the subject tree (BAL), and competitor stand density index (SDI). Additionally, stocking of trees in the stem-mapped plot prior to treatment was significant (TPH_{pre}). None of the distance-dependent measures of competition were significant. BAL had the largest FI value at 22%. All competition measures had significant negative correlations with ΔBA_{inc} ranging from r = - 0.349 for SDI to r = - 0.429 for BAL (Figure 3.7). Tree factors that affected ΔBA_{inc} in the thinned matrix were related to initial size and crown vigor (Table 3.8). Initial DBH and relative age were significantly related to ΔBA_{inc} during the three years following treatment (Figure 3.8). Both variables were positively correlated with ΔBA_{inc} (r= 0.253 and r = 0.307) and with each other (r = 0.558). Measures of crown vigor (i.e. crown area, live crown ratio, and crown condition) were all positively correlated with ΔBA_{inc}. For crown condition (Figure 3.9), a pairwise comparison of least-squared means suggests that a rating of four corresponded to significantly better growth than a rating of one or two and a rating of three corresponds to significantly better growth than a rating of one.

Discussion

Western hemlock

The results of this study indicate that western hemlock retained in the subcanopy after thinning had the ability to respond to the release of resources with increased growth rates in the six years following VDT. Western hemlock is a shade tolerant species that can persist in heavily shaded conditions for long periods of time (Packee, 1990), so it is not surprising to find that western hemlock is able to respond to the thinning. Subcanopy western hemlock did not have increasing growth rates over time in the unthinned patches (Figure 3.10). The increasing growth rate seen in subcanopy trees retained in the thinned matrix of the stand suggests that the thinning produced better growth than would be expected in the absence of thinning.

Although ΔBA_{inc} was not statistically different in thinned and unthinned areas over the first three years, differences in the mean ΔBA_{inc} suggest that the thinned matrix was already starting to respond with increased growth rates. Other studies have found periods of unchanged or reduced growth following harvest in advanced regeneration and retained understory trees (Kneeshaw et al., 2002; Halpern et al., 2005) and young plantation trees (Harrington and Reukema, 1983). Kneeshaw et al. (2002) suggests that this period corresponds to a period of increased root growth in which the trees are reallocating resources while adjusting to new site conditions. Increased growth rates generally followed this reduced growth period. The results of this study indicated that subcanopy trees responded very quickly with increased above-ground growth rates following thinning.

Local conditions and management history may have played a role in the ability of subcanopy western hemlock to quickly respond to the thinning. At Rail, for instance, thinning was not significantly related to ΔBA_{inc} over the six years following treatment. Rail had received a light commercial thinning in 1986 (11 years prior to this study), so it may be that in the five years prior to the VDT, trees at Rail were still benefiting from the previous thinning operation. Additionally, although the difference in ΔBA_{inc} was not significant due to large variation, the mean ΔBA_{inc} in the thinned matrix was greater than the mean ΔBA_{inc} in the unthinned patches (Figure 3.11). Given more time, these differences may become significant.

The release of midstory western hemlock appears to be related to crown vigor factors. The specific measures of crown health that were significantly related to ΔBA_{inc} were crown area, live crown ratio, and crown fullness. These measures (as opposed to measures like crown condition or condition of leader) suggest that any measure of the size of the crown may be a good predictor of growth. However, the timing of data collection (i.e. all crown vigor measures were taken at the end of the study period) makes it difficult to draw firm conclusions from this relationship. It could be that subcanopy trees with larger crowns were better able to take advantage of the new site conditions and grew better after the thinning or it could be that where the thinning provided the right conditions for subcanopy trees to grow well, trees responded by also growing 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. The results of this study support the theory that tree vigor is important to tree growth and health.

Tree vigor should also be affected by the competitive pressure experienced by the tree. Crown overlap appeared to be the only measure of competition that was significantly related to ΔBA_{inc} for subcanopy western hemlock. Crown overlap is a measure of local crowding with similar sized trees, so this result indicates that the growth of western hemlock in the subcanopy was affected by competition with other subcanopy trees and local crowding (similar to results of Canham et al., 2004). Measures of inter-strata competition, like overtopping from canopy trees and BAL, were not significantly related to the ability of subcanopy western hemlock to increase growth after the thinning, but this may just be an indication that the thinning intensity in the matrix was sufficient to reduced competition pressure from overstory trees.

Western redcedar

Similar to western hemlock, the results of this study suggest that western redcedar retained in the midstory after a VDT can respond with increased basal area growth. However, the western redcedar appear to have responded almost immediately (within three years) to the thinning. Harrington and Weirman (1985) similarly found that western redcedar in a thinned treatment had significantly greater radial growth than an unthinned control in the third year following treatment.

The trend in average annual increment in the unthinned patches was increasing over time, so we would expect subcanopy western redcedar at these sites to be increasing their basal area growth over time (Figure 3.12) in the absence of a treatment. Western redcedar is shade tolerant and is known to maintain acceptable growth rates in uneven-aged stands (Minore, 1990), so this result is not unexpected. The trend in the thinned matrix was a steeper increase in growth, indicating that subcanopy western redcedar in the thinned matrix was growing better than those in the unthinned patches.

Initial size was an important factor related to the ability of western redcedar to release. As expected, trees that were larger were able to take better advantage of reduced competition pressure and grew better. There was also a significant relationship between initial size and relative age suggesting that western redcedar had been growing fairly steadily in the subcanopy at these sites (Figure 3.13). In fact, relative age appeared to be a better indicator of ΔBA_{inc} than initial size, as its FI was greater (31% compared to 25% for initial size). Subcanopy western redcedar were generally 10-15 years younger than the canopy trees, indicating that they are of a younger cohort than the canopy trees and not suppressed canopy-aged trees.

Distant–independent measures of local competition (within 10 meters) were consistently related to ΔBA_{inc}. In the thinned matrix, the measures of competition generally had lower means and higher variance than in the unthinned patches, indicating that the “local” competitive environment in the thinned matrix was more variable which correspondingly had an influence on the variability in ΔBA_{inc} (Figure 3.14). Distant-dependent competition indices were never significantly related to ΔBA_{inc}.

Measures of crown vigor were significantly related to ΔBA_{inc}. As with western hemlock, crown size was important, but also a measure of overall crown condition was related to ΔBA_{inc}. Crown condition rating was subjectively based on the condition of the crown to put on height growth. To that end, it seems that the ability to put on height growth may also be related to ΔBA_{inc}.

Conclusions

Overall the treatment appears to be creating spatial heterogeneity in these stands. On average, subcanopy trees in the thinned matrix grew better than those in the unthinned patches. 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 size and age classes of the trees (Spies and Franklin, 1991; Old-growth definition task group, 1986). Managing for heterogeneity in structure makes it necessary to induce variation in individual tree growth within the stand. During the six years following VDT, there appeared to be variation in the growth of subcanopy trees at the OHDS sites. Another study at the OHDS examining the effect of VDT on canopy tree growth (Roberts and Harrington, unpublished) is finding similar results. Canopy trees in the thinned matrix and on edges of skid trails and canopy gaps appear to be growing better than canopy tree 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, 1997). Although developing forest structure is a long-term process, early results support the idea that it can be accelerated through management practices.

In this study, there was considerable variation in the results at different blocks. This variability suggests that results may also vary for 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, the results of this study of subcanopy response to the treatment suggest that variable-density thinning can result in increased growth of subcanopy trees 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). The rating system used in this study is subjective. The scores could be influenced by the knowledge of the data collector and the vantage point from which he or she is viewing the crown. Future studies could look at the ratings used in this study in order to determine how well they correlate with growth under different conditions. Also, the crown vigor measurements could be taken prior to implementing a thinning treatment in order to separate the effect of crown vigor on growth and growth on crown vigor.

The structural diversity in late-successional forests provides critical habitat for many plant and animal species such as the threatened Northern Spotted Owl (*Strix occidentalis caurina* Merriam). As the term generally applied to late-successional forests, "old-growth,' implies, in nature these systems are formed over the course of centuries. In the short term of six years it can be hard to assess the success of relatively new treatments, like VDT for restoring harvested or degraded sites. Early response to the treatment 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 is a good management option for creating variation in growth rates of residual trees.

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Tables

Table 3.1 Site characteristics by block for OHDS sites used in this study.

Block	Age	Primary tree species	Elevation	Annual precipitation[a]	Initial stocking[b]	
			m	*mm*	*Trees* ha^{-1}	$m^2 ha^{-1}$
Rail	51	Douglas-fir, western hemlock	275	1150-2390	788	50
Fresca	51	Western hemlock, Sitka spruce	150	2650	547	71.6
Clavicle	52	Western hemlock, Sitka spruce	475	2100	678	85.6
Bait	39	Douglas-fir, western hemlock	190-335	3180	856	69.2
Triton	67	Western redcedar, western hemlock	400	3050	1151	58.6
Snow White	67	Douglas-fir	430- 580	1450-1950	1592	62.3

[a] 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).
[b] Stocking values based on pre-treatment conditions in stem-mapped plots

Table 3.2 Number (N) of measured subcanopy trees by species, block, and VDT thinning at the OHDS.

Species	Block	Thinned N	Unthinned N
Western hemlock	Rail	8	9
	Fresca	14	1
	Clavicle	3	13
	Bait	23	14
	Triton	10	3
	Snow	54	17
Western redcedar	Clavicle	8	-
	Triton	29	7
	Snow	42	9

Table 3.3 List of distance-dependent competition indices calculated for individual subcanopy trees at the OHDS. The maximum distance was 10m and trees that were less than 10m from the stem-mapped plot border were not used in analyses.

Index	Calculation	Competitor size
Ci1	$\Sigma\ (DBH_{comp}/DBH_{target})/DIST$	all
Ci1a	$\Sigma\ (DBH_{comp}/DBH_{target})/DIST$	larger only
Ci2	$\Sigma\ (DBH_{comp}/DBH_{target})/DIST^2$	all
Ci2a	$\Sigma\ (DBH_{comp}/DBH_{target})/DIST^2$	larger only
Ci3	$\Sigma\ (DBH_{comp}/DBH_{target})^2\ /DIST$	all
Ci3a	$\Sigma\ (DBH_{comp}/DBH_{target})^2\ /DIST$	larger only
Ci4	$\Sigma\ (DBH_{comp}/DBH_{target})/DIST$	smaller only

Table 3.4 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	0.0676	16
1-6 years	156	0.0497 *	19
3-6 years	156	0.0479 *	19

* Significant at α= 0.05

Table 3.5 Sample size, P-value, and fit statistics (FI) for factors significantly related to ΔBA_{inc} over the six years following VDT in the thinned matrix using single factor mixed model analysis for western hemlock.

Factor	**N**	**Factor P-value**	**FI**
			%
Crown overlap	90	0.0035	24
Crown area	99	0.0137	27
Live crown ratio	100	0.0296	27
Crown fullness	100	0.0071	31

Table 3.6 Sample size (N), P-value for treatment effect, and fit statistics (FI) for mixed model analysis of treatment effects on subcanopy western redcedar release.

Time Period following thinning	**N**	**Treatment P-value**	**FI**
			%
1-3 years	94	0.0333 *	25
1-6 years (no Triton)	58	0.0869	20
3-6 years (no Triton)	58	0.1318	13
1-6 years (Snow only)	50	0.0815	8
3-6 years (Snow only)	50	0.1153	6

* Significant at α= 0.05

Table 3.7 Sample size (N), P-value, and fit statistics (FI) for local competition factors that were significantly related to ΔBA_{inc} over the three years following VDT in the thinned matrix and in the unthinned patches using single factor mixed model analysis for western redcedar.

Factor	N	Thinned p-value	FI	N	Unthinned p-value	FI
			%			%
AvgCompDBH	53	0.4211	12	14	0.0414 *	30
ΣCompBA	53	0.0117 *	21	14	0.2400	32
BAL	53	0.0062 *	22	14	0.2418	32
SDI	53	0.0227 *	20	14	0.3111	35
Pre-treatment TPH	78	<0.0001 *	19	16	0.1057	18
Crown overlap	77	0.5844	18	16	0.0453 *	39

* Significant at α= 0.05

Competition measures that include competition with 10m of the target tree at the time of treatment are average competitor DBH (AvgCompDBH), the sum of basal area of all trees (ΣCompBA), 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).

Table 3.8 Sample size (N), P-value, and fit statistics (FI) for tree factors that were significantly related to ΔBA_{inc} over the three years following VDT in the thinned matrix and in the unthinned block using single factor mixed model analysis for western redcedar.

Factor	N	Thinned p-value	FI	N	Unthinned p-value	FI
			%			%
Initial DBH	78	0.0234 *	25	16	0.0632	23
Relative age	78	0.0007 *	31	16	0.0719	34
Total crown area	75	0.0057 *	28	16	0.0245 *	31
Live crown ratio	78	<0.0001 *	35	16	0.1173	17
Crown condition	78	0.0079 *	31	16	0.7451	23

* Significant at α= 0.05

Figures

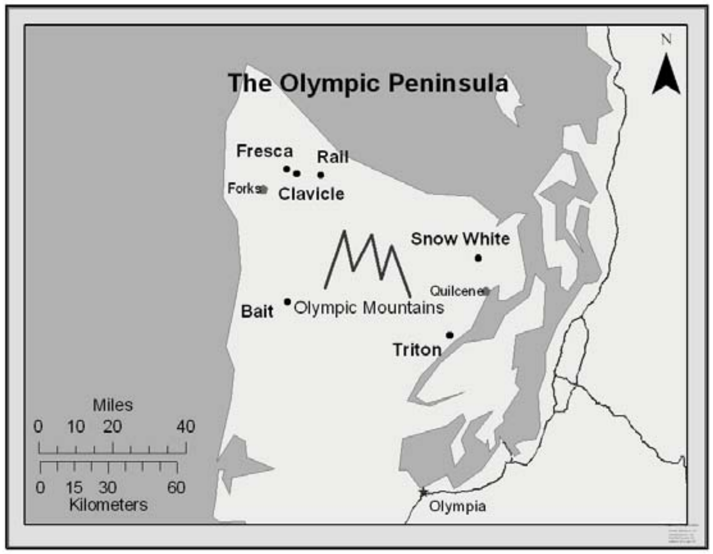

Figure 3.1 Locations of the six OHDS blocks used in this study on the Olympic Peninsula.

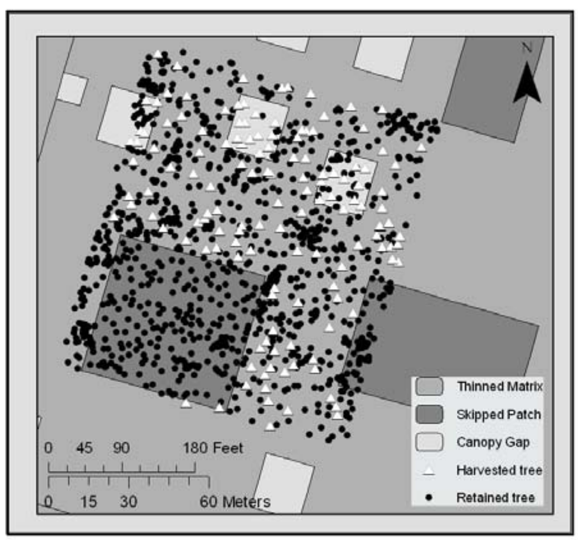

Figure 3.2 An example of a stem-mapped plot (Rail) at the OHDS.

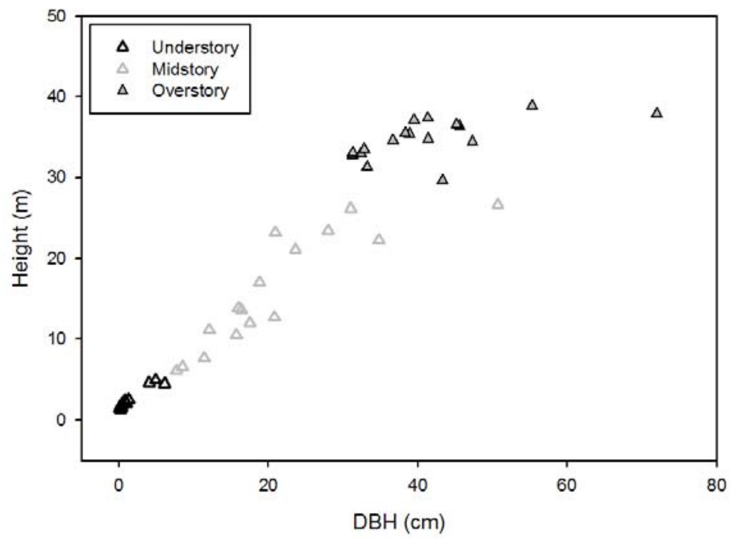

Figure 3.3 Height to diameter relationship for all trees measured for height in 1999 at Snow White and visually estimated height ranges for overstory, midstory, and understory trees.

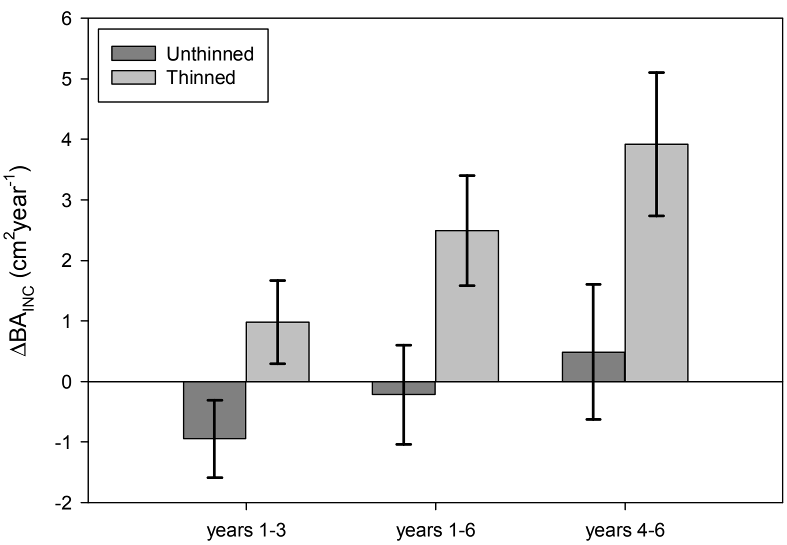

Figure 3.4 Mean change in annual basal area increment and 95% confidence limit interval from the five years prior to treatment to 1-3 years following treatment, 1-6 years following treatment, and 4-6 years following treatment for subcanopy western hemlock in the unthinned patches and thinned matrix.

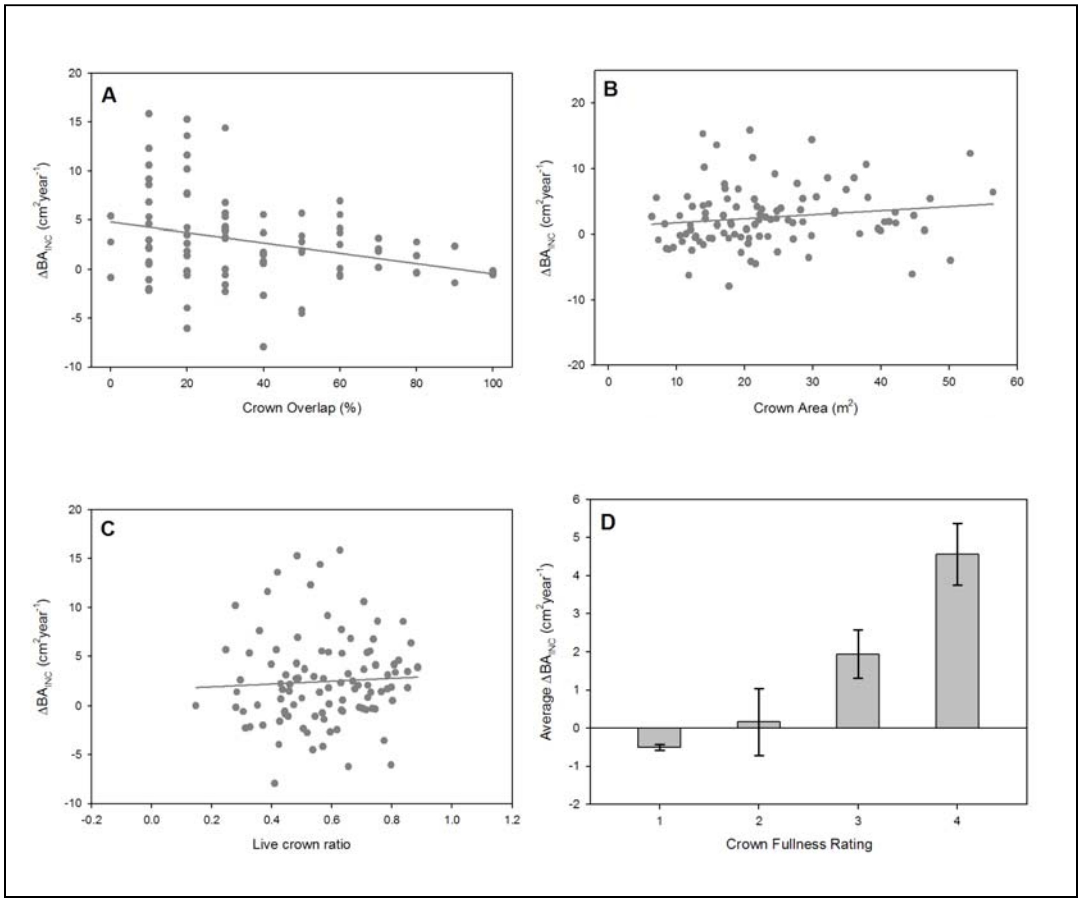

Figure 3.5 Local environment and individual tree characteristics that were significantly related to ΔBA_{inc} for subcanopy western hemlock in the thinned matrix. (A) Crown overlap (%) with neighboring tree crowns (B) Total crown cross-sectional area at widest point (C) Live crown ratio and (D) Crown fullness rating.

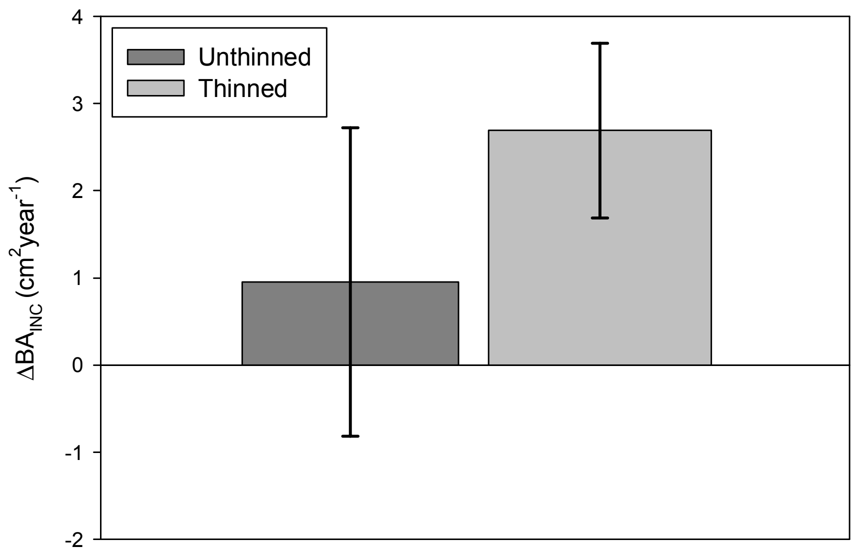

Figure 3.6 Mean change in annual basal area increment from the five years prior to treatment to 1-3 year following treatment and 95% confidence limit intervals for subcanopy western redcedar in the unthinned patches and thinned matrix.

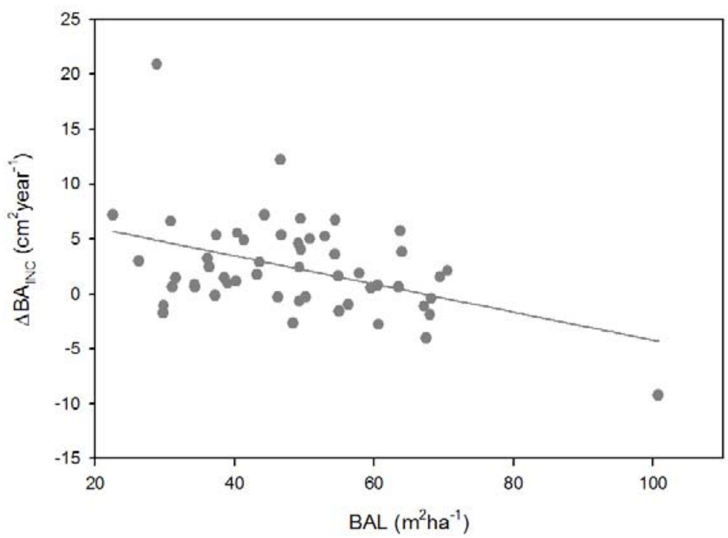

Figure 3.7 Basal area in trees with larger diameters than subject tree (BAL converted to a per hectare value) plotted against ΔBA_{inc} for subcanopy western redcedar in the thinned matrix.

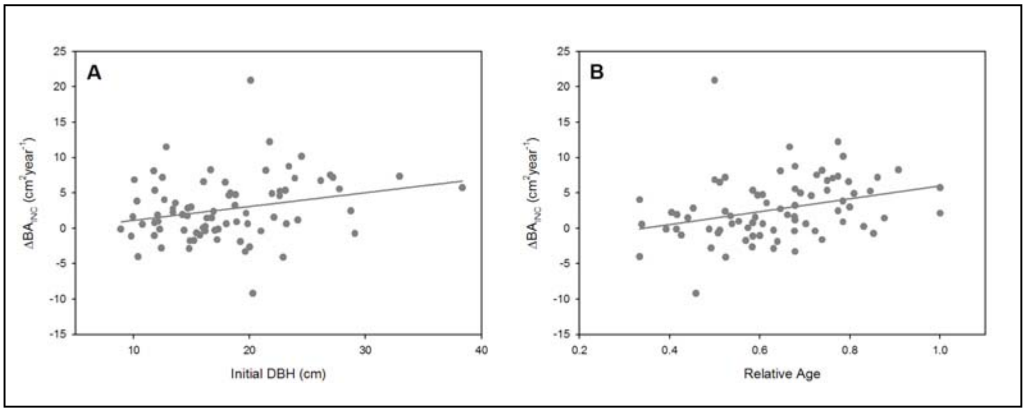

Figure 3.8 (A) Initial DBH (5 years prior to treatment) and (B) relative age (age of tree relative to oldest subcanopy tree in block) plotted against ΔBA_{inc} for subcanopy western redcedar in the thinned matrix.

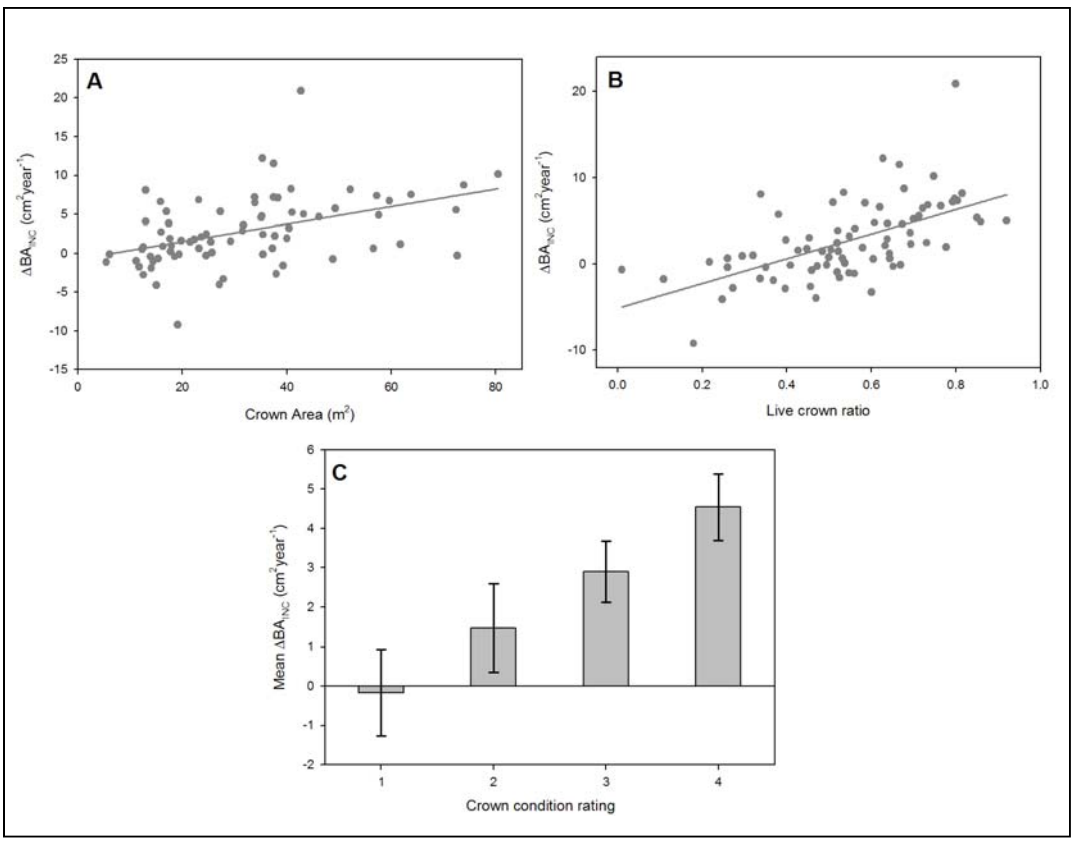

Figure 3.9 Significantly correlated crown vigor characteristics plotted against ΔBA_{inc} for subcanopy western redcedar in the thinned matrix. (A) Total crown cross-sectional area at its widest point (B) Live crown ratio and (C) Crown condition rating: a rating of 4 is the highest vigor category.

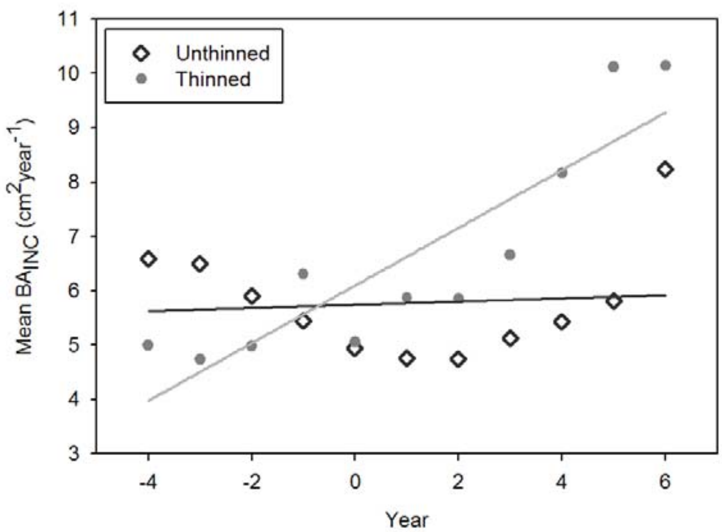

Figure 3.10 Trend in mean annual basal area increment for all subcanopy western hemlock in the unthinned patches and in the thinned matrix prior to and following thinning. Year 0 is the time of VDT.

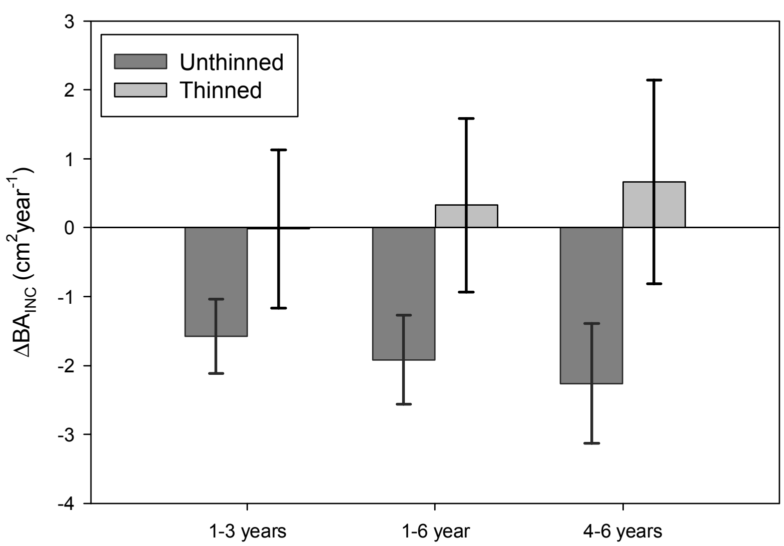

Figure 3.11 Mean ΔBA_{inc} for western hemlock in the unthinned patches and thinned matrix during the 1-3 years, 1-6 years, and 3-6 years following treatment at Rail (103) only.

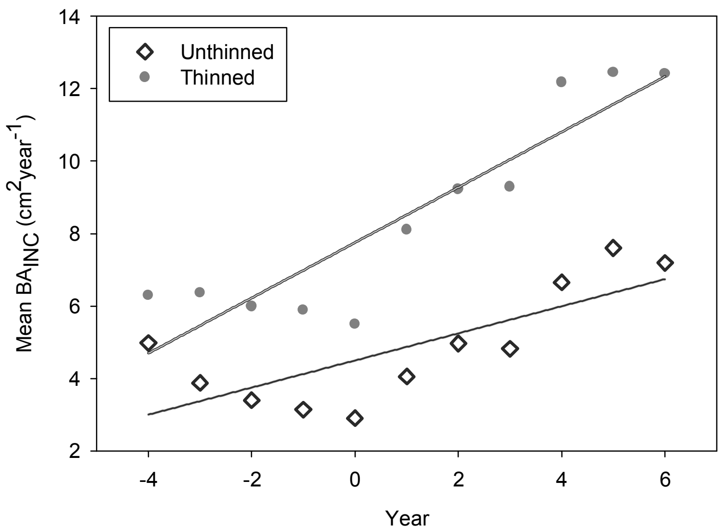

Figure 3.12 Trend in average annual basal area increment in the thinned matrix and in the unthinned patches for western redcedar prior to and following thinning. Year 0 is the treatment year.

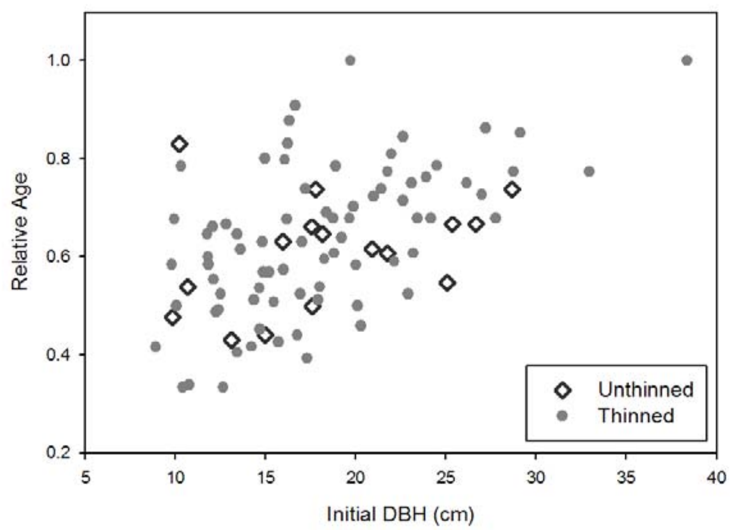

Figure 3.13 Initial DBH (cm) plotted against relative age for subcanopy western redcedar in the unthinned patches and in the thinned matrix.

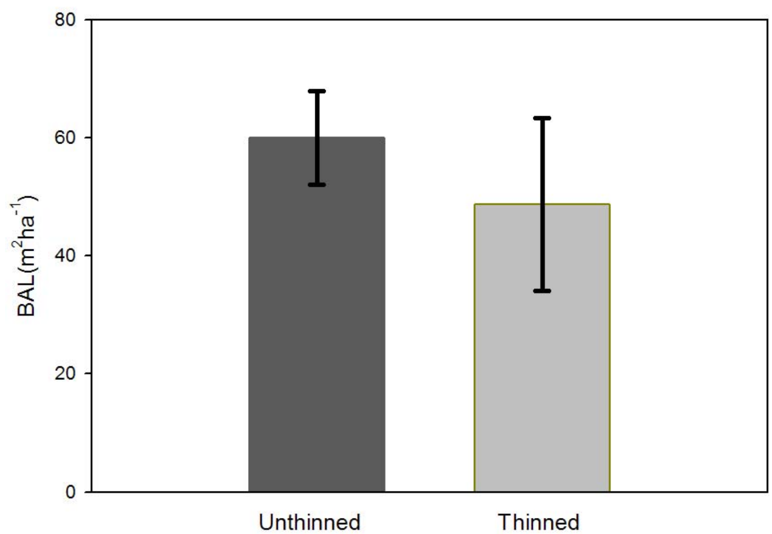

Figure 3.14 Mean basal area of trees with larger diameters within 10m of the target tree (BAL converted to per hectare) for western redcedar in the unthinned patches and in the thinned matrix.

CHAPTER 4

SUMMARY AND CONCLUSIONS

The structural diversity in late-successional forests provides critical habitat for many plant and animal species such as the threatened Northern Spotted Owl (*Strix occidentalis caurina* Merriam). As the term generally applied to late-successional forests, “old-growth,’ implies, in nature these systems are generally formed over the course of centuries. Curtis et al. (1998) express concern that second-growth stands formed under current silvicultural regimes may never develop the same structural characteristics that existed prior to the original harvest due to changes in site conditions, stocking of mature stands, competitive pressures from non-native species, and rising deer and elk populations among other reasons. Alternative management practices will be essential to maintaining old-growth ecosystems and the plants, animals, and industries that rely on them. In the short term it can be hard to assess the success of relatively new treatments like VDT for restoring harvested or degraded sites. Early response of the previously established subcanopy trees and post-thinning cohorts to the treatment can help managers determine if they are on the right track or if other options should be explored.

This study examined the response of two structurally important strata of trees, the subcanopy and the post-thinning regeneration cohorts to different variations of variable-density thinning. Because traditional management practices have been more concerned with crop trees, the response of these strata to thinning are not well known.

Summary of findings for regeneration cohort:

- A larger average number of species was found in the post-VDT cohort in gap thinned subplots than in lightly thinned subplots. However, the regeneration cohort was dominated by Douglas-fir (82%). The average number of live Douglas-fir in the post-VDT cohort was greater in the gap thinning than in the light thinning.
- Initial height (in 2002) was significantly correlated with height growth from 2002 to 2005 for Douglas-fir in the gap thinning, but not in the light thinning.
- Measures of live crown size were important for height growth of post-VDT cohort Douglas-fir in the gap thinning and in the light thinning. Measures of intra-cohort and intra- strata competition were important for height growth of post-VDT cohort Douglas-fir in the gap thinning.
- Density of overstory trees was significantly related to the stocking of smaller regeneration (<1.3m in height).

At the FES, the VDT treatment appears to be achieving the goals of increasing woody plant diversity and spatial heterogeneity as set out in the FES study plan. A variety of species have established in the understory and the different forest blocks and thinning intensities support slightly different assemblages of species. The Douglas-fir in the post-VDT cohort vary in height growth according to treatment and other local conditions, so the VDT is successful in creating spatial heterogeneity in the growth rates of understory trees which may equate to accelerated structural heterogeneity in the stands as they continue to mature. This supports the results from other studies that are looking at alternative management options, such as similar VDT treatments and variable-retention harvests, for accelerating the development of late-successional structure in second-growth forest (Halpern et al., 2005; Reutebuch et al., 2004; Harrington et al., 2005).

Summary of findings for residual subcanopy strata:

- Subcanopy western hemlock and western redcedar in the thinned matrix responded to the thinning with greater increases in basal area growth than trees in unthinned patches.
- Factors that affected the growth response of western hemlock in the thinned matrix included measures of crown vigor and intra-strata competition (crown overlap).

- Factors that affected the growth response of western redcedar in the thinned matrix included measures of initial size, crown vigor, and amount of competition within 10m.

Similar to the findings for the regeneration cohorts, the results of the study of residual subcanopy response to VDT at the OHDS suggest that the treatment can induce variability in the growth of subcanopy trees. Subcanopy trees in the thinned matrix are expected to increase in basal area growth as long as conditions are amenable for the growth of vigorous crowns.

Future studies at both the FES and OHDS could look at the crown vigor categories prior to implementing a thinning treatment in order to separate the effects of crown vigor on growth from the effects of growth on crown vigor for subcanopy trees. Additionally, the future height growth of these trees will be important in determining if the VDT treatment can help create a multilayered canopy. This will determine the longer term sustainability of the treatment.

The OHDS study sites were specifically chosen to represent a range of initial conditions. There was some variation from block to block, but the trend in subcanopy growth response was the same. Although individual site characteristics may affect the time required for significant growth responses to be observed, the treatment would be expected to achieve similar results at other 30- to 70-year old second-growth conifer forests. On the other hand, Fort Lewis was chosen for the FES study because of the similarity in physiographical site conditions over a large intact forest. Blocks could offer replications of treatments while minimizing influences from adjacent untreated areas (Carey et. al., 1999). The droughty conditions at Fort Lewis may not be representative of underlying conditions at typical “old-growth” forests, which are generally found on moist sites (Old growth definition task group, 1986). Harrington et. al. (2005) examined the response of regeneration (greater than 25cm in height) five years following VDT at four of the OHDS sites. They did not find a consistent pattern to the regeneration and suggest that past management history at these stands may be responsible for the large variation.

At both studies, the VDT is creating variation in the growth of different subcanopy strata. The results support the growing body of evidence that VDT is a good management option for creating spatial heterogeneity in composition and growth rates.

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APPENDIX

SUBCANOPY TREE VIGOR AND COMPETITION INDICES

Tree vigor indices

Condition of leader

4: Single, dominant leader. Apparently healthy and in good condition for height growth.

3: Single, dominant leader. Perhaps not original leader, or suffered past damage, but recovered and in good condition for height growth.

2: Single, dominant leader. Not in good condition for height growth, but may recover.

1: No dominant leader, not in good condition for height growth and not likely to recover in the near future.

Crown Condition

4: Conical shape. Apparently healthy and in good condition for height growth.

3: Not quite conical. Some signs of die back or other damage, but recovering and in good condition for height growth.

2: Round shape or flattened top. Suffering from die back or other damage, but likely to recover in the future

1: Flattened top. Suffering from die back or other damage and not likely to recover.

Fullness

For fullness the tree was divided in to four equal sized quadrants. For each quadrant that was 50% or more full (i.e. no missing or dead branches), the tree was given a point.

Stem Condition

Stem condition was evaluated in term of damage that may affect crown vigor.

4: Heathy, straight stem with no visible defects.

1: Stem damage that will likely eventually kill tree.

Lesser damage such as split tops, severe bends, and basal scars with associated rot were given scores of 2 or 3 depending on the severity and recency of the damage and the likelihood of recovery (i.e. more severe or recent damage and less likelihood of recovery were given 3 and less severe, older damage that trees appeared to be recovering from given 2).