AN ABSTRACT OF THE THESIS OF

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Title: Establishment and Growth of Natural and Planted Conifers Ten Years after Overstory Thinning and Vegetation Control in 50-year-old Douglas-fir Stands

Abstract approved:

Michael Newton John D. Bailey

Forest managers of public lands in western Oregon and Washington have become increasingly interested in creating additional conifer cohorts in young, even-aged, second-growth Douglas-fir stands. The purpose of our research was to assess the establishment, survival, and growth of naturally-regenerated and underplanted conifers 10-13 years after overstory thinning and understory vegetation control in 50-year-old Douglas-fir stands. Two sites within the Oregon Coast Range were used in our study. One site was relatively dry (~130 cm of annual precipitation) and contained a mostly pure Douglas-fir overstory. The second site was moister (~175 cm of annual precipitation) and contained a Douglas-fir/western hemlock mixed-species overstory. At each site, stands were thinned to basal areas ranging from approximately 18 to 32 m^2/ha using either a uniform or gappy thinning pattern. In the gappy treatment, 20% of the total area was comprised of 0.06- and 0.10-ha gaps. Understory vegetation was controlled across a portion of each thinning plot using a broadcast application of herbicides prior to thinning. After thinning, the following species were underplanted: Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), and grand fir (*Abies grandis*, dry site only).

Establishment of natural regeneration and survival of underplanted conifers was greater for all species under lower overstory densities at the drier site, but on the moister site, where western hemlock regenerated prolifically in the understory, no differences were detected. At both sites, underplanted and dominant naturally-regenerated conifers growing under lower overstory retention levels were generally taller and had larger diameters after ten years. Thinning pattern had no effect on the establishment, survival, or growth of understory conifers at the overall stand level, but the tallest individuals were located within gaps. Controlling competing vegetation increased the rate of establishment for naturally-regenerated Douglas-fir and the rate of survival for planted Douglas-fir and western hemlock. Vegetation control generally resulted in larger underplanted seedlings of all species after ten years, but the size of dominant naturally-regenerated conifers was not affected. Shade-tolerant species generally outperformed Douglas-fir in understories except where western redcedar suffered heavy browsing damage. Natural regeneration of western hemlock may contribute to the development of an understory conifer layer when a seed source is present in the overstory, but in mostly pure Douglas-fir stands, underplanting would likely be required to supplement sporadic and slow-growing natural regeneration. In either case, future thinnings of rapidly closing overstory canopies would be required to maintain the long-term development of an understory conifer layer.

Establishment and Growth of Natural and Planted Conifers Ten Years after Overstory Thinning and Vegetation Control in 50-year-old Douglas-fir Stands

by

Mark R. Nabel

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Mark R. Nabel, Author

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CONTRIBUTION OF AUTHORS

Dr. Mike Newton assisted with study design, data collection, and draft editing for chapters 1 through 4. Liz Cole also contributed to the study design and data collection, and she reviewed chapter 3.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ANOVA	Analysis of Variance
BA	Basal Area
DBH	Diameter at Breast Height
HSD	Honest Significant Difference
NVC	No Vegetation Control
ODF	Oregon Department of Forestry
RD	Relative Density
RDI	Relative Density Index
SAS	Statistical Analysis System
SDI	Stand Density Index
USDA	United States Department of Agriculture
USDI	United States Department of the Interior
VC	Vegetation Control

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CHAPTER 1: INTRODUCTION

A large portion of late-successional forest in the Oregon Coast Range has been lost or fragmented by fires and intensive, even-aged forest management practices over the past 125 years. While attempts to estimate the historic abundance of late-successional forest (Teensma et al. 1991, Ripple 1994, Wimberly et al. 2000) have been viewed with skepticism by those who cite high levels of variability associated with large, infrequent stand-replacing fires in the region (Newton, personal communication), there is a general consensus that more of the Coast Range was historically comprised of late-successional forest than the 11% that remained at the end of the 20th century (Wimberly et al. 2000). As a result, a shift in management philosophies on some public lands has sparked interest in trying to re-create late-successional characteristics across a portion of the landscape previously managed primarily for commodity-based objectives (USDA and USDI 1994, Oregon Department of Forestry 2001). Because large areas of the Coast Range are currently dominated by relatively young, second-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests, much of the focus has been on how to expedite the development of late-successional characteristics in these relatively dense, homogeneous stands. Currently, few experiments have demonstrated how silviculture may be used to place these stands on a trajectory towards the development of late-successional structure.

Late-successional forests, as defined by the Northwest Forest Plan, include stands in both mature (80-200 years old) and old-growth (>200 years-old) age classes (USDA and USDI 1994). As Douglas-fir forests in western Oregon and Washington approach the old-growth age class, they are typically characterized by large overstory trees, moderate to high canopy closure, a multilayered canopy comprised of multiple species and age classes, and high accumulations of dead standing and downed wood (Spies and Franklin 1991, McComb et al. 1993). These characteristics have been identified in both the Northwest Forest Plan and the Northwest Oregon State Forests Management Plan as critical elements of structural complexity in Oregon Coast Range forests (USDA and USDI 1994, Oregon Department of Forestry 2001). While the Northwest Forest Plan does not provide a quantitative definition of a multilayered stand, the Oregon Department of Forestry (ODF, 2001) describes a “layered” stand as one in which overstory trees 45 cm or larger in diameter at breast height (DBH) and >100 feet tall are predominant in the overstory with at least 30 percent of the stand comprised of layered patches. Patches are defined as layered “when at least 60 percent of the vertical space from the top of the main tree canopy to the forest floor is filled with layered tree crowns, branches with foliage, and a significant amount of shrubs.” The ODF definition also states that understory trees in “layered” stands should be at least 9.1 m tall. The development of a multilayered canopy consisting of multiple species and age classes in dense, young, even-aged Douglas-fir stands first requires thinning of the overstory stand.

Overstory thinning to levels below those typically used for timber production has been hypothesized and even proposed as one approach to increase vertical stratification in young, even-aged stands (USDA and USDI 1994, Hayes et al. 1997, Tappeiner et al. 1997, Bailey and Tappiner 1998, Oregon Department of Forestry 2001). One way thinning increases vertical stratification is by promoting the creation of deeper crowns on retained overstory trees (Marshall et al. 1992, Barbour et al. 1997). Thinning to lower overstory densities also provides potential for vertical stratification by increasing the percentage of available sunlight reaching the forest floor (Drever and Lertman 2003, Chan et al. 2006), thus improving conditions for the establishment and growth of understory trees.

Several recent studies have already demonstrated some potential for promoting the establishment and growth of understory trees through overstory thinning (Chan et al. 2006, Maas-Hebner et al. 2005, Harrington 2006, Brandeis et al. 2001, Bailey and Tappeiner 1998, Miller and Emmingham 2001). In studies looking specifically at natural regeneration, Bailey and Tappeiner (1998) and Chan et al. (2006) reported higher densities of naturally-regenerated seedlings in thinned stands versus unthinned stands, and Bailey and Tappeiner (1998) also noted an inverse relationship between seedling densities and overstory relative density index. Miller and Emmingham (2001) reported higher densities and better growth for naturally-regenerated Douglas-fir under stands thinned more frequently and to lower stocking levels, but the authors did not note similar differences for other conifer species. In general, natural regeneration included a higher percentage of shade-tolerant species than was present in the overstory (Miller and Emmingham 2001, Chan et al. 2006), especially under higher overstory densities, and western hemlock displayed slightly better growth than Douglas-fir (Bailey and Tappeiner 1998, Chan et al. 2006).

In studies where conifers were underplanted, Chan et al. (2006) and Maas-Hebner et al. (2005) reported higher survival of underplanted conifers in thinned stands versus unthinned stands, and Chan et al. (2006) and Brandeis et al. (2001) noted an inverse relationship between seedling survival and overstory density. Chan et al. (2006), Brandeis et al. (2001), and Harrington (2006) all reported a negative correlation between overstory density and the growth of underplanted conifers. Shade-tolerant western hemlock seedlings generally outperformed Douglas-fir seedlings under all levels of overstory retention (Maas-Hebner et al. 2005, Chan et al. 2006, Harrington 2006; however, Brandeis et al. (2001) noted poor survival (<50%) for both of these species, possibly due in part to marginal planting conditions. Results for western redcedar and grand fir were mixed. Maas-Hebner et al. (2005) and Harrington (2006) reported poor performance for western redcedar seedlings due to severe browsing; however, in a study where browsing was limited, Brandeis et al. (2001) noted high survival of planted western redcedar (70-95%) relative to other planted species, and growth comparable to other shade tolerants. Ketchum (1995), Brandeis et al. (2001), and Maas-Hebner et al. (2005) reported relatively high survival for grand fir, especially under lower overstory densities (< 25 m^2/ha basal area), but Maas-Hebner et al. (2005) found signs of chlorotic foliage on most individuals eight years after planting. Growth of grand fir was generally comparable to (Maas-Hebner et al. 2005) or slightly better than (Brandeis et al. 2001) Douglas-fir.

Most studies evaluating the influence of overstory thinning on the development of understory conifers have utilized relatively uniform spacing during the implementation of thinning treatments. However, thinning that entails variable spacing with the inclusion of gaps has been suggested as a means of promoting a more heterogeneous understory (Tappeiner and Zasada 1993, Thysell and Carey 2000, Davis et al. 2007), in terms of biological and structural diversity, due to the uneven distribution of light (Franklin and Van Pelt 2004). While few studies have evaluated the effects of gap creation on the development of understory conifers in young Douglas-fir stands (< 80 years old) (see Brandeis et al. 2001), studies in older stands have generally indicated higher seedling establishment and greater growth in canopy gaps than under closed canopy forest (Spies et al. 1990, Gray and Spies 1996, Van Pelt and Franklin 1999). In a study looking at gaps created in younger Douglas-fir stands, Brandeis et al. (2001) noted higher survival of planted seedlings in canopy gaps than under the surrounding thinned forest matrix. However, these authors also noted high rates of overtopping by rapidly-growing shrubs and in some cases hardwoods under higher light environments often associated with gaps.

In addition to overstory thinning, controlling competing understory vegetation has the potential to improve tree seedling establishment, survival, and growth in an understory environment. Growth and survival of planted seedlings in clearcuts have been shown to increase dramatically following vegetation control (Newton and Preest 1988, Roth and Newton 1996, Stein 1997, Wagner et al. 1999, Rose and Ketchum 2002, Rose et al. 2006). Although few studies have examined responses of natural tree regeneration to vegetation control in the Pacific Northwest, studies from other regions have demonstrated improvements in the establishment and growth of natural regeneration following vegetation control as well (Cain 1991, Zackrisson et al. 1997, Lorimer et al. 1994, Caccia and Ballare 1998, Lof et al. 1998). While the response of understory vegetation to overstory thinning differs somewhat from the response following complete overstory removal, many studies have shown rapid increases in the cover and growth of shrubs and other herbaceous vegetation following thinning (Tappeiner and Zasada 1993, Huffman et al. 1994, Bailey and Tappeiner 1998, Bailey et al. 1998, Thysell and Carey 2001, Chan et al. 2006). Many of these species sprout vigorously and compete intensely with understory conifers for belowground resources and have the potential to overtop newly established seedlings (Bailey and Tappeiner 1998, Brandeis et al. 2001, Thysell and Carey 2001). In a limited number of studies evaluating the early effects of vegetation control in thinned stands (Brandeis et al. 2001, Harrington 2006), marked improvements in the growth and occasionally in the survival of planted conifers were observed when competing vegetation was removed. Growth responses in the first years following vegetation control were generally greater under lower overstory densities (Brandeis et al. 2001), especially for Douglas-fir (also Harrington 2006).

While many of the aforementioned studies provide valuable insight into the potential for growing conifers in an understory environment and more specifically under thinned stands comprised of a young, even-aged overstory dominated by Douglas-fir, several questions remain only partially answered. First, many of these studies assessed only the development of *underplanted* conifers (Brandeis et al. 2001, Maas-Hebner et al. 2005, Harrington 2006), without evaluating natural regeneration. Second, those studies that did evaluate natural regeneration (Chan et al. 2006, Bailey and Tappeiner 1998, Miller and Emmingham 2001) occurred on sites with relatively few shade-tolerant conifers (western hemlock, western redcedar, grand fir) in the overstory to provide a substantive seed source for natural regeneration of these species. Third, with the exception of Brandeis et al. (2001), whose study provided early (fourth-year) results on the survival and growth of underplanted conifers from the same long-term experiment used in our study, no known studies have directly compared the establishment, survival, and growth of understory conifers between uniformly thinned stands and stands thinned to similar overall overstory retention levels but with the creation of small gaps. Finally, the role of vegetation control has been explored in very few studies assessing understory conifer development in thinned stands (Miller and Emmingham 2001, Harrington 2006), especially with regard to effects on natural regeneration.

The purpose of our study is to provide further understanding regarding the effects of overstory retention level, overstory tree distribution, and understory vegetation control on the establishment, survival, and growth of naturally-regenerated and underplanted conifers in thinned Douglas-fir stands within the Coast Range of western Oregon. One of the two sites used in our study contains a significant component of western hemlock in the overstory. In chapter two, we examine the density, frequency of occurrence, and size class distribution of naturally-regenerated conifer seedlings 10-13 years after thinning and understory vegetation control. We also compare the establishment of natural regeneration to the survival of underplanted conifers to evaluate the feasibility of relying on natural regeneration alone to provide for the eventual development of a multilayered canopy.

In chapter three, we examine the size, current growth rate, and vigor of underplanted seedlings and dominant naturally-regenerated seedlings ten years after thinning and vegetation control to determine how these factors influence the development of an understory conifer layer. We also evaluate which species are most suited for growth under thinned stands, what sort of damaging agents are limiting growth, and what the longer-term prospects are for continued growth towards the development of a midstory conifer layer. For the species of natural regeneration that occurred on each site, general comparisons are made between the size and growth of planted seedlings and similarly aged dominant naturally-regenerated seedlings to determine whether one regeneration approach has a clear advantage over the other in terms of the expeditious development of a multilayered canopy.

This study is part of a larger long-term research project designed to evaluate the extent to which management can promote the development of late-successional characteristics such as large trees, a multilayered canopy, and a diverse understory in young, relatively homogeneous even-aged stands. Our results focus strictly on the contribution of understory conifers towards the development of an initial understory conifer layer, the first step towards the eventual creation of a multilayered canopy. We acknowledge that the creation of a multilayered canopy may require further management of both the overstory and the understory (McComb et al. 1993). Although the performance of both natural and planted conifers are discussed, the emphasis of this thesis is on natural regeneration.

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CHAPTER 2: ESTABLISHMENT OF NATURALLY-REGENERATED CONIFERS 10-13 YEARS AFTER OVERSTORY THINNING AND UNDERSTORY VEGETATION CONTROL IN 50-YEAR-OLD DOUGLAS-FIR STANDS

INTRODUCTION

Forest managers in the Pacific Northwest, especially in the public sector, have expressed a growing interest in managing for late-successional characteristics in addition to maintaining a sustainable supply of timber (USDA and USDI 1994, Oregon Department of Forestry 2001). Many of the areas targeted for this type of management within the Coast Range of western Oregon are comprised of young, dense, even-aged stands, dominated by Douglas-fir. Although the Northwest Forest Plan and the Northwest Oregon State Forests Management Plan provide a general direction for management on public lands within the Coast Range, in developing these plans, managers did not have the benefit of documentation of long-term research describing how silvicultural strategies provide long-term sequences of habitat development. Our study, along with many related studies, is a first step in providing insights associated with intensive management toward structural and habitat goals in second-growth Douglas-fir forest.

The creation of a multilayered canopy is a key element in the development of late-successional forest structure (Spies and Franklin 1991, McComb et al. 1993). While exact definitions of "multilayered" differ, the Oregon Department of Forestry (ODF) definition of "layered" includes the development of patches across at least 30% of the stand where understory trees are >9.1 m tall and where at least 60 percent of the vertical space between ground level and the tops of the tallest trees is occupied by living foliage (Oregon Department of Forestry 2001, see chapter one for a more detailed definition). In existing second-growth Douglas-fir stands, the creation of a multilayered canopy first, requires successful tree establishment, growth, and continued survival in an understory environment.

Researchers have recently initiated several studies in the Douglas-fir region of western Oregon and Washington to evaluate the survival and growth of underplanted conifers in young, even-aged stands (Brandeis et al. 2001, Maas-Hebner et al. 2005, Chan et al. 2006, Harrington 2006). Results from these studies generally support a need for overstory thinning prior to underplanting to increase the survival of underplanted seedlings (Maas-Hebner et al. 2005, Chan et al. 2006). Survival of underplanted seedlings has also been related to residual overstory density, with greater survival of Douglas-fir reported under lower overstory densities (Brandeis et al. 2001, Chan et al. 2006). On a drier site on the eastern edge of the Coast Range, Brandeis et al. (2001) also noted an inverse relationship between overstory densities and survival rates for western hemlock, western redcedar, and grand fir.

While the aforementioned studies examined the effects of overstory thinning on the survival of underplanted conifers, only one of these studies (Chan et al. 2006) also attempted to characterize the establishment of natural regeneration for comparison to underplanted seedlings. Planting has several advantages over relying on natural regeneration including the ability to control density, distribution, and species composition. Several studies have also documented early growth benefits associated with planting (Ackzell 1993, Holgén and Hånell 2000, Clason 2002, Jennings et al. 2005, Shepperd et al. 2006). However, the potential for low survival of planted seedlings in an understory environment (Dunlap and Helms 1983, Chen 1997, Mailly and Kimmins 1997, Brandeis et al. 2001, Chan et al. 2006) could in some cases reduce or negate the benefits normally derived from planting. In these cases, relying on natural regeneration could be a more cost-effective alternative.

Studies that have assessed the establishment of naturally-regenerated conifers under thinned stands have generally found higher seedling densities and frequencies (# of plots containing at least one seedling) in thinned stands versus unthinned stands (Bailey and Tappeiner 1998, Chan et al. 2006). Researchers have also reported generally higher densities of naturally-regenerated conifers in stands thinned to lower levels of overstory retention (Bailey and Tappeiner 1998, Jerra and Vogt 1998, Miller and Emmingham 2001). The distribution of natural regeneration under thinned stands is typically variable, but contrary to reports in clearcuts, establishment does not appear to be strictly limited to exposed mineral soil (Williamson and Ruth 1976, Bailey and Tappeiner 1998, Miller and Emmingham 2001). Germination on litter and other organic substrates under partial overstories (especially for small-seeded species like western hemlock) is made possible by the abundance of surface soil moisture and moderate surface temperatures (Gray and Spies 1997).

While studies evaluating natural regeneration under thinned stands seem to adequately describe seedling establishment under various levels of overstory retention, most of these studies occurred on sites with predominantly single-species overstories. Not surprisingly, with the exception of a few sites reported in Bailey and Tappeiner (1998), most naturally-regenerated seedlings were of the same species that dominated the overstory. Very little research has been conducted on sites where a dominant Douglas-fir overstory also contained a significant component of western hemlock, a common condition in western portions of the Coast Range. In this situation, differences in seed rain, germination requirements, tolerance ratings, and growth rates between these two species provide the potential for different patterns to occur within the development of the understory conifer layer relative to those under a single species overstory.

Furthermore, very few studies have explored the role of competing shrubs on understory conifer establishment and development under different levels of overstory cover. While Brandeis et al. (2001) and Harrington (2006) evaluated the survival of underplanted conifers in the presence and absence of vegetation control, natural regeneration was not considered in these papers. A preliminary investigation of natural regeneration on one of the sites used in our study showed higher conifer seedling densites four years after thinning accompanied by understory vegetation control (Jerra and Vogt 1998).

The purpose of our research is to evaluate natural regeneration in a previously established controlled experiment designed specifically to evaluate ways of enhancing undestory conifers. This paper describes the establishment and early development of naturally-regenerated conifers 10-13 years after manipulating levels of overstory density, overstory tree distribution, and understory vegetation. In this experiment, these three factors were controlled using a combination of thinning and vegetation control in stands 50-55 years old.

The four objectives for this study were (i) to evaluate the progression of overstory and understory cover during the 10 years following thinning and vegetation control to help characterize effects on naturally-regenerated conifers, (ii) to determine how overstory density, overstory tree distribution, and competition from understory vegetation affect the density, frequency, and height class distribution of naturally-regenerated conifers 10-13 years after management to control these factors occurred, (iii) to compare the composition and development of natural regeneration under a Douglas-fir-dominated overstory to the composition and development of natural regeneration under a Douglas-fir/western hemlock mixed-species overstory, and (iv) to compare the establishment of naturally-regenerated conifers to the survival of underplanted conifers in an effort to determine whether natural regeneration alone can provide for the development of an understory canopy layer.

METHODS

Study site description

The study area includes two sites located within the Coast Range of western Oregon (Table 2.1). The first site, McDonald, established in 1993, and the second site, Blodgett, established in 1995, are part of a long-term study originally designed primarily to examine the relationship between overstory density management, understory planting, and the long-term development of stand structure. These sites were selected because they fall within 50-55 year-old even-aged stands managed by Oregon State University's College of Forestry, they had a history of thinning, and because they fall at relatively different points along the spectrum of the Oregon Coast Range in terms of moisture regime, site productivity, and overstory composition.

The McDonald site is located on eastern flanks of the Coat Range, eight kilometers north of Corvallis. At the time of thinning, stands were dominated by 50-year-old Douglas-fir with scattered bigleaf maple (*Acer macrophyllum* Pursh), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), Pacific madrone (*Arbutus menziesii* Pursh), and bitter cherry (*Prunus emarginata* (Dougl. ex Hook) D. Dietr.) intermixed. Prior to thinning, basal areas ranged from 26.7-45.1 m^2/ha, averaging 33.9 m^2/ha. Fully stocked Douglas-fir stands at this site, mostly classified as Site II and III, would have 48.0-49.0 m^2/ha at age 50 (McArdle et al. 1961). Prior to thinning, understory vegetation was generally well-developed and consisted of western sword fern (*Polystichum munitum* (Kaulfuss) K. Presl.), western bracken fern (*Pteridium aquilinum* (L.) Kuhn), trailing blackberry (*Rubus ursinus* Cham.& Schldl.), Pacific poison oak (*Toxicodendron diversilobum* Torr. & Gray) Greene)), hazel (*Corylus cornuta* Marsh.), and ocean spray (*Holodiscus discolor* (Pursh) Maxim.), with a variety of other species intermixed (Brandeis et al. 2001). The climate at McDonald is described as Mediterranean with average annual temperatures ranging from 9.4 and 12.2° C (Knezevich 1975), a frost-free period between 165 and 200 days (Knezevich 1975), and only roughly 10 percent of annual precipitation occurring between June and September (Taylor and Hannan 1999).

The Blodgett site is located in the northern Oregon Coast Range, ten kilometers west of Clatskanie and five kilometers south of the Columbia River. Stands were dominated by a mixture of 50-55 year-old Douglas-fir and western hemlock at the time of thinning, with a small amount of red alder (*Alnus rubra* (Bong.)) and western redcedar (*Thuja plicata* Donn ex D. Don) intermixed. Pre-thinning basal areas ranged from 31.4-55.8 m^2/ha, averaging 42.9 m^2/ha. The majority of the study area is classified as Site II with portions of Site I intermixed. At this age and level of site productivity, stands are considered fully stocked at 48.0-51.4 m^2/ha (McArdle et al. 1961) for Douglas-fir and 66.6 to 67.5 m^2/ha (Barnes 1962) for western hemlock. Some advanced regeneration of western hemlock was present at the time of study inception, but seedlings were generally small (<50 cm tall) and patchily distributed. Other understory vegetation included western sword fern, salal (*Gaultheria shallon* Pursh), Oregon grape (*Berberis nervosa* Pursh), vine maple (*Acer circinatum* Pursh), western bracken fern, salmonberry (*Rubus spectabilis* Pursh), deer fern (*Blechnum spicant* (L.) Roth), and red huckleberry (*Vaccinium parvifolium* Smith), with several other species present in lesser amounts. The climate at Blodgett is described as temperate with average annual temperatures ranging from 7.2 and 11.1° C (Smythe 1986) and a frost-free period between 140 and 180 days (Smythe 1986), with occasional occurrence of severe frost events in late spring and early fall. Although only roughly 12 percent of annual precipitation occurs between the months of June and September (Taylor and Hannan 1999), this seems to be sufficient to prolong the growing season into late summer.

Experimental design and treatments

The study was laid out using a randomized complete block, split-split plot design and included three 15-ha (Blodgett) or 20-ha (McDonald) blocks at each site, each representing a full replicate (Figure 2.1*a*). At McDonald, the blocking factor was slope position, with soil depth and site quality increasing on lower slopes. The blocking factor at Blodgett was the level of hemlock present in the overstory, which varied from 15.8 to 55.1% of total basal area after thinning. Each block included two 7.5-ha (Blodgett) or 10.0-ha (McDonald) units (Figure 2.1*b*), and each unit was randomly assigned to either a uniform or “gappy” thinning pattern. In the uniform thinning, residual trees were relatively evenly spaced throughout the unit. The gappy thinning incorporated relatively even spacing with the creation of nine (Blodgett) or twelve (McDonald) 0.1-ha and 0.06-ha gaps per unit, comprising about 20% of the total area. Gap sizes correspond to gap diameter to tree height ratios of 0.99 and 0.77, respectively, at McDonald, and 0.86 and 0.67, respectively, at Blodgett.

Each unit contained three (Blodgett) or four (McDonald) 2.5-ha plots (Figure 2.1*b*), and each plot was randomly assigned to be thinned to one of three (Blodgett) or four (McDonald) overstory retention levels. The thinning was designed so that total basal area was the same in gappy and uniform plots, meaning that the matrix of gappy plots was roughly 25% denser than uniform plots. Plots were thinned in 1993 at McDonald and in 1995 at Blodgett using a combination of cable- and ground-skidding equipment. The average basal area associated with each retention level differed slightly between sites to account for the higher productivity and greater potential for windthrow at Blodgett. At McDonald, the low, medium, high, and very high overstory retention level plots were thinned to 16.7-18.8, 19.3-25.1, 26.9-29.6, and 27.7-32.9 m^2/ha, respectively. These retention levels represent average relative densities (RD) of 2.6, 3.3, 4.0, and 4.6, respectively (see Curtis 1982), and a relative density index (RDI) of 0.18, 0.23, 0.27, and 0.31 (see Reineke 1933). In 2001, when it became apparent that the continued growth and vigor of understory conifers was in jeopardy, medium and high retention plots were re-thinned to original target densities. At Blodgett, the low, medium, and high retention levels averaged 18.6-21.1, 24.5-28.2, and 30.8-33.5 m^2/ha of basal area, respectively, which correspond to average RD's of 3.0, 3.9, and 4.9 and RDI's of 0.17, 0.23, and 0.27, respectively. The comparatively lower RDI's relative to RD's at Blodgett reflect the substantial component of western hemlock in the overstory. While RD's were calculated the same regardless of species mix, the SDI_{max} used to calculate RDI was weighted proportionally by species as described in Shaw (2006). An SDI_{max} of 598 was used for Douglas-fir while 850 was used for western hemlock (Tappeiner et al. 2007). None of the plots at Blodgett were re-thinned through year 10.

Each plot was further subdivided into two 0.75-ha (Blodgett) or three 0.50-ha (McDonald) subplots plus an 18-meter buffer, which was thinned to the same configuration as the subplots (Figure 2.1*b*). Different understory vegetation control treatments were randomly assigned to each subplot. Treatments applied at both sites included (i) a control where no vegetation was controlled beyond the effects of harvesting and (ii) a broadcast herbicide application aimed at substantially reducing the leaf area of perennial shrubs and forbs. A third vegetation treatment applied at McDonald involved spot spraying of glyphosate (2% aqueous solution) or triclopyr ester (1.5%), depending on cover species, within a one-meter radius of planted seedlings. However, due to its limited effectiveness and because this "release" treatment was not repeated at Blodgett, "released" subplots were not used for this study.

The mixture of herbicides used for the vegetation control treatment varied across the two sites to account for the presence of different vegetation. At McDonald, understory vegetation was controlled prior to thinning in late summer 1993 with a broadcast application of glyphosate (1.68 kg a.e./ha) and imazapyr (0.14 kg a.e./ha) (Brandeis et al 2001). At Blodgett, sprayed subplots were treated with a broadcast application of glyphosate (1.68 kg of acid equivalent (a.e.) per ha), imazapyr (0.21 kg of active ingredient (a.i.) per ha), and sulfometuron (0.16 kg a.i./ha) prior to thinning. Herbicide applications were made in August 1995 using backpack sprayers and the "waving wand" technique described in Newton et al. (1998). Due to weather constraints, logs could not be removed in some areas until fall 1996. To ensure a full year of vegetation control following disturbance, sprayed subplots received an additional application of sulfometuron (0.16 kg a.i./ha) and either 2,4-D (1.22 kg a.i./ha) or triclopyr ester (2.24 kg a.i./ha) in October 1996 after logging operations were completed.

Subplots at each site were underplanted with conifer seedlings during the winter following the application of vegetation control and thinning treatments to provide a means of comparing the establishment of natural regeneration to the survival of planted conifers. At McDonald, subplots were planted in late winter 1994 with double rows of bare root 1+1 Douglas-fir and grand fir, plug+1 western hemlock, and plug+2 western redcedar, at a 3 x 3-meter spacing. Subplots at Blodgett were planted in February 1997 with double rows of plug+1 Douglas-fir, western hemlock, and western redcedar at a 3 x 4-meter spacing. Grand fir was not planted at Blodgett because this portion of the Coast Range is outside of the natural range for this species.

Measurements

Overstory, shrub and understory conifer cover

Ocular estimates of overstory cover, understory shrub cover, and understory conifer cover were made from ten (McDonald) or 15 (Blodgett) sample points per subplot to determine how cover changed following the application of thinning and vegetation control treatments and continued to respond during the following ten years. Estimates were taken from an imaginary five-meter radius cylinder projected vertically from each sample point. Any vegetation greater than five meters above the ground was considered to be overstory cover while shrub cover estimates included woody perennials and ferns occurring up to five meters above ground level. Understory conifer cover estimates included only naturally-regenerated conifers, and individuals were only included in estimates if the fullest portion of their crown occurred at or below five meters above ground level. Cover estimates were made one, three, five, seven, and ten years post-thinning.

Evaluation of natural conifer establishment

Counts of naturally-regenerated conifer seedlings were made to evaluate the rate of understory conifer establishment. Individuals greater than 30 cm tall were tallied by one-meter height classes within a fixed distance of previously established, systematically placed sample points within each subplot. Although many understory trees in this study were greater than 1.37 meters tall and thus considered saplings, to improve readability, all understory trees in this paper will be referred to as seedlings. At McDonald, ten sample points were originally placed within each subplot during the installation of the study, but only five points were used during seedling tallies. The selection of either even- or odd-numbered points was done randomly for each subplot. At Blodgett, the same procedure was used to select seven or eight of fifteen systematically placed sample points. At McDonald, seedling tallies were conducted for all species within a five-meter radius of each sample point. At Blodgett, where establishment rates were higher, tallies for Douglas-fir and other conifers were conducted within a three-meter radius of each sample point, while tallies for western hemlock were limited to a 1.5-meter radius. Sampling was conducted in fall 2006, 13 years after thinning at McDonald and 10 years after thinning at Blodgett. While conducting seedling tallies, no attempt was made to differentiate between seedlings that established shortly before or after the time of thinning. However, individuals that were clearly greater than 20 years old (based on visual observations of branch whorls and bud scars) were excluded from the tally.

Evaluation of underplanted conifer survival

Ten growing seasons after planting (fall 2003 at McDonald and fall 2006 at Blodgett), planted conifers from four randomly selected seedling grids within each subplot were evaluated for survival. Each grid contained six (McDonald) or ten (Blodgett) seedlings of each species minus losses to mortality meaning 1,152 seedlings (McDonald) or 1,440 seedlings (Blodgett) of each species were evaluated for survival across each study site.

Statistical analysis

Analysis of variance (ANOVA) was used to evaluate the effects of thinning pattern, overstory retention level, and vegetation control on the density and frequency of occurrence (% of sample points with one or more individuals) of natural seedlings and on the survival of planted seedlings within each subplot. We used PROC MIXED in SAS 9.1 (SAS Institute Inc. 2004) to fit the following three-way ANOVA model to the data for each species:

$$Y_{ijkl} = \mu + \beta_i + p_j + o_k + v_l + (po)_{jk} + (pv)_{il} + (ov)_{kl} + (pov)_{jkl} + \psi_{ij} + \lambda_{ijk} + \varepsilon_{ijkl}$$

where μ is the overall mean of Y,

β_i is the random effect of the ith block on the variation of Y; ($\beta_i \sim N(0,\sigma^2_b)$ and $Cov(\beta_i, \beta_{i'}) = 0$),

p_j is the fixed effect of the jth thinning pattern (j = even or gappy),

o_k is the fixed effect of the kth level of overstory retention (k = low, medium, or high),

v_l is the fixed effect of the lth level of vegetation control (l = no vegetation control or total vegetation control),

$(po)_{jk}$ is the fixed effect of the interaction between thinning pattern *j* and overstory retention level *k,*

$(pv)_{jl}$ is the fixed effect of the interaction between thinning pattern *j* and vegetation control level *l,*

$(ov)_{kl}$ is the fixed effect of the interaction between overstory retention level *k* and vegetation control level *l,*

$(pov)_{jkl}$ is the fixed effect of the interaction between thinning pattern *j*, overstory retention level *k,* and vegetation control level *l,*

ψ_{ij} is the random effect of the units on the variability of Y; ($\psi_{ij} \sim N(0,\sigma^2_\psi)$ and $Cov(\psi_{ij}, \psi_{i'j'}) = 0$),

λ_{ijk} is the random effect of the plots on the variability of Y; ($\lambda_{ijk} \sim N(0,\sigma^2_\lambda)$ and $Cov(\lambda_{ijk}, \lambda_{i'j'k'}) = 0$),

ε_{ijkl} is the random effect of the subplots on the variability of Y; ($\varepsilon_{ijkl} \sim N(0,\sigma^2)$ and $Cov(\varepsilon_{ijkl}, \varepsilon_{i'j'k'l'}) = 0$),

and all random effects are independent.

Several data transformations were necessary to correct issues with non-constant variance (Sabin and Stafford 1990), which were detected using PROC UNIVARIATE and GPLOT in SAS 9.1 (SAS Institute Inc. 2004). Variance in seedling density data at Blodgett tended to increase around larger expected values, requiring a square root transformation. Seedling density data at McDonald included numerous low values leading to non-constant variance that could not be corrected with a log or square root transformation. As a result, for Douglas-fir establishment data at McDonald, subplot averages were ranked and an ANOVA was carried out on ranked data using Friedman's test. Finally, an arc sine square root transformation was used on frequency and survival data because a high percentage of data points at both sites fell near zero or one. After making necessary transformations, we used the model to test the following null hypotheses:

1. Thinning pattern (p) has no effect on the density or frequency of occurrence for naturally-regenerated conifers or on the survival of planted conifers.
2. Overstory retention level (o) has no effect on the density or frequency of occurrence for naturally-regenerated conifers or on the survival of planted conifers.
3. Understory vegetation control (v) has no effect on the density or frequency of occurrence for naturally-regenerated conifers or on the survival of planted conifers.

4. No interactions exist between the effects of thinning pattern (p), overstory retention level (o), and vegetation control (v).

One additional modification of the above model was used to compare seedling densities within created gaps to those in the surrounding matrix of gappy units. To evaluate whether densities within gaps differed from densities in the surrounding matrix and whether these differences varied by treatment, we removed thinning pattern from the model (because only gappy units were used) and added a term for "gap" or "matrix" to the end of the model along with necessary interaction terms. The difference between gap and matrix was determined on the ground by drawing an imaginary line between the boles of overstory trees on the outer edge of each gap.

After running each ANOVA model to check for treatment effects and interactions, we used the same model to generate least-squares means for transformed seedling density, frequency, and survival data within each treatment level. Then, pairwise or multiple comparisons were made for each response variable across treatment levels. A Tukey HSD adjustment was used to derive p-values and confidence intervals from all multiple comparisons. Although all analyses were conducted on transformed data, to aid comparisons to other studies, seedling densities and frequencies presented in this paper represent untransformed means.

Due to differences in the study design and year of study inception between the two sites used in this study, all statistical analyses were conducted independently for each site. When applicable, comparisons between sites are made in the discussion section of this chapter.

RESULTS

Overstory cover

In plots thinned to low, medium, high, and very high retention levels at McDonald, overstory cover was reduced to an average of 28, 35, 39, and 47%, respectively, in uniformly thinned units, and 26, 34, 35, and 39%, respectively, in gappy units (Figure 2.2*a*). Although basal areas within each overstory retention level were fairly consistent across subplots and between blocks, there was a higher degree of within-plot and between-block variability for overstory cover. Overstory cover increased rapidly immediately following thinning, with the greatest increases occurring in plots thinned to higher retention levels. Differences in overstory cover between gappy and uniformly thinned units were generally small during the five years immediately following thinning. However, by year 7 in the medium and high overstory retention levels (prior to re-thinning), and by year 10 in the very high retention level, there was some indication that the rate of crown closure was slowing in the gappy units relative to the uniformly thinned units. Surprisingly, there appeared to be little increase in overstory cover between year 7 and year 10 in the low retention level despite vigorous basal area growth.

Thinning treatments at Blodgett reduced overstory cover for the low, medium, and high overstory retention levels to 37, 44, and 53%, respectively, in uniformly thinned units, and to 34, 45, and 59%, respectively, in gappy units (Figure 2.2*b*). After thinning, overstory cover increased at a fairly steady rate of approximately 1.8, 1.3, and 1.0% per year for the low, medium, and high retention levels, respectively, regardless of thinning pattern.

Understory cover

At McDonald, subplots receiving no vegetation control beyond the effects of thinning averaged 13% shrub cover after one year, while in sprayed subplots, cover was reduced to 4% (Figure 2.3*a*). Shrub cover increased more rapidly in unsprayed subplots, at a rate of 6-13% per year, versus 1-5% per year in subplots where vegetation was controlled. The rate of recovery was generally similar across thinning treatments, with the exception of sprayed subplots in the very high retention level, where recovery appeared to be slower than in other sprayed subplots. A re-thinning of the medium and high overstory retention levels at year 8 caused sufficient ground disturbance to reduce shrub cover across the study site by year 10. Naturally-regenerated conifers made a small contribution to the understory layer in both sprayed and unsprayed subplots (Figure 2.3*c*), increasing from approximately 0.2% at year one to 0.6% at year 10.

At Blodgett, shrub cover was slightly higher than at McDonald one year after thinning, averaging 17% cover in unsprayed plots and 7% cover in sprayed plots (Figure 2.3*b*). Over the next nine years, shrub cover increased steadily across the study site, recovering slightly faster in unsprayed subplots (2-7% per year) than in sprayed subplots (0-4% per year). The rate of recovery was generally similar across thinning treatments; however, by year 10, the rate of increase appeared to slow somewhat under the high overstory retention level. Dense patches of primarily western hemlock regeneration also established following thinning, forming a significant conifer component in the understory by year 10. Understory conifer cover increased from 1% at year one to 28% at year 10 (Figure 2.3*d*), with no difference in the rate of increase between sprayed and unsprayed subplots or between thinning treatments.

Naturally-regenerated conifer development

Seedling establishment

<u>McDonald</u>

At McDonald, natural conifer regeneration was dominated by Douglas-fir, accounting for 73% of all naturally-regenerated seedlings. Grand fir accounted for the remaining 27%. However, on subplots where grand fir was present in the overstory (11 of 48 subplots), grand fir dominated understory regeneration, comprising 72% of all naturally-regenerated seedlings. This relative abundance of grand fir regeneration occurred despite the fact that on these subplots, grand fir still only comprised 4.7% of overstory basal area.

Across the study site, an average of 449 Douglas-fir seedlings/ha were present 13 years after study inception, but the distribution was variable, with only 44% of 5-meter radius sample plots containing at least one Douglas-fir seedling. Both the density and frequency of Douglas-fir establishment were affected by overstory retention level and vegetation control (Table 2.2), with generally higher densities and frequencies under lower retention levels and when vegetation was controlled (Table 2.3 and 2.4). The effect of vegetation control tended to decrease under the very high retention level, where seedling densities and frequencies were low in both sprayed (51 seedlings/ha) and unsprayed subplots (59 seedlings/ha). Thinning pattern did not have a statistically significant effect on Douglas-fir establishment (Table 2.2); however, within the gappy thinning pattern, there was marginal evidence to suggest that Douglas-fir densities tended to differ between gaps and the surrounding matrix depending on whether vegetation was controlled ($F_{1,7}$=5.23, p=0.0561). In the absence of vegetation control, a lower proportion of Douglas-fir was generally found in gaps on a per hectare basis than in the surrounding matrix, but virtually no difference existed when vegetation was controlled (Figure 2.4). This trend was likely due to the rapid response of competing understory vegetation to increased sunlight in unsprayed subplots following gap creation.

Grand fir was only present on 15% of 5-meter radius sample plots at McDonald, but where it occurred, densities were generally high, leading to an average of 167 seedlings/ha across the study site. The low rate and irregularity of establishment for grand fir rendered moot a statistical analysis of treatment effects on the density and frequency of establishment for this species. Although seedlings were not formally aged, field personnel noted a second pulse of grand fir regeneration in several plots re-thinned in year 8 if grand fir was present in the overstory. A similar pulse was not readily apparent for Douglas-fir.

The establishment of natural regeneration at McDonald did not appear to be limited to skid trails. There was also no indication that logging method influenced the density of understory regeneration, with nearly an equal number of seedlings present in subplots where cable logging was used (630 seedlings/ha) as those that were ground-skidded (603 seedlings/ha).

Blodgett

At Blodgett, western hemlock regenerated prolifically with Douglas-fir present in lesser amounts. One sample plot contained a naturally-regenerated western redcedar seedling, suggesting sporadic establishment of this species. Overall, western hemlock accounted for 98% of naturally-regenerated seedlings. However, in one unit, where western hemlock only constituted 5% of overstory basal area (versus 48% across the rest of the study site), an equal amount of western hemlock (1,722 seedlings/ha) and Douglas-fir (1,778 seedlings/ha) regeneration was present.

Western hemlock regeneration averaged 51,580 seedlings/ha across the study site ten years after study inception, with 78% of 1.5-meter radius sample plots containing at least one western hemlock seedling. Thinning pattern, overstory retention level, and vegetation control did not have statistically significant effects on western hemlock densities or on the frequency of western hemlock occurrence ten years after study inception (Table 2.2). However, the generally lower densities noted in Table 2.3 under the gappy thinning pattern, lower overstory retention levels, and with vegetation control may have been the result of greater seedling size leading to intra-specific competition-induced mortality and also a lack of continued establishment. Field personnel observed many dead seedlings in smaller size classes and generally lower stem counts after canopy differentiation had started to occur within dense western hemlock thickets. While statistical differences in western hemlock densities did not exist between the gappy and uniform patterns ten years after thinning, fewer seedlings were found in gaps (26,781 seedlings/ha) than in the surrounding matrix (46,161 seedlings/ha) of the gappy thinning pattern ($F_{1,10}$=7.93, p=0.0183). Visual observations suggested this difference was attributable to the rapid occupation of growing space by dominant western hemlock seedlings, shrubs, and herbaceous vegetation within gaps.

The Blodgett site averaged 1,208 Douglas-fir seedlings/ha, and this species was detected on 68% of 3-meter radius sample plots. Thinning pattern and overstory retention level did not have an effect on the density or frequency of occurrence of Douglas-fir ten years after study inception (Table 2.2). However, within the gappy thinning pattern, a relationship did exist between overstory retention level and whether a sample point fell within a gap or the surrounding matrix. Although Douglas-fir densities were not statistically different between gaps and the surrounding matrix across the study site as a whole ($F_{1,10}$=2.85, p=0.1226), Douglas-fir seedlings tended to be more closely associated with gaps as overstory densities within the surrounding matrix increased ($F_{2,10}$=4.15, p=0.0486) (Figure 2.5). With regard to vegetation control, both the density and the frequency of occurrence were higher for this species in sprayed subplots (Tables 2.3 and 2.4).

As with McDonald, natural regeneration of conifers at Blodgett did not appear to be confined to skid trails. While western hemlock seedlings were commonly found on rotting logs and stumps, regeneration of this species was also prolific at ground level on both mineral and organic seedbeds. Although the study was not designed to test the influence of logging method on the establishment of natural regeneration, there is some evidence that the higher level of ground disturbance associated with ground skidding may have resulted in more natural regeneration than cable logging. Comparing the two blocks with similar overstory compositions (e.g., percentage of western hemlock versus percentage of Douglas-fir), 10 of 12 subplots in the block where ground-skidding was used had more natural regeneration (averaging 101,300 seedlings/ha) than subplots with the same treatment combination in the block that was primarily cable-logged (averaging 45,400 seedlings/ha).

Height class distribution

At both sites, the height class distribution of naturally-regenerated seedlings 13 (McDonald) or 10 (Blodgett) years after thinning resembled the reverse-J shape commonly associated with the early development of natural regeneration (Figures 2.6, 2.7, and 2.8). However, the relationship between the applied treatments and height class distribution varied somewhat by species.

For Douglas-fir, a visual comparison of trends at both sites suggested a generally higher number of seedlings across all height classes under lower overstory retention levels, when vegetation was controlled, and to a lesser extent, under the gappy thinning pattern. At McDonald, although understory conifers taller than four meters were rare across the study area 13 years after study inception, those that were detected were only found under the gappy thinning pattern-low overstory retention level treatment combination (Figure 2.6). Additionally, no Douglas-fir taller than three meters were detected within the high or very high retention levels. Ten years after thinning at Blodgett, Douglas-fir taller than four meters were only detected under the gappy thinning pattern and when understory vegetation was controlled (Figure 2.7). Also, the detection of Douglas-fir taller than two meters was limited to the low and medium retention levels.

For western hemlock at Blodgett, the slope of the height class distribution appears to be flatter under the gappy thinning pattern, lower overstory retention levels, and when vegetation was controlled, with generally fewer seedlings in the 0-1 meter height class and more seedlings in the larger height classes (Figure 2.8). This distribution pattern is likely attributable to the rapid growth of western hemlock seedlings under lower levels of overstory and inter-specific understory competition, which led to intra-specific competition-induced mortality of smaller individuals and a lack of continued seedling establishment under dense thickets containing larger hemlock seedlings.

Survival of underplanted conifers

At McDonald, survival of underplanted Douglas-fir and western hemlock was low ten years after outplanting. Most mortality occurred within the first year (Brandeis et al. 2001), which may have been partly attributable to conditions at the time of planting. Weather conditions during planting were dry and windy with temperatures near freezing. Survival of both species after ten years was affected by both overstory retention level and vegetation control, with generally lower survival rates under higher retention levels and when vegetation was not controlled (Table 2.5). For Douglas-fir, the effect of overstory retention level was more pronounced under the gappy thinning pattern than under the uniform thinning pattern, where survival rates for the low, medium, and high retention levels were similar.

Survival of underplanted western redcedar and grand fir at McDonald generally exceeded 50% across the study site. Survival was higher under lower levels of overstory retention for both species (Table 2.5), but thinning pattern and vegetation control did not have a statistically significant effect.

Ten-year survival of underplanted Douglas-fir and western hemlock was higher at Blodgett than at McDonald, a possible reflection of moister site conditions, higher seedling vigor at the time of planting, or more favorable planting conditions. Survival of planted western redcedar at Blodgett was also remarkably high considering the high rate of browsing and frequent overtopping by shrubs and dense thickets of natural conifer regeneration. However, the extremely low net growth for most western redcedar seedlings following ten years of repeated browsing limits the potential for this species to make a significant contribution to the development of a midstory layer at this site (see Chapter 3). Thinning pattern and overstory retention level did not have a statistically significant effect on seedling survival at Blodgett, but all three planted species demonstrated better survival when vegetation was controlled (Table 2.5).

DISCUSSION

General observations

At both sites used in our study, a higher proportion of understory conifer regeneration was comprised of shade-tolerant western hemlock (Blodgett) and grand fir (McDonald) than was represented in the overstory. At each site, these species were considered the climax species for their respective plant association (Franklin and Dyrness 1973). Similar trends regarding the regeneration of shade-tolerant species were also found on other sites in northwestern Oregon following overstory thinning (Miller and Emmingham 2001, Chan et al. 2006).

The prolific and potentially excessive amount of western hemlock regeneration observed at Blodgett was consistent with findings from other thinning studies where western hemlock was well represented in the overstory (Williamson and Ruth 1976, Coates 2002). Overtopping of Douglas-fir seedlings by dense thickets of western hemlock regeneration was common under all levels of overstory retention at this site, limiting the potential for understory Douglas-fir to contribute to structural development in these stands. Dense thickets of western hemlock regeneration also provided visual evidence of reduced shrubs and herbaceous vegetation, presumably limiting understory biodiversity in these areas.

Conifer regeneration was common on skid trails in our study, and western hemlock seedlings were often located on decaying logs and stumps, a substrate commonly occupied by western hemlock seedlings in closed canopy forests (Christy and Mack 1984, Harmon and Franklin 1989). However, seedling establishment was not limited to these microsites, and in fact, seedlings occurring on organic seedbeds on the forest floor and on non-compacted mineral soil away from skid trails were often much larger after 10-13 years. Other studies have also reported seedling establishment on a variety of substrates including litter in thinned stands (Williamson and Ruth 1976, Gray and Spies 1997, Miller and Emmingham 2001). Under partial overstories, seedling desiccation and heat-related cambial damage on organic substrates do not appear to be as prevalent as they are in full sunlight (Silen 1960, Hermann and Chilcote 1965, Helgerson 1990, Gray and Spies 1997).

The negligible increase in overstory cover observed in some instances during the most recent five years at McDonald was somewhat surprising (Figure 2.2). While overstory cover would be expected to peak relatively early under higher retention levels, especially in gappy plots where overstory density in the surrounding matrix was 25% higher than in corresponding uniformly-thinned plots, the lack of observed increase between years 5 and 7 in the gappy plots thinned to medium and high retention levels occurred earlier than expected. The lack of observed increase between years 7 and 10 in plots thinned to the low retention level was even more unexpected, given the ample growing space for continued crown expansion. While these trends could suggest some stabilization in understory light conditions, measurement error associated with these ocular estimates could also be a factor. Furthermore, our estimates of overstory cover do not take into account tree heights or crown lengths, which are increasing and also play a significant role in the understory light environment (Parker et al. 2002). Re-measurement of overstory cover at year 15 will provide further insight into the temporal development of the overstory canopy layer.

Overstory management

General trends

The effect of overstory retention level on the density and frequency of natural regeneration differed between sites in our study. At the drier, less productive site where Douglas-fir dominated the overstory, the density and frequency of Douglas-fir regeneration increased with decreasing overstory densities. However, at the moister, more productive site, where a substantial portion of the overstory was comprised of western hemlock and this species dominated understory regeneration, the level of overstory retention did not have a significant effect on the density or frequency of either Douglas-fir or western hemlock natural regeneration. Other studies also showed no clear trends regarding the effects of overstory retention level on seedling establishment. Bailey and Tappeiner (1998) reported higher seedling densities and frequencies under heavier overstory thinnings, but noted low levels of regeneration in some stands with RDI values around 0.25, possibly due to lower seed rain or a greater presence of competing vegetation, under which natural regeneration was generally absent. Miller and Emmingham (2001) found higher Douglas-fir seedling densities under stands thinned to lower stocking levels; however, Buermeyer and Harrington (2002) and Chan et al. (2006) did not report differences in seedling establishment across different levels of overstory thinning (though Chan et al. (2006) did report higher seedling densities in thinned versus unthinned stands). In a study looking specifically at western hemlock establishment in western Washington, Williamson and Ruth (1976) noted abundant and probably excessive levels of regeneration across all levels of overstory thinning. However, the authors reported the greatest number of western hemlock seedlings under basal areas of 23 to 44 m^2/ha, with decreasing seedling densities outside of this range.

The effect of ovestory retention level on 13th-year conifer seedling densities at McDonald is similar to what was reported by Jerra and Vogt (1998) four years after thinning. Thirteenth-year seedling densities in low and medium retention levels were very similar to reported fourth-year seedling densities, indicating little net change over the past nine years. However, conifer seedling densities in the high and very high retention levels were reduced by approximately 30 and 70%, respectively. While some mortality may have occurred in the high retention level as a result of damage related to re-thinning operations, the reduction in seedling densities in the very high retention level suggests a high rate of seedling mortality between year 4 and year 13 related to a rapidly closing overstory canopy.

While the density and frequency of natural conifer regeneration was only affected by overstory retention level at one site in our study, trends in the data generally showed more seedlings in larger height classes under lower overstory densities at both sites. Results were similar to studies conducted by Miller and Emmingham (2001) and Buermeyer and Harrington (2002), which reported taller Douglas-fir seedlings under lower overstory densities, and to a study by Williamson and Ruth (1976), who found an inverse relationship between overstory density and the height of western hemlock regeneration. However, Chan et al. (2006) reported similar mean heights for Douglas-fir and western hemlock regeneration across all thinning treatments in their study, despite having a wider range of overstory densities than those used in our study.

The lack of difference in seedling establishment between the gappy and uniform thinning patterns in our study was not surprising considering that only the distribution, not the overall density of the overstory differed between these two treatments. However, the relationship between conifer seedling densities and immediate overstory cover (gap versus matrix) within the gappy thinning pattern proved more interesting. No clear trends developed between species or between sites. However, notable trends appeared to develop for each species within each site. For western hemlock, differences in seedling densities after ten years appeared to be mostly related to the high level of intra-specific competition occurring within gaps. On the other hand, for Douglas-fir, the proportion of seedlings in gaps versus the surrounding matrix tended to differ depending on the level of shrub and herbaceous competition within gaps and/or the level of overstory competition present in the surrounding matrix.

Other studies have compared seedling establishment between gaps with total overstory removal to surrounding stands with only partial or no overstory removal (Gray and Spies 1996, Gray and Spies 1997, Coates 2002), but these studies have only partially evaluated how establishment differs when other aspects of competition change. For example, Coates (2002) noted higher seedling recruitment for western hemlock and other species in canopy gaps than in the adjacent undisturbed forest five years after thinning; however, in this study, competition within the understory conifer layer appeared to have little effect on western hemlock seedling densities, and the level of competition from understory vegetation and from overstory trees in the undisturbed forest was not considered. Gray and Spies (1996) reported higher Douglas-fir and western hemlock establishment in gaps than under neighboring closed canopy forest two years after gap creation and noted a relationship between seedling establishment in closed canopy areas and the density of the canopy; however, under no circumstances, did densities in the closed canopy forest exceed those within gaps. In another paper published on the same study, Gray and Spies (1997) also noted generally lower establishment of western hemlock and Douglas-fir seedlings when overtopped by understory vegetation (except for the most exposed areas of larger gaps where shade from understory vegetation appeared to facilitate Douglas-fir establishment), but the authors did not elaborate on how the level of understory vegetation cover differed between gaps and neighboring closed canopy forest. Our study suggests that the relative benefit of gap creation on seedling establishment depends both on the level of understory competition within gaps versus the surrounding forest and on the degree of crown closure within the surrounding forest.

Future prognosis

Thirteen years after initial overstory thinning at McDonald, while the density and distribution of naturally-regenerated conifers under the lowest overstory retention level (RD 2.6, 18 m^2/ha) may have been adequate to promote future stand structure, especially when accompanied by vegetation control, recruitment into larger height classes was slow and likely to become slower under a rapidly closing canopy (Newton and Cole 1987). Under higher retention levels at McDonald, the patchy distribution of Douglas-fir seedlings accompanied by slow recruitment suggests even lower potential for the development of future stand structure from natural conifer regeneration in these stands. Furthermore, the difference in reported seedling densities between year 4 (Jerra and Vogt 1998) and year 13 in the highest retention levels indicates increased levels of Douglas-fir (and to a lesser extent grand fir) seedling mortality at this drier site when overstory cover exceeds 60%. It is unclear whether re-thinning the medium and high retention levels eight years after initial overstory thinning increased the rate of recruitment of Douglas-fir seedlings into larger height classes; however, Figure 2.6 does not show any marked differences between overstory retention levels that were re-thinned and those that were not re-thinned. Unless nearly pure 50-year-old Douglas-fir stands are thinned more heavily or more frequently than those in our study, it appears unlikely that more than a few naturally-regenerated conifers growing outside of gaps would exceed 9.1 meters in height (a key component in the ODF definition of “layered” stands) within 50 years after initial overstory thinning.

Across most of the Blodgett study site ten years after thinning, the density and distribution of conifer regeneration was considered adequate under all levels of overstory retention to provide for the creation of an understory canopy layer. The only portion of the study site where seedling establishment may have been marginally low was on a gentle south-facing slope where salal dominated the understory and western hemlock comprised less than 10% of overstory basal area. Despite high establishment across all three levels of overstory retention, recruitment of western hemlock into larger height classes (> 4-m) was much higher under the lowest overstory retention level (RD 3.0, 20 m^2/ha). This also appears to be the only retention level where naturally-regenerated Douglas-fir might contribute to future stand structure. Although at least one additional overstory thinning would likely be required over this time span to maintain understory conifer growth, the Douglas-fir/western hemlock mixed-species stands used in our study generally appeared to be on a trajectory to attain the ODF definition of “layered” within 30 years following initial overstory thinning to RD 3.0. However, depending on the uniformity of growth of the understory conifer layer and/or the level of ongoing establishment of conifers and other vegetation underneath this undestory conifer layer, future understory thinnings may be required. The reader should note that some of the tallest understory trees in these stands established several (1-7) years prior to study inception; however, because many 10-year-old western hemlock were also greater than five meters tall and adding nearly a meter of height growth annually (see Chapter 3), a similar trajectory towards the development of an understory conifer layer might be expected even in the absence of advanced regeneration. Although they did not provide specific time frames, Bailey and Tappeiner (1998) and Chan et al. (2006) expressed similar optimism regarding the potential to create structural diversity in more heavily thinned stands. This study will be continued to evaluate these questions for an extended time span.

Understory vegetation management

Very few studies have specifically examined the effect of controlling competing vegetation on the establishment of natural regeneration under thinned stands in the Pacific Northwest. However, the higher rate of Douglas-fir establishment following spraying in our study was not surprising given the general relationship between understory vegetation cover and seedling establishment reported in other studies (Bailey and Tappeiner 1998, Miller and Emmingham 2001). Although vegetation was not controlled in their study, Bailey and Tappeiner (1998) found a strong negative correlation between shrub cover and seedling density and frequency in thinned stands. Furthermore, Miller and Emmingham (2001) reported that patches of dense shrub and ground cover often excluded conifer regeneration in repeatedly thinned stands. Miller and Emmingham (2001) also noted abundant regeneration in a 50-year-old stand thinned to 26 m^2/ha where spot scarification and light grazing had occurred. Thirteenth-year results at McDonald were similar to fourth-year results reported by Jerra and Vogt (1998), indicating little net change in the effect of vegetation control on seedling densities during the past nine years.

Our findings regarding the effect of understory vegetation control on western hemlock establishment were somewhat more surprising. The marginally higher density of western hemlock seedlings found in unsprayed subplots with greater shrub cover differed from the findings of Bailey and Tappeiner (1998) and Miller and Emmingham (2001), who generally found lower seedling densities, regardless of species, under high levels of shrub cover. However, western hemlock regeneration in these studies generally appeared to be limited by seed source, resulting in lower seedling densities overall than those in our study and negligible levels of intra-specific competition within the understory conifer layer. In comparison, higher early growth rates for western hemlock seedlings following vegetation control in our study appeared to increase the level of resource utilization by understory conifers and expedite canopy differentiation within the understory conifer layer, leading to a lower rate of ongoing seedling establishment and some mortality of smaller overtopped seedlings after ten years. The resulting structure of the understory conifer layer ten years after vegetation control in our study demonstrates how controlling competing vegetation may allow resources to be captured more effectively by desired conifer species, and also promote greater resource utilization by potential crop trees at an earlier age in situations where heavy conifer regeneration occurs.

Comparison to planted conifers

Although our study design was not set up to allow direct comparisons between the establishment/survival of naturally-regenerated conifers and underplanted conifers, results of our study did allow us to make several general observations regarding the potential for each regeneration approach to meet possible management objectives. At McDonald, where natural regeneration was generally dominated by Douglas-fir and establishment was sporadic, underplanting clearly had the potential to increase the density, distribution, and species diversity within the understory conifer layer, at least in the first decade. While unusually high mortality of underplanted Douglas-fir and western hemlock during the first year after outplanting limited the full realization of this potential (Brandeis et al. 2001), we would expect few foresters to argue in favor of relying on natural regeneration alone versus underplanting on this site if management objectives included having a productive layer of conifers in the understory. The reader should note that several studies have been more successful in establishing Douglas-fir under thinned stands (Chen and Klinka 1997, Seidel and Head 1983, Maas-Hebner et al. 2005, Harrington 2006), and that cold, windy conditions at the time of planting likely played a major role in the high rate of Douglas-fir mortality observed in our study (Brandeis et al. 2001).

While results from McDonald generally concur with the findings of Maas-Hebner et al. (2005) and Chan et al. (2006) suggesting that natural regeneration alone should not be relied upon to provide for the development of an undestory conifer layer in thinned stands, results from Blodgett are not as clear. Throughout most of this site, the significant presence of western hemlock in the overstory resulted in abundant and fairly well-distributed natural regeneration of this species. In many cases, dense thickets of western hemlock overtopped not only naturally-regenerated Douglas-fir seedlings, but all three species of underplanted seedlings as well, leading to decreased growth and some mortality of suppressed individuals. As a result, reliance on natural regeneration at this site may lead to at least partial achievement of structural objectives (though risks of overachievement are an important consideration), with potential benefits of underplanting generally only coming from portions of the stand unoccupied by naturally-regenerated western hemlock. If objectives favored understory conifer species diversity or specifically Douglas-fir, underplanting across a large portion of the study site would likely be necessary; however, benefits of underplanting would only be derived if natural regeneration of western hemlock was controlled first, either through a pre-commercial thinning or in some cases through prior removal of the western hemlock seed source during overstory thinning.

Management implications

Results from the two sites used in this study show different levels of potential for creating a multilayered canopy in thinned stands within the Oregon Coast Range, depending on overstory species composition and site quality. These results have the following management implications:

(1) In less productive portions of the Coast Range (Site Class II-III), pure or nearly pure Douglas-fir stands thinned to RD 3.0 or higher are likely to have natural regeneration establishment that is too sparse and/or too suppressed to contribute significantly to the development of an understory conifer layer. Despite higher observed seedling densities in stands thinned to RD 2.5 to RD 3.0, recruitment into larger height classes was still slow. In either situation, underplanting, especially with shade-tolerant species, may improve distribution, enhance growth within the understory conifer layer, and/or increase species diversity.

(2) In more productive portions of the Coast Range (Site Class I-II), Douglas-fir stands with a major western hemlock component are likely to have prolific hemlock establishment in the understory following thinning to RD 3.0 to RD 5.0. Establishment will be fairly well-distributed across suitable seedbeds; however, underplanting may still be desired in some areas to enhance the achievement of stocking objectives and/or increase species diversity within the understory conifer layer.

(3) If shade-tolerant western hemlock and grand fir are present in the overstory alongside Douglas-fir, a higher proportion of these species should be expected to establish in the understory than what is present in the overstory. This trend does

not hold true for western redcedar, possibly due to heavy browsing of newly established seedlings.

(4) While reducing the level of overstory retention from an RD of 4.6-4.9 to an RD of 2.6-3.0 appears to increase the rate of *recruitment* for both naturally-regenerated Douglas-fir and western hemlock into larger height classes, this reduction only tends to increase the rate of *establishment* for Douglas-fir. When a significant component of western hemlock is present in the overstory, regeneration of this species will be prolific across the range of overstory retention levels used in this study.

(5) Controlling competing vegetation immediately prior to thinning using appropriate herbicides and the "waving wand" technique described in Newton et al. (1998) will increase the rate of recruitment for both naturally-regenerated Douglas-fir and western hemlock into larger height classes; however, vegetation control may only increase the rate of establishment for Douglas-fir. Effects will vary depending on the composition and abundance of understory vegetation.

(6) The creation of 0.06- to 0.10-ha gaps may increase the rate of recruitment for Douglas-fir and western hemlock seedlings and expedite canopy differentiation and dominance assertion within dense western hemlock thickets; however, relative differences in seedling establishment between gaps and the surrounding forest depend both on the response of competing understory vegetation and on the amount of overstory cover present in the surrounding forest.

(7) Where they occur, dense thickets of western hemlock will overtop other conifer species and reduce levels of non-coniferous understory vegetation, potentially compromising the achievement of other structural objectives, including species diversity. Understory thinning may be required to enhance species diversity and promote the development of additional conifer layers.

(8) Re-thinning of rapidly closing overstories will likely be required to maintain desired growth rates and minimize mortality of understory conifers. The frequency and intensity of subsequent thinnings will depend on a variety of issues including costs, rate of canopy closure, level of natural disturbance, and the

desired rate of development and species composition of the understory conifer layer. Depending on the harvesting method used and the care of the loggers in protecting understory conifers during subsequent thinnings, some damage and mortality should be expected during each re-entry (Newton and Cole 2006).

The reader should note that although local topography varied somewhat, the majority of our study occurred on generally flat or northerly aspects. Results may differ on warmer and drier south-facing slopes, although overstory cover would be expected to regulate temperature and moisture extremes somewhat. The two sites used in this study occur at fairly different "points" along the spectrum in the Oregon Coast Range with regard to site productivity, moisture regime, and species composition. Where similar trends developed at both sites, the scope of inference may be expanded somewhat to sites with conditions in between those present in our study. However, where trends differed, care should be taken in expanding the scope of inference to other sites.

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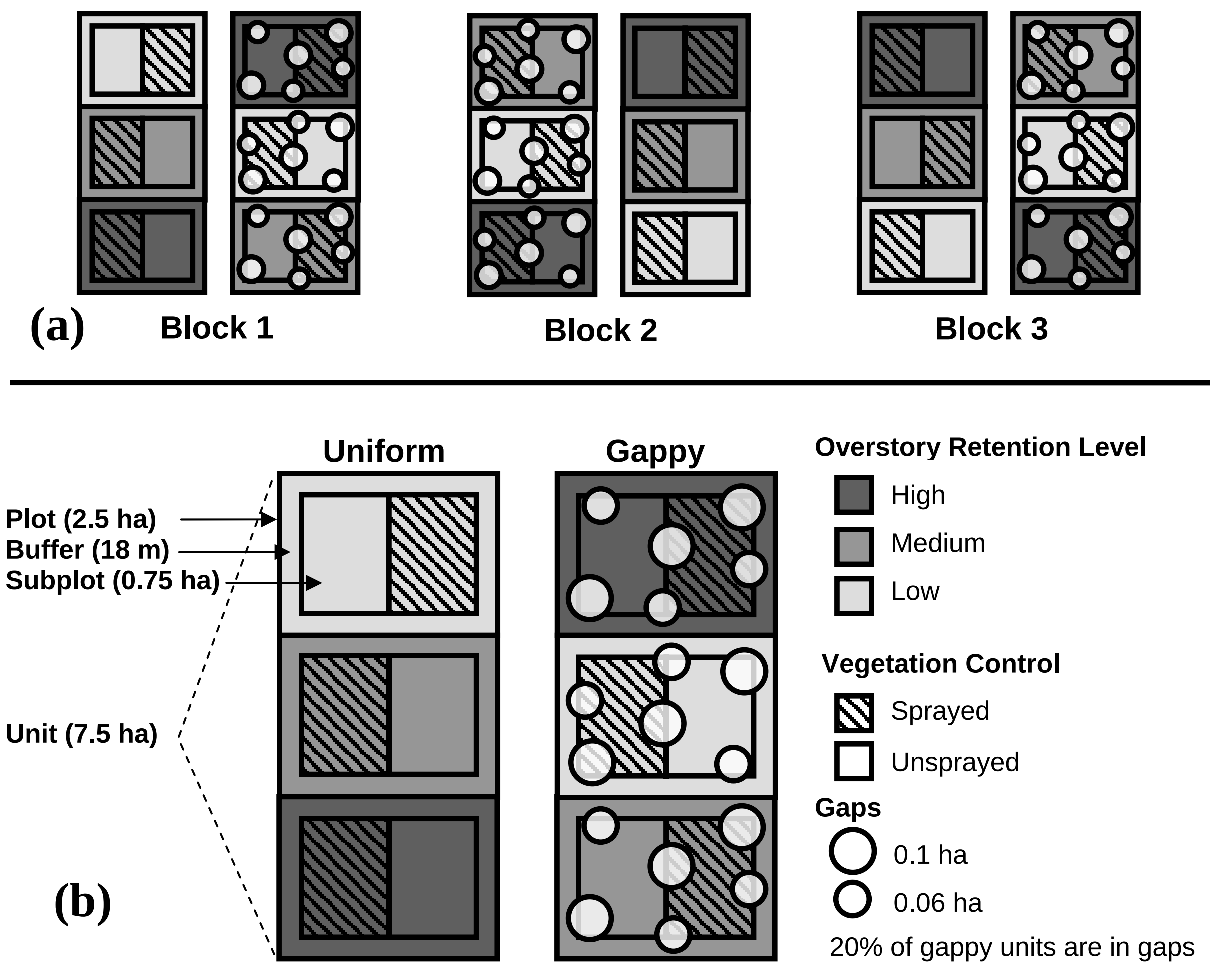

Figure 2.1. Study layout at Blodgett. A similar layout was used at McDonald except at McDonald, a fourth overstory retention level (very high), and a third vegetation control treatment (plant/release) were also included. Due to the low effectiveness of the plant/release treatment relative to the control, this treatment level was not considered for analysis in this paper.

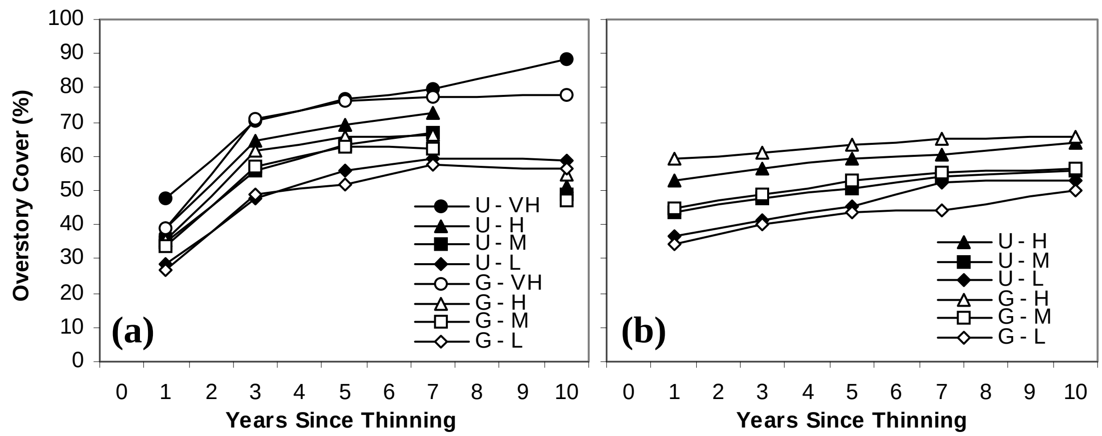

Figure 2.2. Changes in overstory cover at (a) McDonald and (b) Blodgett during the ten years following initial thinning. Changes are shown for each combination of thinning pattern (G = gappy, U = uniform) and overstory retention level (VH = very high, H = high, M = medium, L = low). Medium and high retention levels at McDonald were re-thinned at year 8.

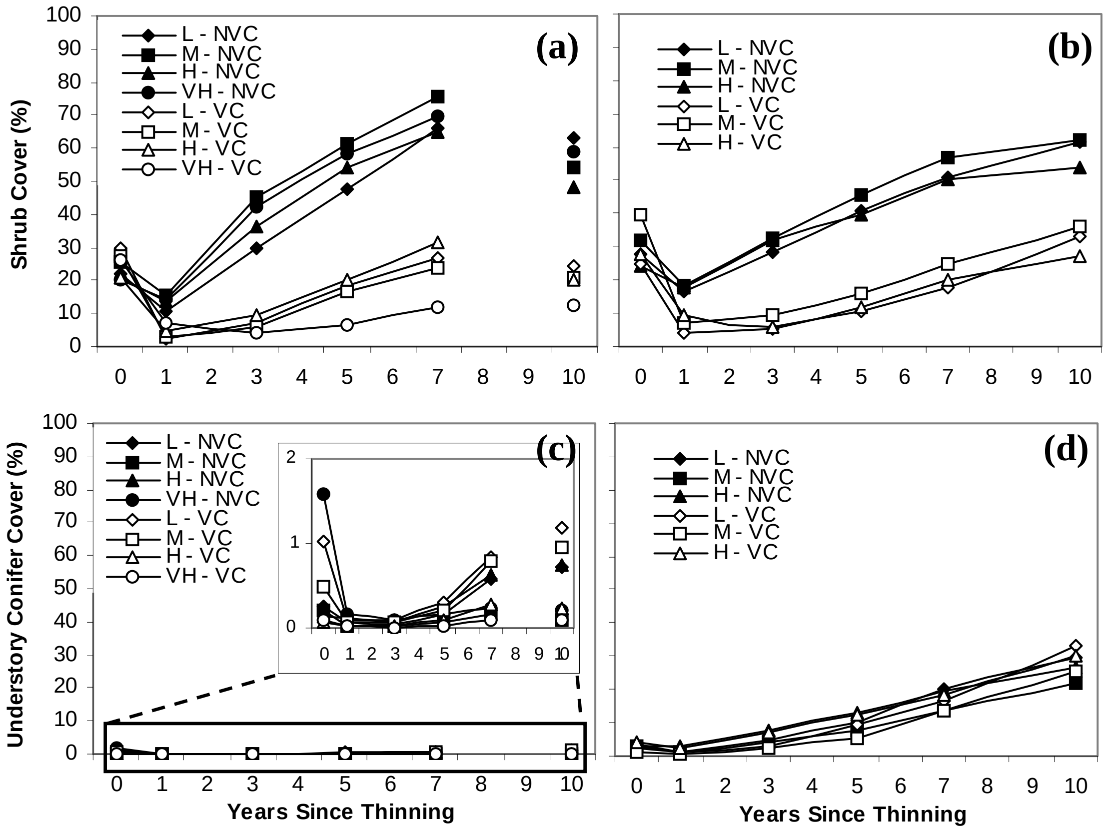

Figure 2.3. Changes in understory shrub and conifer cover at (a,c) McDonald and (b,d) Blodgett, respectively, during the ten years following initial overstory thinning and vegetation control. Changes are shown for each combination of overstory retention level (L = low, M = medium, H = high, and VH = very high) and vegetation treatment (VC = vegetation control, NVC = no vegetation control). Medium and high retention levels at McDonald were re-thinned at year 8, leading to ground disturbance throughout most of the study site.

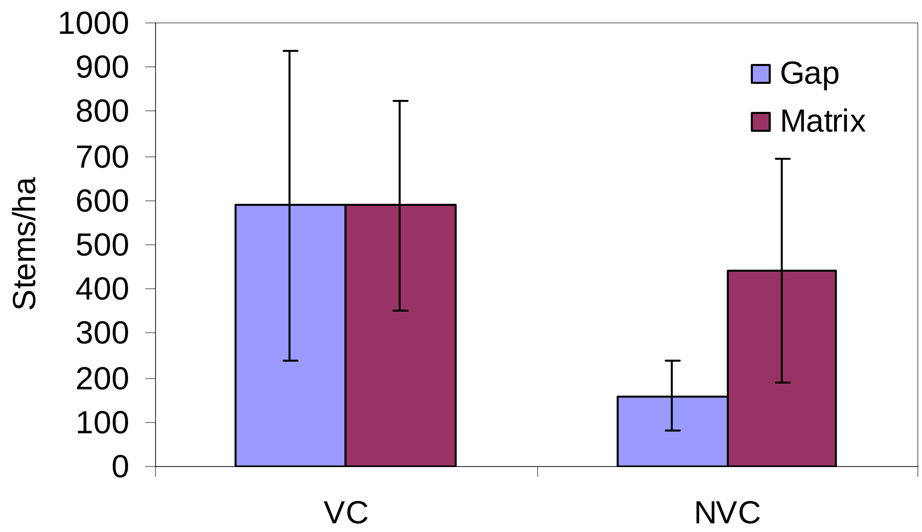

Figure 2.4. Mean seedling densities of naturally-regenerated Douglas-fir in gaps and the surrounding forest matrix 13 years after overstory thinning at McDonald. This graph highlights differences in the proportion of Douglas-fir in gaps vs. matrix depending on whether competing understory vegetation was controlled (VC = vegetation control, NVC = no vegetation control). Error bars represent standard errors.

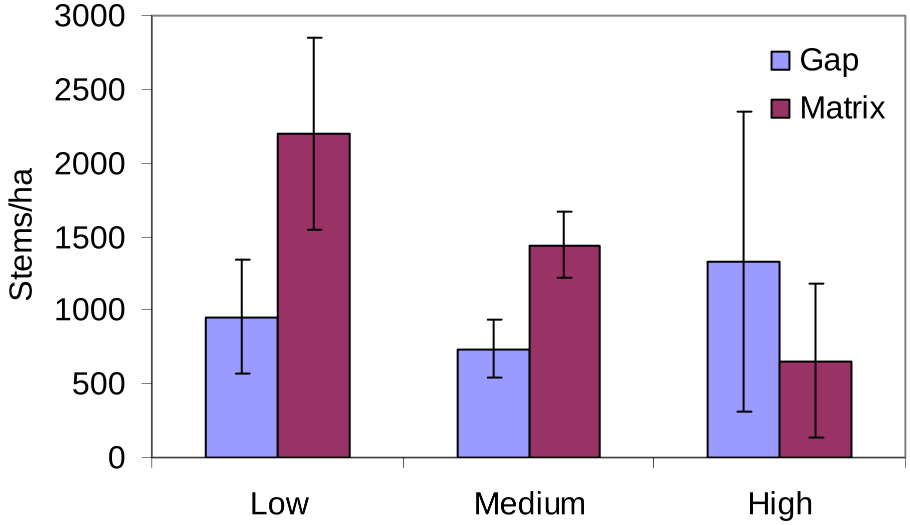

Figure 2.5. Mean seedling densities of naturally-regenerated Douglas-fir in gaps and the surrounding forest matrix 10 years after overstory thinning at Blodgett. This graph highlights differences in the proportion of Douglas-fir in gaps vs. matrix depending on the level of overstory retention. Error bars represent standard errors.

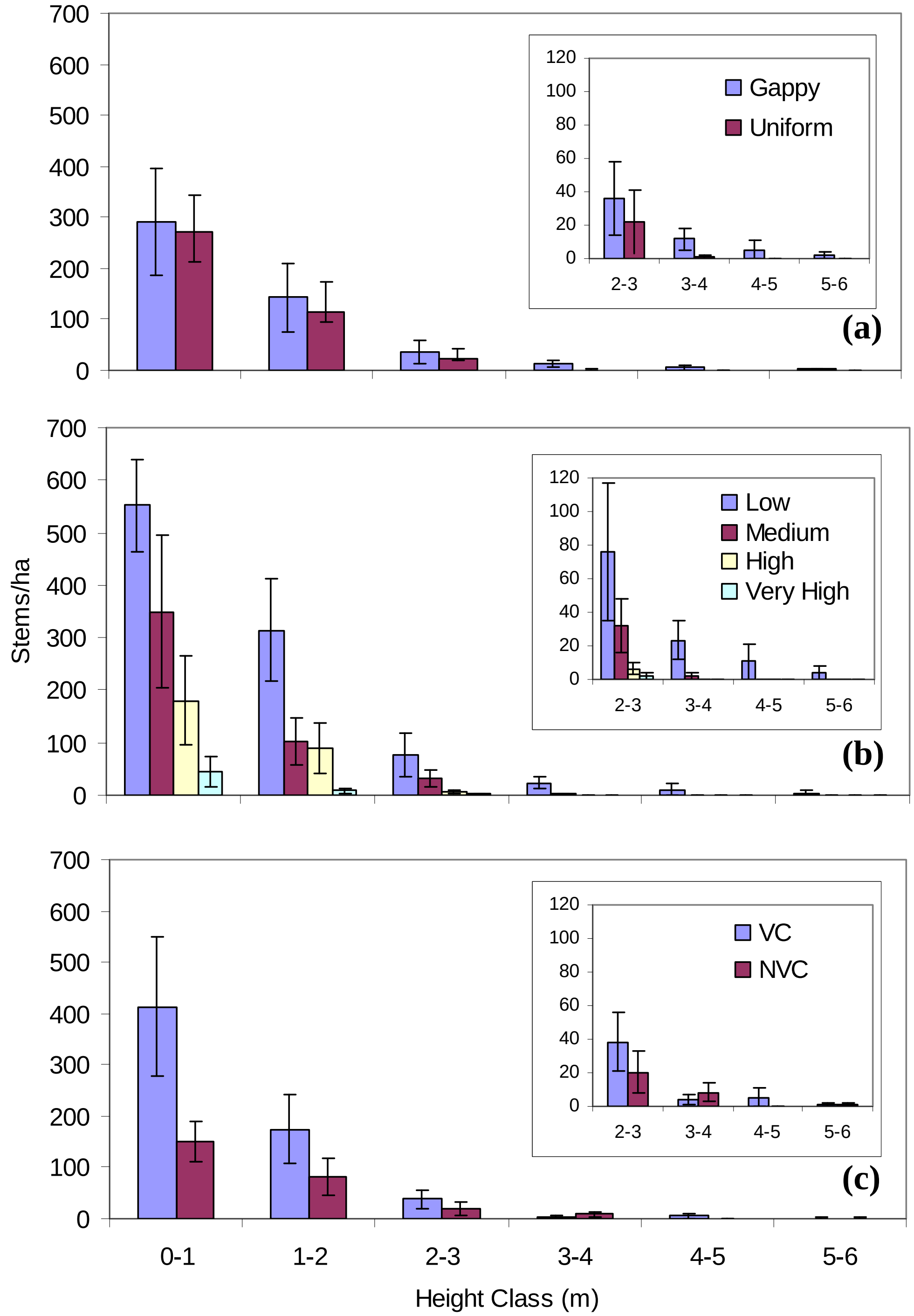

Figure 2.6. Height class distribution of naturally-regenerated Douglas-fir at McDonald 13 years after overstory thinning. Comparisons are made between (a) gappy and uniform thinning patterns, (b) low, medium, high, and very high overstory retention levels, and (c) vegetation control and no vegetation control. Insets expand the y-axis for larger height classes. Error bars represent standard errors.

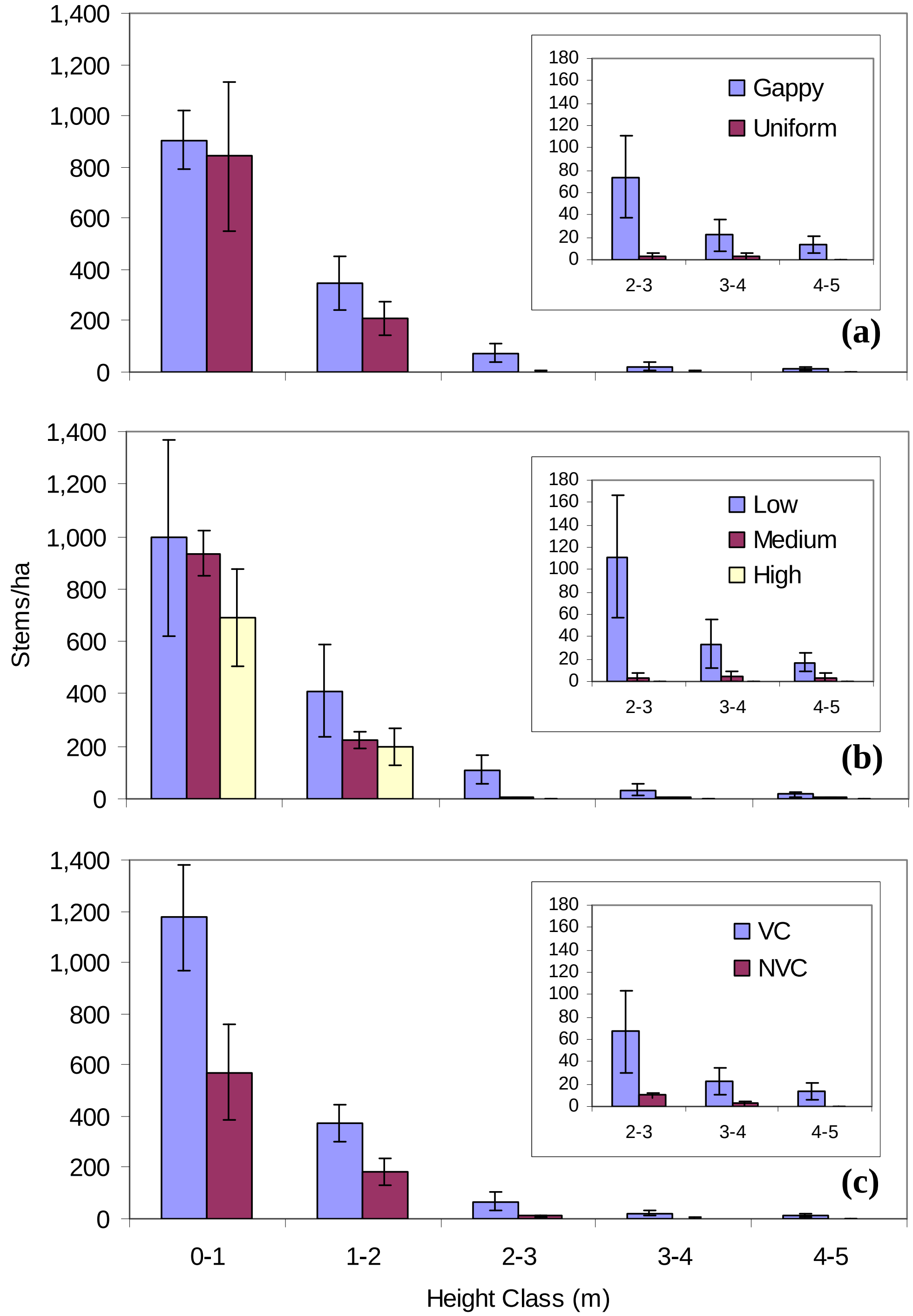

Figure 2.7. Height class distribution of naturally-regenerated Douglas-fir at Blodgett ten years after overstory thinning. Comparisons are made between (a) gappy and uniform thinning patterns, (b) low, medium, and high overstory retention levels, and (c) vegetation control and no vegetation control. Insets expand the y-axis for larger height classes. Error bars represent standard errors.

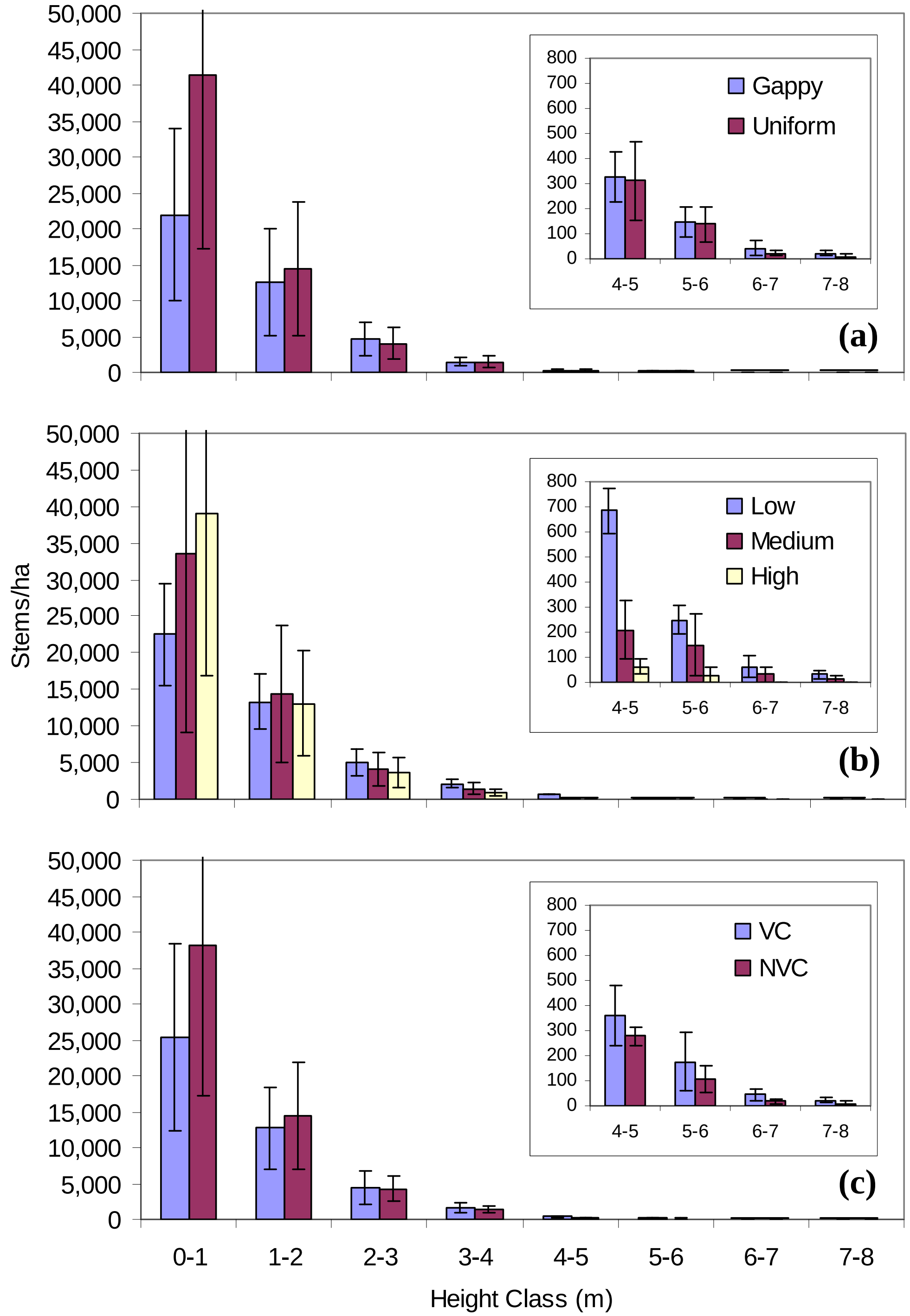

Figure 2.8. Height class distribution of naturally-regenerated western hemlock at Blodgett ten years after overstory thinning. Comparisons are made between (a) gappy and uniform thinning patterns, (b) low, medium, and high overstory retention levels, and (c) vegetation control and no vegetation control. Insets expand the y-axis for larger height classes. Error bars represent standard errors.

Table 2.1. Description of study sites.

Descriptor	Blodgett	McDonald
County	Columbia	Benton
Location	46°4'N, 123°21'W	44°39'N, 123°16'W
Annual Precip (cm)	152-200	102-152
Site $Index_{50}$ (m)[a]	36.6-42.7	33.5-39.6
Elevation (m)	270-370	245-395
Aspect	N-E	NW-N
Slope (%)	0-70	0-60
Soil Series	Scaponia-Braun silt loams, Tolke silt loam	Price-Ritner complex, Jory silty clay loam
Soil Subgroup (Class)	Umbric Dystochrepts (Scaponia), Dystric Eutochrepts (Braun), Mesic Haplumbrepts (Tolke)	Dystric Xerochrepts (Price and Ritner), Xeric Haplohumults (Jory),
Soil Texture	Silt loam	Silty clay loam
Previous Thin	1987	1964, 1980
Overstory Composition	55% Douglas-fir, 41% western hemlock, 3% red alder, 1% western redcedar	88% Douglas-fir, 8% bigleaf maple 1% grand fir, 1% Pacific madrone, 1% bitter cherry

[a] See King (1966).

Table 2.2. ANOVA table for year 10 seedling densities and frequency of occurrence. Bold indicates statistical significance at α=0.05. P, thinning pattern; O, overstory retention level; V, vegetation control; PSME, Douglas-fir; TSHE, western hemlock; ABGR, grand fir; N, numerator; D, denominator.

	df	Density		Frequency	
Effect	N,D	F	Pr > F	F	Pr > F
McDonald					
PSME					
P	1,2	4.44	0.1695	2.19	0.2774
O	3,12	**14.01**	**0.0003**	**19.65**	**0.0000**
P*O	3,12	0.56	0.6523	0.22	0.8791
V	1,16	**9.28**	**0.0077**	**11.93**	**0.0033**
P*V	1,16	1.36	0.2601	0.19	0.6680
O*V	3,16	2.39	0.1072	2.14	0.1351
P*O*V	3,16	2.02	0.1515	2.23	0.1245
Blodgett					
PSME					
P	1,2	0.12	0.7605	0.01	0.9465
O	2,8	1.37	0.3075	1.84	0.2195
P*O	2,8	0.74	0.5069	0.67	0.5395
V	**1,12**	**26.56**	**0.0002**	**51.67**	**0.0000**
P*V	1,12	0.26	0.6226	0.23	0.6735
O*V	2,12	0.15	0.8610	0.14	0.8736
P*O*V	2,12	0.88	0.4395	0.19	0.8313
TSHE					
P	1,2	0.20	0.7000	0.15	0.7383
O	2,8	0.09	0.9150	0.05	0.9473
P*O	2,8	0.05	0.9536	0.26	0.7755
V	1,12	3.53	0.0847	0.91	0.3579
P*V	1,12	1.19	0.2963	0.00	0.9811
O*V	2,12	0.89	0.4349	0.01	0.9859
P*O*V	2,12	1.17	0.3447	0.07	0.9310

Table 2.3. Comparison of seedling densities (TPH) across treatment levels 13 (McDonald) or 10 (Blodgett) years after thinning. The numbers shown are untransformed means, but statistical analyses were conducted on ranked (McDonald) or square root transformed (Blodgett) data. Values for each treatment type within a given row with different letters are significantly different (p<0.05). PSME, Douglas-fir; TSHE, western hemlock.

	Thinning Pattern		Overstory Retention Level				Vegetation Control	
	Gappy	Uniform	Low	Medium	High	V. High	Yes	No
McDonald								
PSME	489 a	409 a	980 a	486 ab	276 bc	55 c	637 a	261 b
Blodgett								
PSME	1362 a	1055 a	1566 a	1173 a	887 a	----	1649 a	768 b
TSHE	41273 a	61889 a	44058 a	53840 a	56845 a	----	44648 a	58515 a

Table 2.4. Frequency of occurrence of at least one seedling on sample plots 13 (McDonald) or 10 (Blodgett) years after thinning. The numbers shown are untransformed means, but an arc sine (square root) transformation was used for statistical analyses. Sample plots had a 5-meter radius at McDonald, a 3-meter radius for Douglas-fir at Blodgett, and a 1.5-meter radius for western hemlock at McDonald. Values for each treatment type within a given row with different letters are significantly different ($p<0.05$). PSME, Douglas-fir; TSHE, western hemlock.

	Thinning Pattern		Overstory Retention Level				Vegetation Control	
	Gappy	Uniform	Low	Medium	High	V. High	Yes	No
McDonald								
PSME	0.53 a	0.34 a	0.77 a	0.40 b	0.43 b	0.15 c	0.55 a	0.33 b
Blodgett								
PSME	0.68 a	0.68 a	0.74 a	0.73 a	0.56 a	----	0.88 a	0.48 b
TSHE	0.82 a	0.75 a	0.77 a	0.81 a	0.78 a	----	0.83 a	0.74 a

Table 2.5. Survival of planted conifers ten years after thinning. The numbers shown are untransformed means, but an arc sine (square root) transformation was used for statistical analyses. Values for each treatment type within a given row with different letters are significantly different ($p<0.05$). PSME, Douglas-fir; TSHE, western hemlock; THPL, western redcedar; ABGR, grand fir.

	Thinning Pattern		Overstory Retention Level				Vegetation Control	
	Gappy	Uniform	Low	Medium	High	V. High	Yes	No
McDonald								
PSME	0.30 *a*	0.20 *a*	0.39 *a*[1]	0.30 *ab*	0.24 *b*[1]	0.06 *c*	0.28 *a*	0.21 *b*
TSHE	0.23 *a*	0.28 *a*	0.38 *a*	0.26 *ab*	0.26 *ab*	0.13 *b*	0.31 *a*	0.20 *b*
THPL	0.81 *a*	0.77 *a*	0.89 *a*	0.80 *ab*	0.78 *ab*	0.68 *b*	0.80 *a*	0.78 *a*
ABGR	0.64 *a*	0.64 *a*	0.76 *a*	0.68 *a*	0.61 *ab*	0.50 *b*	0.68 *a*	0.59 *a*
Blodgett								
PSME	0.80 *a*	0.82 *a*	0.83 *a*	0.84 *a*	0.76 *a*	----	0.86 *a*	0.76 *b*
TSHE	0.67 *a*	0.74 *a*	0.70 *a*	0.71 *a*	0.70 *a*	----	0.76 *a*	0.65 *b*
THPL	0.69 *a*	0.84 *a*	0.80 *a*	0.80 *a*	0.69 *a*	----	0.81 *a*	0.71 *b*

[1] Difference is only statistically significant under the gappy thinning pattern.

CHAPTER 3: TEN-YEAR GROWTH RESPONSES OF PLANTED AND NATURAL CONIFERS FOLLOWING OVERSTORY THINNING AND UNDERSTORY VEGETATION CONTROL IN 50-YEAR-OLD DOUGLAS-FIR STANDS

INTRODUCTION

The past 50 years were a time when management objectives in the Pacific Northwest primarily favored maximizing timber yields. This emphasis drove the practice of intensive, even-aged management that resulted in the creation of dense, second-growth Douglas-fir stands (*Pseudotsuga menziesii* (Mirb.) Franco) throughout large portions of the Oregon Coast Range. However, objectives favoring late-successional forest structure and biological diversity have become increasingly common in this region in recent years (USDA and USDI 1994, Oregon Department of Forestry 2001). Thinning young, second-growth Douglas-fir stands to levels below those typically associated with timber production has been hypothesized as one way to increase within-stand structural and biological diversity (McComb et al. 1993). Thinning has already proven effective in increasing biological diversity over the short term, resulting in increased densities and growth of understory shrubs and hardwoods in stands previously dominated by closed-canopy Douglas-fir (Tappeiner and Zasada 1993, Huffman et al. 1994, O'Dea et al. 1995). However, the longer-term development of late-successional forest structure, including a multilayered canopy, depends on the successful establishment and growth of conifers in an understory environment.

Previous research has demonstrated that overstory density and the pattern of overstory tree distribution influences understory conifer development. However, the scope of inference for these studies is somewhat restricted because either they focused strictly on the development of *planted* conifers (Brandeis et al. 2001, Maas-Hebner et al. 2005, Harrington 2006), tracked regeneration development over a limited timeframe (Williamson and Ruth 1976, Gray and Spies 1996, Brandeis et al. 2001, Harrington 2006), or were not conducted as controlled experiments (Bailey and Tappeiner 1998, Miller and Emmingham 2001). Furthermore, very few studies have explored the role of competing shrubs and herbaceous vegetation on understory conifer development (Brandeis et al. 2001, Harrington 2006). The purpose of my research is to use a previously established controlled experiment to compare the growth of planted and naturally-regenerated conifers 10 years after manipulating levels of overstory density, overstory tree distribution, and understory vegetation. In the experiment, these three factors were controlled using a combination of thinning and vegetation control in stands 50-55 years old.

Once established, the development of understory conifers into a substantive midstory, an important step in the development of a multilayered canopy and late-successional forest structure, depends on the continued growth and vigor of established seedlings over time. The three objectives for this study were (i) to determine how overstory density, overstory tree distribution, and competition from understory vegetation affects the size, recent height growth rate, and vigor of understory conifers 10 years after management to control these factors occurred, (ii) to determine whether these effects are similar for both planted and similarly-aged naturally-regenerated conifers and (iii) to determine whether differences in size, growth, and vigor varied by species.

METHODS

Study site description

The two study sites used in this study were the same as those used in chapter two. Refer to chapter two for a detailed description of each study site.

Experimental design and treatments

The experimental design and application of treatments in this study were the same as those used in chapter two. Refer to chapter two for a detailed description of the experimental design and applied treatments.

Measurements

Evaluation of underplanted conifers

Ten growing seasons after planting (fall 2003 at McDonald and fall 2006 at Blodgett), planted conifers from four randomly selected seedling grids within each subplot were measured and evaluated for damage, disease, and other conditions that may affect growth. Each grid contained six (McDonald) or ten (Blodgett) seedlings of each species minus losses to mortality. After mortality, the average subplot at McDonald was represented by six Douglas-fir, six western hemlock, 19 western redcedar, and 15 grand fir seedlings, whereas the average subplot at Blodgett was represented by 32 Douglas-fir, 28 western hemlock, and 31 western redcedar seedlings. During data collection, a seedling was classified as "damaged" if it showed any physical symptoms of damage or disease that were deemed capable of reducing growth potential and/or survival. A seedling was considered "browsed" if it showed any signs that it had been browsed within the past three years. Measurements included total height and basal diameter (at 15 cm above ground level),. From these measurements, we calculated H:D ratios for each seedling. We also calculated recent annual height growth rates, averaged over the past three growing seasons, from current and previous height measurements. Analysis of height growth was conducted on absolute height growth rather than relative height growth because the primary objective of the study was to evaluate the current rate at which understory conifers were growing towards the development of an understory canopy layer. Similarly, height growth was analyzed rather than diameter growth, despite the evidence that responses to competition are often reflected to a greater extent in diameter growth.

Evaluation of dominant naturally-regenerated conifers

Dominant naturally-regenerated understory conifers were selected for measurement from within a 3-meter (Blodgett) or 5-meter (McDonald) radius circle around previously established, systematically placed sample points within each subplot. At Blodgett, fifteen sample points were originally placed within each subplot during the installation of the study, but only seven or eight points were used during the selection of dominant understory conifers. The selection of either even- or odd-numbered points was done randomly for each subplot. At McDonald, the same procedure was used to initially select five of ten systematically placed sample points. However, if less than four sample points within a subplot contained a naturally-regenerated Douglas-fir, the predominant species at McDonald, additional points were randomly added to the sample until at least four dominant Douglas-fir seedlings were sampled or until all ten points had been evaluated for the presence of Douglas-fir regeneration. Dominant naturally-regenerated understory conifers were selected based on their perceived potential to outcompete neighboring conifers and reach a position in the midstory. Generally, the tallest seedling/sapling of each species was selected for measurement unless a comparably sized individual had greater recent growth and/or higher vigor (i.e. a much fuller crown).

On each dominant understory conifer, height, basal diameter (at 15 cm above ground level), and annual height growth (internodal measurements between branch whorls or bud scars) over the past three growing seasons were measured, total age was estimated, and trees were evaluated for damage, disease, and other conditions that may inhibit growth. Seedlings were classified as “damaged” or “browsed” using the same criteria used for planted seedlings. As with planted seedlings, we also calculated H:D ratios and recent average annual height growth rates. Measurements at both sites were taken in fall 2006, which was 13 growing seasons after thinning and planting at McDonald and 10-11 growing seasons after thinning and ten growing seasons after planting at Blodgett. Because naturally-regenerated seedlings at McDonald were measured three years after planted seedlings, direct comparisons of basal diameters were not possible at this site. Direct height comparisons were made possible at McDonald by using branch whorls to estimate year 10 heights. Measurements of planted and naturally-regenerated seedlings were made during the same year at Blodgett.

Although some advanced regeneration was present, especially at Blodgett, at the time of study inception and a limited amount of regeneration continued to establish during the ten years following thinning, only conifers estimated to have established within two years of thinning (+ or – two years) at each sample point are used for analysis in this paper. At Blodgett, 69% of all dominant naturally-regenerated conifers were estimated to have established within two years of thinning while 74% of all dominant naturally-regenerated conifers at McDonald met this criterion. Similar observations were made by Jerra and Vogt (1998) four years after thinning at McDonald.

Statistical analysis

Analysis of variance (ANOVA) was used to evaluate the effects of thinning pattern, overstory retention level, and vegetation control on the height, basal diameter, recent height growth rate, H:D ratio, damage rate, and browsing rate of underplanted and dominant naturally-regenerated understory conifers. After averaging responses across each subplot, we used PROC MIXED in SAS 9.1 (SAS Institute Inc. 2004) to fit the following three-way ANOVA model to the data for each species and regeneration method:

$$Y_{ijkl} = \mu + \beta_i + p_j + o_k + v_l + (po)_{jk} + (pv)_{il} + (ov)_{kl} + (pov)_{jkl} + \psi_{ij} + \lambda_{ijk} + \varepsilon_{ijkl}$$

where μ is the overall mean of Y
β_i is the random effect of the i^{th} block on the variation of Y; ($\beta_i \sim N(0,\sigma^2_b)$ and $Cov(\beta_i, \beta_{i'}) = 0$)
p_j is the fixed effect of the j^{th} thinning pattern (j = even or gappy)
o_k is the fixed effect of the k^{th} level of overstory retention (k = low, medium, or high)
v_l is the fixed effect of the l^{th} level of vegetation control (l = no vegetation control or total vegetation control)
$(po)_{jk}$ is the fixed effect of the interaction between thinning pattern *j* and overstory retention level *k*

$(pv)_{jl}$ is the fixed effect of the interaction between thinning pattern *j* and vegetation control level *l*

$(ov)_{kl}$ is the fixed effect of the interaction between overstory retention level *k* and vegetation control level *l*

$(pov)_{jkl}$ is the fixed effect of the interaction between thinning pattern *j*, overstory retention level *k,* and vegetation control level *l*

ψ_{ij} is the random effect of the units on the variability of Y; ($\psi_{ij} \sim N(0,\sigma^2_\psi)$ and $Cov(\psi_{ij}, \psi_{i'j'}) = 0$)

λ_{ijk} is the random effect of the plots on the variability of Y; ($\lambda_{ijk} \sim N(0,\sigma^2_\lambda)$ and $Cov(\lambda_{ijk}, \lambda_{i'j'k'}) = 0$)

ε_{ijkl} is the random effect of the subplots on the variability of Y; ($\varepsilon_{ijkl} \sim N(0,\sigma^2)$ and $Cov(\varepsilon_{ijkl}, \varepsilon_{i'j'k'l'}) = 0$)

and all random effects are independent.

For each model, normality and constant variance were checked using PROC UNIVARIATE and GPLOT in SAS 9.1 (SAS Institute Inc. 2004). Because variance increased around larger expected values for height, basal diameter, and recent height growth rate, a log transformation was used on these variables prior to analysis. After making necessary transformations, we used the model to test the following null hypotheses:

1. Thinning pattern (p) has no effect on the mean height, basal diameter, recent height growth rate, H:D ratio, damage rate, or browsing rate for understory conifers.
2. Overstory retention level (o) has no effect on the mean height, basal diameter, recent height growth rate, H:D ratio, damage rate, or browsing rate for understory conifers.
3. Understory vegetation control (v) has no effect on the mean height, basal diameter, recent height growth rate, H:D ratio, damage rate, or browsing rate for understory conifers.
4. No interactions exist between the effects of thinning pattern (p), overstory retention level (o), and vegetation control (v).

After running the ANOVA model to check for treatment effects and interactions, we used the same model to generate least-squares means for height, basal diameter, recent height growth rate, H:D ratio, and rate of damage and browse for seedlings within each treatment level. In addition to overall browsing rates, browsing rates were also generated for seedlings specifically less than 1.5 meters tall at year 7 to assess the impact of browsing on seedlings that were still within range of large ungulates. Then, pairwise or multiple comparisons were made for each response variable across treatment levels. A Tukey HSD adjustment was used to derive p-values and confidence intervals from all multiple comparisons. The reader should note that values for height, basal diameter, and recent height growth rate presented in this paper are back transformed from least-squares means and represent the median. In most cases, medians are slightly lower than means calculated from untransformed data.

Several modifications of the above model were required to fully answer research questions posed in this paper. To evaluate whether growth within gaps in gappy units differed from growth in the surrounding matrix and whether these differences varied by treatment, we removed thinning pattern from the model (because only gappy units were used) and added a term for "gap" or "matrix" to the end of the model along with necessary interaction terms. The difference between gap and matrix was determined by drawing an imaginary line between the boles of overstory trees on the outer edge of each gap. To determine whether damaged or browsed seedlings experienced less height growth over the last three years than undamaged or unbrowsed seedlings and to see whether differences varied by treatment, we added terms for "damaged" and "browsed" to the model along with interaction terms. Finally, to evaluate whether response variables differed among species and whether these differences varied by treatment, we modified the above model to include a term for species along with interaction terms. Because species arrangements within planted seedling grids were the same across each plot, comparisons of planted species were made using a randomized complete block split-split-*strip* plot design. The aforementioned comparisons were all conducted on least squares means generated for each response variable and a Tukey HSD adjustment was used where appropriate.

Due to differences in the study design and year of study inception between the two sites used in this study, all statistical analyses were conducted independently for each site. When applicable, comparisons between sites are made in the discussion section of this chapter.

RESULTS

Seedling heights

Underplanted conifers

At McDonald, western hemlock was the tallest of the underplanted species, followed by western redcedar, grand fir, and Douglas-fir, respectively, at year 10 (Figure 3.1*a*). Planted seedling heights were inversely related to overstory density (Tables 3.1 and 3.2). Thinning pattern did not have a statistically significant effect on the heights of any of the planted species (Table 3.1), but seedlings within gaps of the gappy units were generally taller than those in the surrounding matrix (Table 3.3). While vegetation control appeared to lead to an increase in the height of all planted conifers (Table 3.2), only the effects on western hemlock, western redcedar, and grand fir were statistically significant (Table 3.1).

At Blodgett, the tallest underplanted seedlings were western hemlock, followed by Douglas-fir and western redcedar, respectively (Figure 3.1*b*). Thinning pattern did not affect the median seedling height for any of the three species (Table 3.4), but the heights of Douglas-fir and western redcedar increased with decreasing overstory densities (Table 3.2). However, because western redcedar seedlings were heavily browsed by deer (*Odocoileus hemionis columbiana*) and elk (*Cervus elaphus roosevelti*), even at the low overstory retention level, the median height of planted redcedar was only 70 cm. As a result, height differences for this species were considered to be minor. There appeared to be a general trend of increasing western hemlock heights with decreasing overstory densities (Figure 3.2); however, a three-way interaction between thinning pattern, overstory retention level, and vegetation control prevented the direct interpretation of the effect of overstory retention level on western hemlock heights (Table 3.4). This interaction was caused largely by one subplot (receiving the uniform-low-vegetation control treatment combination) where overstory cover was unusually high due to an abundance of hardwoods. Removal of this outlier from the ANOVA model eliminated the three-way interaction and revealed a strong negative correlation between overstory retention level and the height of underplanted western hemlock seedlings.

The use of vegetation control led to greater heights for planted Douglas-fir at Blodgett. An interaction between thinning pattern, overstory density, and vegetation control inhibited the direct interpretation of the main effect of vegetation control on western hemlock heights (Table 3.4); however, the removal of the same outlier mentioned previously eliminated this interaction and showed that planted western hemlock seedlings were generally taller following vegetation control.

Heights of all planted species at Blodgett were greater in the gaps of gappy units than in the surrounding matrix (Table 3.3). Western hemlock experienced greater percentage and absolute height gains in gaps than Douglas-fir, while the gains of western redcedar were minor due to browsing.

Dominant naturally-regenerated conifers

At McDonald, Douglas-fir was the only species that established from seed in large enough quantities to evaluate growth. Ten years after thinning, the median height of dominant Douglas-fir seedlings was 94 cm (95% confidence interval: 82 to 107 cm) in the low, medium, and high overstory retention levels, combined. Insufficient establishment of Douglas-fir regeneration prevented a growth analysis in the very high retention level. There was only marginal evidence to suggest an effect of overstory density on the height of dominant seedlings (Table 3.1).

Dominant naturally-regenerated western hemlock seedlings significantly outgrew dominant Douglas-fir seedlings in height at Blodgett during the ten years after thinning (Figure 3.1*b*), and the median height for both species increased with decreasing overstory density (Table 3.2).

Thinning pattern and understory vegetation control did not have a statistically significant effect on median seedling heights for dominant naturally-regenerated conifers at either site (Tables 3.1 and 3.4). There was marginal evidence to suggest that dominant Douglas-fir seedlings were taller in gaps than in the surrounding forest matrix at McDonald ($F_{1,3}$=8.02, p=0.0661), but not at Blodgett ($F_{1,3}$=0.83, p=0.4292) where growing space in gaps was quickly occupied by western hemlock regeneration.

Dominant western hemlock seedlings at Blodgett were significantly taller in gaps (Table 3.3), where they had a median height of 361 cm after ten years.

Recent height growth rates

Underplanted conifers

Overstory density generally had the greatest effect of the three applied treatments on the recent height growth rate (averaged over the past three years) of underplanted seedlings, followed by vegetation control and thinning pattern. Underplanted seedlings at both sites displayed greater recent height growth under decreasing overstory densities (Table 3.5), although the effect of overstory retention level on the growth rate of grand fir at McDonald was only significant when vegetation was not controlled. All species generally also exhibited greater recent height growth in sprayed subplots (Table 3.5), though effects of vegetation control on Douglas-fir growth at McDonald were only marginally significant (Table 3.1). Thinning pattern did not affect recent growth rates at the subplot level (Tables 3.1 and 3.4); however, all species except grand fir exhibited significantly greater recent height growth in the gaps of gappy units than in the surrounding matrix (Table 3.3). Not surprisingly, species that produced the tallest seedlings during the first ten years following thinning generally continued to exhibit the highest growth rates over the past three years. However, grand fir was no longer growing at a faster rate than Douglas-fir at McDonald.

Dominant naturally-regenerated conifers

Recent height growth rates for dominant naturally-regenerated conifers differed across overstory retention levels at Blodgett (Table 3.5), but not at McDonald where medium and high retention plots were re-thinned at year 8. Differences were not significant between sprayed and unsprayed subplots or between uniform and gappy units (Tables 3.1 and 3.4). Of the natural regeneration occurring on both sites, only dominant western hemlock seedlings at Blodgett displayed greater recent height growth in gaps of gappy units versus the surrounding matrix (Table 3.3). Median height growth of this species in gaps was 51 cm/year over the past three years. At Blodgett, recent height growth for western hemlock, which was already taller, continued to outpace Douglas-fir (t_{22}=12.39, $p<0.0001$).

Basal diameters

Trends regarding tenth-year basal diameters of planted and dominant naturally-regenerated seedlings at McDonald and Blodgett (13th-year for natural Douglas-fir at McDonald) were generally similar to those described for seedling heights (Table 3.6). Trends for all species and regeneration methods at both sites show increasing diameters with decreasing levels of overstory retention and greater diameters when vegetation was controlled. However, as with heights, differences between sprayed and unsprayed plots were not statistically significant for naturally-regenerated seedlings. Although seedlings generally tended to have slightly larger diameters in gappy units versus uniformly thinned units, these differences were not statistically significant. While diameter trends may have been similar to trends in height after ten years, not surprisingly, percentage gains in diameter were greater with reductions in overstory density and the removal of competing vegetation than percentage gains in height. Douglas-fir, in particular, showed a much greater diameter response than height response following removal of competing understory vegetation.

Species rankings were generally similar to those for heights with one notable exception. At McDonald, where western redcedar seedlings were larger than western hemlock seedlings at the time of planting, differences between planted western hemlock and planted western redcedar were not statistically significant at year 10.

Height:diameter ratios

Not surprisingly, the aforementioned greater percentage increase in basal diameters versus heights under lower overstory retention levels and when vegetation was controlled also generally led to lower H:D ratios at these treatment levels (Table 3.7). Planted species at both sites and natural Douglas-fir at Blodgett all had significantly lower H:D ratios in sprayed subplots. The degree to which H:D ratios differed between sprayed and unsprayed subplots generally increased with higher overstory densities and differences were also somewhat larger in uniformly thinned units. Differences between the highest and lowest retention levels used at each site were only statistically significant at McDonald, and only in unsprayed subplots for planted western redcedar and planted Douglas-fir. Differences in H:D ratios between the low, medium, and high overstory retention levels at McDonald were clouded by the re-thinning of the medium and high retention levels two years prior to measurement.

Comparisons of H:D ratios between species are generally inappropriate because some species, such as western hemlock, tend to be taller for a given diameter. However, the general lack of difference in H:D ratios between western hemlock and Douglas-fir at McDonald was notable along with the comparatively higher H:D ratio for Douglas-fir under the very high retention level. Planted seedlings tended to have smaller H:D ratios than natural seedlings. Higher H:D ratios for both planted and naturally-regenerated seedlings at Blodgett versus McDonald may have been partially a function of site differences, but also due to high levels of competition from western hemlock natural regeneration at Blodgett.

Seedling damage

A variety of agents were responsible for damaging planted and naturally-regenerated seedlings. Browsing by black-tailed deer at McDonald and both black-tailed deer and elk at Blodgett resulted in moderate to severe damage on Douglas-fir and western redcedar. Many seedlings also suffered top dieback. Although a variety of causes contributed to the observed dieback, including antler rubbing and rodent girdling, symptoms, especially on western hemlock, were often similar to those associated with water stress (Zimmermann 1983, Kavanagh and Zaerr 1997) and damage from low temperatures in spring and fall.

Underplanted conifers

At McDonald, Douglas-fir was the most heavily damaged species, followed by western redcedar (Table 3.8). Grand fir and western hemlock suffered the least damage and the difference between these species was not statistically significant. Although the terminal leader of many western redcedar seedlings, and to a lesser extent Douglas-fir seedlings had grown beyond the reach of browsers at this site, browsing damage was still severe on seedlings less than 1.5 meters tall (Table 3.8). The most common damage reported on western hemlock and grand fir was top dieback. At least slight dieback occurred on 12.0% of measured grand fir seedlings and 10.0% of measured hemlock seedlings. Deer racking was common on larger western redcedar and western hemlock trees. The level of damage to western hemlock and grand fir and the overall level of damage and browse on Douglas-fir were not affected by overstory density, thinning pattern, or vegetation control. However, the overall rate of browsing on western redcedar was affected by overstory retention level ($F_{3,12}$=10.44, p=0.0012) and vegetation control ($F_{1,16}$=6.28, p=0.0234), with more seedlings browsed under higher retention levels and in unsprayed subplots. The increased rate of browse at these treatment levels was likely related to more seedlings having terminal leaders that remained within browsing range. When looking only at seedlings less than 1.5 meters tall across all treatments, overstory retention level and vegetation control had no effect on browsing rates. While vegetation control had no effect on the overall browsing rate of Douglas-fir, browsing rates were marginally higher for Douglas-fir seedlings less than 1.5 meters tall in sprayed subplots (61.3%) versus unsprayed subplots (42.2%) (t_{12}=1.89, p=0.0820). Damaged seedlings at McDonald, and Douglas-fir and western redcedar seedlings suffering specifically from browsing damage, all experienced lower recent height growth rates than their undamaged counterparts (Table 3.9).

Western redcedar was the most heavily damaged species at Blodgett, followed by Douglas-fir and western hemlock, respectively (Table 3.8). The majority of damage on western redcedar and Douglas-fir at this site was caused by deer and elk browse, while top dieback and dieback of lateral branches was common on western hemlock. Out of all measured western hemlock seedlings, 22.6% suffered at least slight dieback. Thinning pattern, overstory retention level, and vegetation control did not affect the overall level of damage on western hemlock, Douglas-fir and western redcedar at Blodgett; however, vegetation control did affect the rate of browsing on Douglas-fir ($F_{1,12}$=6.18, p=0.0286) and western redcedar seedlings ($F1_{,12}$=4.09, p=0.0660), most of which were still within browsing range. For Douglas-fir seedlings specifically less than 1.5 meters tall, 47.0% were browsed in sprayed subplots versus 30.0% in subplots where vegetation was not controlled (t_{12}=2.32, p=0.0386). For western redcedar, 67.1 % of seedlings less than 1.5 meters tall were browsed in sprayed subplots versus 55.5% in unsprayed subplots (t_{12}=2.12, p=0.0554). Recent height growth rates for damaged seedlings of all three planted species at Blodgett were lower than rates for undamaged seedlings (Table 3.9).

Dominant naturally-regenerated conifers

Damage to naturally-regenerated Douglas-fir was severe at McDonald, with 63.3% of dominant seedlings suffering some form of visible damage (Table 3.8). Most of the damage was caused by deer browsing, with 50.8% of dominant Douglas-fir seedlings browsed at least once over the past three years. Thinning pattern, overstory retention level, and vegetation control had no effect on the overall rate of damage or browsing and no effect on the browsing rate for seedlings less than 1.5 meters tall.

At Blodgett, 46.2% of dominant naturally-regenerated Douglas-fir seedlings suffered some form of damage, while only 12.1% of western hemlock seedlings were damaged (Table 3.8). The most prevalent form of damage to Douglas-fir was due to deer and elk browsing, with 28.3% of all measured dominants suffering browse damage during at least one of the past three years. Thinning pattern and overstory retention level had no effect on damage or browsing rates for Douglas-fir, but vegetation control had a significant effect on overall browsing rates ($F_{1,10}$=5.52, p=0.0407) and browsing rates for seedlings less than 1.5 meters tall ($F_{1,10}$=5.09, p=0.0477). Out of all seedlings less than 1.5 meters tall, 37.4% suffered browsing damage in subplots where vegetation was controlled, while only 19.7% were browsed in unsprayed subplots. A variety of agents were responsible for the limited damage to western hemlock. However, mountain beavers were the primary damaging agent despite trapping efforts, clipping the tops of 2.6% of measured seedlings. Elk occasionally damaged western hemlock leaders at earlier ages. Damage to western hemlock seedlings was not affected by overstory density, thinning pattern, or vegetation control.

Differences in recent growth rates between damaged and undamaged seedlings were more evident at McDonald than at Blodgett. At McDonald, Douglas-fir seedlings suffering from any type of damage and damage specifically from browsing had lower recent height growth rates than undamaged seedlings (Table 3.9). At Blodgett, despite the high incidence of damage on Douglas-fir natural regeneration, especially by browsing, there was no evidence to indicate that growth rates were lower for damaged or browsed seedlings. No differences in height growth existed between damaged and undamaged natural western hemlock at this site either.

DISCUSSION

Overstory management

General trends

Underplanted and dominant naturally-regenerated conifer seedlings of all species used in our study were generally larger in height and basal diameter and continued to exhibit greater absolute height growth under lower overstory retention levels after ten years. The lack of statistical significance with regard to natural Douglas-fir at McDonald was likely attributable to a generally smaller sample size and to the re-thinning of the medium and high retention levels at year 8, which reduced overstory cover by 11-21% in re-thinned plots (Figure 2.2). According to Jerra and Vogt (1998), an inverse relationship did exist between overstory density and the height of dominant naturally-regenerated conifers at this site four years after thinning.

The increase in size and recent height growth of the four species used in this study under decreasing levels of overstory cover was not surprising. Other studies have also demonstrated increases in conifer growth under decreasing overstory cover (Williamson and Ruth 1976, Dunlap and Helms 1983, Jaeck et al. 1984, Harrington 2006) or associated increases in sunlight availability (Wang et al.1994, Chen 1997, Mailly and Kimmins 1997, Drever and Lertzman 2001, Chan et al. 2006). While some authors have noted a relative leveling off in the growth of western redcedar and young grand fir once light availability increases beyond a certain point (30-40% full sunlight for western redcedar, Foiles et al. 1990, Carter and Klinka 1992, Wang et al. 1994, Coates and Burton 1999, Drever and Lertzman 2001, Harrington 2006), no such leveling off was observed within the range of overstory densities used in our study.

The creation of small gaps across 20% of a stand within a relatively uniform thinning regime did not dramatically improve understory growing conditions for conifer seedlings at the stand level relative to a fully uniform thin. However, seedlings growing in gaps themselves clearly demonstrated superior growth to those in the surrounding matrix. The increase in seedling growth between gaps and the matrix were similar for all species providing some indication that light levels within gaps as a whole in our study were not sufficiently high to favor moderately shade-intolerant species such as Douglas-fir. However, differences in browsing pressure somewhat limit the ability to make comparisons between species.

The two gap sizes used in this study were relatively small compared to sizes considered in other studies. Spittlehouse et al. (2004) showed that 0.1 ha gaps surrounded by 25 m tall trees (smaller than those surrounding gaps in my study) had a very similar solar, wind, and thermal environment as the surrounding forest. Their study demonstrated that the majority of a 1.0-ha gap received greater than 70% full sunlight, but a large portion of 0.1-ha gaps received only 0-20% more sunlight than the understory of the surrounding forest with a maximum of 50-60% full sunlight near the northern edge. Furthermore, in a study of gaps between 0.1 and 1.0 ha in size in a Sierran mixed-conifer forest in northern California (York et al 2007), many conifer species showed dramatic increases in mean seedling height growth as gap sizes increased from 0.1 to 0.3 ha. Douglas-fir even continued to show a growth response in gap sizes between 0.6 and 1.0 ha. Although the incorporation of gap sizes larger than 0.1 ha into stand-level management may result in considerable reductions in overstory stand yield, these studies show the potential benefits of larger gaps on seedling growth.

H:D ratios offer one way to evaluate seedling vigor in response to suppression from competition (Cole and Newton 1987). Excessively high H:D ratios are often associated with poor stem stability, reductions in growth, and even pending mortality (Cole and Newton 1987, Wilson and Oliver 2000, Wonn and O'Hara 2001), while low H:D ratios favor the continuation of rapid height growth (Cole and Newton 1987). In our study, H:D ratios were somewhat lower with decreasing overstory densities, especially for Douglas-fir and western redcedar. These trends were similar to findings reported in other studies (Maas-Hebner et al. 2005, Chan et al. 2006). However, differences between the three lowest overstory retention levels varied at McDonald, suggesting a potential increase in seedling vigor of undamaged trees following re-thinning of the medium and high retention levels. Despite the decrease in H:D ratios under lower overstory densities, H:D ratios remained relatively high across all retention levels. Under lower retention levels, H:D ratios for Douglas-fir still exceeded 70, a level associated with declines from maximum growth rates (Cole and Newton 1987). Under the highest retention levels at both sites, H:D ratios approached 100, indicating a loss of stem stability, little height growth potential, and rapidly declining vigor (Cole and Newton 1987, Wonn and O'Hara 2001). Differences in H:D ratios between overstory retention levels were generally more pronounced in the absence of vegetation control, and H:D ratios were higher for natural regeneration than for planted seedlings.

Species comparison

Western hemlock showed the greatest potential of any species used in our study for growth in an understory environment. This species was the fastest growing at all levels of overstory retention, including within gaps up to 0.1 ha in size. Furthermore, western hemlock appeared to be the best suited of all species for maintaining adequate growth and vigor in the extremely low light conditions associated with >80% overstory cover (see Figure 2.2). Other studies have also demonstrated the superior growth of western hemlock across a wide range of understory environments (Maas-Hebner et al. 2005, Chan et al. 2006, Harrington 2006) When a seed source was available to provide adequate establishment, dominant naturally-regenerated western hemlock seedlings showed comparable growth to planted seedlings through ten years, especially in the absence of vegetation control. However, direct comparisons between these two regeneration methods were not possible because of sampling differences.

The potential for growing western redcedar in an understory environment was evident at McDonald, where large plug+2 seedlings were planted and browsing impacts were less severe. At the lowest retention level used in the study, the size and recent height growth of this species was comparable to that of western hemlock. Other studies have shown that on similar sites, western redcedar reaches near maximum growth rates under light levels only slightly higher than the likely range provided by thinning in this study (Carter and Klinka 1992, Wang et al, 1994, Coates and Burton 1999, Drever and Lertzman 2001, Harrington 2006). Growth of western redcedar at Blodgett was similar to that reported by Maas-Hebner et al. (2005) and Harrington (2006) in studies where browsing pressure was also severe.

The growth of planted Douglas-fir and grand fir in our study was generally adequate under 50-60% overstory cover for maintaining minimum levels of vigor, though at reduced growth rates. Grand fir slightly outperformed Douglas-fir. Maas-Hebner et al. (2005) found no difference between these two species under similar levels of overstory cover, while Ketchum (1995) noted superior growth of Douglas-fir under a more open overstory. In both of these studies, rates of browsing on Douglas-fir were lower than those observed in our study. Most Douglas-fir and grand fir seedlings in 0.06 and 0.1 ha gaps, while growing faster than those in the surrounding matrix, were still growing at less than half of site potential (based on observations in neighboring young, open-grown stands). As a result, if management objectives favored these two species over more shade-tolerant species, the creation of larger gaps and/or lower overstory densities than those used in this study would be desirable. Harrington (2006) found that thinning to shelterwood densities (RD 1.5-2.3) increased Douglas-fir stem volume growth by a factor of 4 to 5 after five years versus stands thinned to RD 3.8, which is similar to our medium retention level.

Growth of naturally-regenerated Douglas-fir on both sites generally appeared to be inferior to that of planted Douglas-fir at all levels of overstory retention. Furthermore, comparatively higher H:D ratios for natural regeneration suggest limited future growth potential and higher susceptibility to damage from ice, snow, and wind. As a result, even if an adequate density and distribution of Douglas-fir seedlings could be achieved through natural regeneration to meet management objectives (see Chapter 2) and overstory cover is maintained below 70%, most naturally-regenerated Douglas-fir seedlings would have limited potential for reaching a position in the midstory.

Future prognosis

While the growth of understory conifers after ten years was generally adequate under the lowest overstory retention levels used in this study to maintain survival, seedlings were growing under a vigorous overstory that exhibited rapid growth and increasing crown closure following thinning. A study by Newton and Cole (1987) suggests that future overstory growth under all retention levels used in our study will eventually suppress understory conifer growth to levels associated with high mortality (Brandeis et al. 2001). In their study, stands thinned more heavily than ours reached 70% full stocking, a level shown in our study to be incompatible with a conifer understory, especially for moderately shade-intolerant species such as Douglas-fir. As a result, future thinnings would be required to maintain minimal levels of seedling vigor and provide opportunities for growth into a midstory layer. Such thinnings would damage or kill a portion of existing understory conifers (Newton and Cole 2006).

Understory vegetation management

A reduction of competing understory vegetation generally led to greater diameters and heights, lower H:D ratios, and continued greater absolute height growth for planted seedlings at both sites. Differences in H:D ratios were larger under higher overstory densities reflecting the potential to offset effects of overstory suppression by reducing sources of suppression within the understory.

The beneficial effects of controlling competing vegetation on the growth of planted seedlings has been well documented in clearcuts (Roth and Newton 1996, Newton and Preest 1988, Stein 1997, Wagner et al. 1999, Rose and Ketchum 2002, Rose et al. 2006), but very few studies have examined growth responses in an understory environment (Brandeis et al. 2001, Harrington 2006). Results from our study concur with the findings of Harrington (2006), which showed an increase in the growth of underplanted seedlings in thinned stands when vegetation was controlled. While relative gains in diameter and height growth rival the 20-40% gains observed in clearcuts after ten years (Stein 1997, Rose et al. 2006), absolute gains in seedling growth attributable to vegetation control were substantially less than what has been documented for open grown seedlings, reflecting limits imposed by overstories.

Differences in basal diameter, height, and recent height growth rates for naturally-regenerated seedlings generally showed a smaller response to vegetation control than planted seedlings, and differences for natural regeneration were not statistically significant. The lack of a more definitive growth difference, especially with regard to diameter (Morris et al.1990; Brand 1991; MacDonald and Weetman 1993, Rose et al.

2006), was somewhat surprising given the response of planted seedlings in this study to vegetation control.

Seedling damage

The rate of damage suffered by western hemlock and grand fir was relatively minor compared to rates for western redcedar and Douglas-fir. The high rate of deer and elk browsing on western redcedar and the limited rate of browsing on western hemlock and grand fir was consistent with reports from prior studies (Omule 1988, Minore and Weatherly 1990, Ketchum 1995, Stein 1997, Brandeis et al. 2002, Grossnickle 2005, Maas-Hebner et al. 2005). However, browsing rates on Douglas-fir were somewhat higher than those reported previously (Black et al. 1979, Schaap and Deyoe 1986, Ketchum 1995, Harrington 2006, Maas-Hebner et al. 2005). This high rate of browsing on Douglas-fir likely contributed to the poor performance of this species in our study. Furthermore, many Douglas-fir seedlings, especially those in the higher overstory retention levels, remained within range of browsing after ten years. Browsing pressure on planted western redcedar seedlings less than 1.5 meters tall at McDonald over the past three years was higher than the 36% rate reported during the first four years after planting (Brandeis et al. 2002). This lower rate of initial browse allowed many western redcedar seedlings (80% under the low overstory retention level) to escape further risk of browsing damage after ten years. The use of large planting stock at McDonald may have played a role in allowing seedlings to grow beyond the range of browsing as well, but this hypothesis was not tested.

While other studies have shown that the rate of browsing may increase under lower overstory densities (Ketchum 1995, Harrington 2006), no clear trends were observed in our study. Browsing frequency on Douglas-fir and western redcedar was slightly higher in lower overstory retention levels at Blodgett, but slightly lower at McDonald. Brandeis et al. (2002) and Maas-Hebner et al. (2005) also found no relationship between overstory cover and browsing frequency.

Evidence suggesting increased rates of browsing in sprayed versus unsprayed subplots for Douglas-fir and western redcedar at Blodgett and for planted Douglas-fir at

McDonald (marginally significant for seedlings <1.5 m tall) is consistent with what has been found in other studies (Hines 1973, Brandeis et al. 2002, Harrington 2006). Newton et al. (1989) suggest that the application of herbicides may increase the level of available browse through the removal of competing taller shrubs that were out of reach of browsers, thus increasing area use by large ungulates. While overall shrub cover was reduced following herbicide application in our study (Figure 2.3), an analysis of the data based on browsing preference was not conducted.

Management implications

Results from this study demonstrate the potential for conifer growth in an understory environment in the decade following thinning to levels below those commonly associated with maximizing wood production. These results suggest that thinning 50- to 55-year-old Douglas-fir dominated stands to RD 2.6-3.0 (17-21 m^2/ha, 25-35% overstory cover) will generally support the growth of both shade-tolerant and moderately shade-intolerant conifer species for ten years following thinning. However, growth rates for all species will be lower than would be expected for open grown seedlings, with height growth for Douglas-fir and grand fir reduced by more than 50%. In stands thinned to RD 4.6-4.9 (28-32 m^2/ha, 45-55% overstory cover), overstory suppression will generally lead to decreasing growth and vigor for most surviving seedlings within ten years of thinning. In our study, western hemlock was the only species that maintained minimum levels of growth and vigor when overstory densities approached RD 5.5 (40 m^2/ha). The poor performance of seedlings when stands exceed RD 5.0 suggests the inability of this overstory density to support a vigorous understory conifer layer. It also suggests the need for repeated thinning in stands initially thinned to lower overstory densities before they reach this threshold if conifer growth in the understory is desired. The creation of small gaps up to 0.1 ha during thinning will improve the growth of both shade-tolerant and moderately shade-intolerant seedlings within gaps somewhat, but not to the extent that larger openings would.

Our study generally supports the recommendation by Chan et al. (2006), which states that thinning to RD 2.2-3.6 followed by subsequent re-thinnings would permit the growth of understory conifers barring excessive damage. However, older stands and stands with lower initial densities exhibit rapid crown closure after thinning and may require re-thinning more frequently than the 15+ years recommended in their study. Our data do not support the recommendation presented in Hayes et al. (1997), which suggests that stands allowed to regrow to RD 6.5 before re-thinning can support the development of an understory conifer layer. The only potential for maintaining conifer growth at RD levels this high might be if initial overstory densities were very high (e.g. previously unthinned stands), resulting in small crowns and slow crown expansion following thinning.

Controlling vegetation prior to planting in an understory environment has the potential to temporarily increase the growth of underplanted, and to a lesser extent, naturally-regenerated seedlings. However, absolute increases in seedling growth are apparently less than those associated with spraying in clearcuts. Based on differences in tenth-year heights and recent height growth rates observed in our study, it would likely take the shade-tolerant planted seedlings used in our study (western hemlock, western redcedar, and grand fir) 2-4 additional years in unsprayed stands to reach the tenth-year heights of shade-tolerant planted seedlings in sprayed stands. This difference was only 1-2 years for planted Douglas-fir and one year or less for dominant natural conifers.

If management objectives favor western hemlock and a seed source is present in the overstory, reliance on natural regeneration to provide an understory conifer layer may be an acceptable alternative to planting. Growth rates of dominant naturally-regenerated western hemlock seedlings were similar to those of planted seedlings. However, the development of a multilayered canopy from natural regeneration also requires adequate distribution (see Chapter 2), gaps for future recruitment of additional layers, and potential care to keep regeneration density low enough to avoid loss of forage and diverse vegetation cover in the understory. Additional silvicultural treatments will likely be needed to accomplish this.

Conclusions

In our study, various combinations of thinning and understory vegetation control were evaluated for their potential to provide for the development of a productive understory conifer layer in even-aged, second-growth Douglas-fir stands. The following summarizes our findings (trends apply to both underplanted and naturally-regenerated seedlings unless otherwise noted):

1) Tenth-year heights and basal diameters of all species were inversely related to overstory density, and recent height growth rates for all species except western hemlock fell to critical levels when overstory cover exceeded 80 percent.
2) The largest seedlings were generally found within the small gaps (up to 0.1 ha) created in this study, but the size of seedlings within these gaps was less than would be expected for open-grown seedlings. Gaps still favored shade-tolerant species.
3) Tenth-year heights and basal diameters of underplanted seedlings were greater when understory vegetation was controlled prior to planting. Data trends suggested a slight positive growth response for dominant naturally-regenerated seedlings to vegetation control, but differences between sprayed and unsprayed areas were not statistically significant.
4) Western hemlock showed the greatest promise for growth in an understory environment. This species demonstrated growth superior to that of other species at all levels of overstory retention, and dominant naturally-regenerated western hemlock seedlings performed nearly as well as planted seedlings ten years after planting/establishment.
5) Western redcedar, a highly valuable commercial species, also showed promise for growth in an understory environment. Planted individuals were nearly as large as planted western hemlock under lower overstory densities on one site. However, growth of western redcedar is highly dependent on levels of browsing pressure and on the ability of seedlings to respond to browsing. Large plug+2 western redcedar seedlings used on one site in this study generally recovered from

moderate levels of browsing and grew beyond the range of browsing within five to ten years after planting.

6) Planted Douglas-fir seedlings outperformed naturally-regenerated Douglas-fir seedlings but still exhibited low levels of height growth (<25 cm/year) and vigor (H:D ratio>75) across all levels of overstory retention. High levels of browsing further restricted Douglas-fir growth. Lower densities and/or larger gaps than those used in our study would be recommended to improve the growth and vigor of Douglas-fir.
7) Grand fir growth was slightly better than that of Douglas-fir, but inferior to that of western hemlock and western redcedar.

Decisions regarding how to manage young, even-aged Douglas-fir dominated stands in the Coast Range of Oregon towards late-successional characteristics are dependent on current stand conditions and specific management objectives. If generating revenue from the sale of timber remains a primary objective, managers will need to decide how and when overstory trees will be removed and what role, if any, understory and/or midstory trees will have on stand development following partial or complete overstory removal. Retention of non-overstory trees may be desirable, but species composition and/or high levels of damage associated with overstory removal might limit the value of retained trees. It is likely that interactions between the overstory and understory will continue to dominate evaluation of long-term prospects for this management approach.

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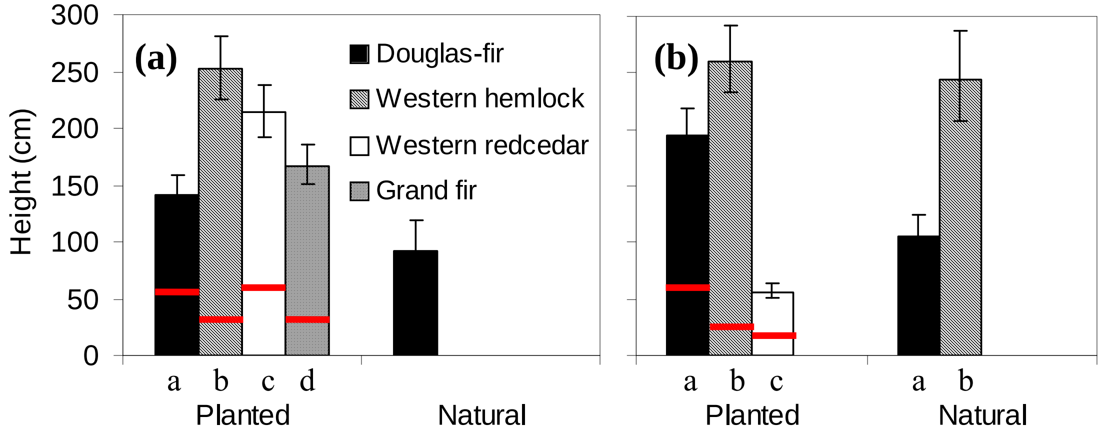

Figure 3.1. Comparison of median conifer heights at (a) McDonald and (b) Blodgett. Letters indicate statistically significant differences within a regeneration method using a Tukey HSD multiple comparison test (α=0.05). Horizontal lines approximate heights at time of planting.

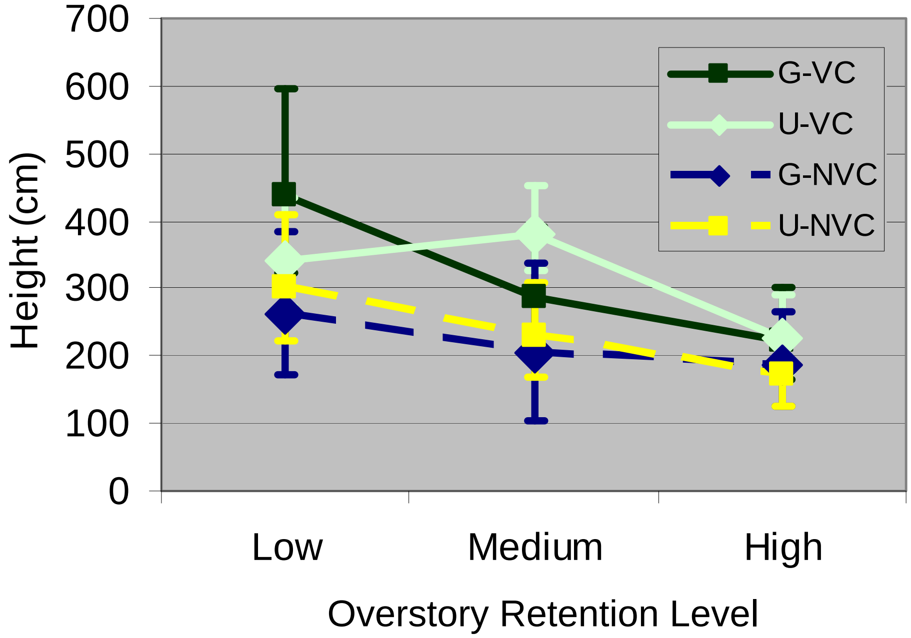

Figure 3.2. Heights of planted hemlock at Blodgett across treatment levels (G = gappy, U = uniform, VC = vegetation control, NVC = no vegetation control). Error bars are 95% confidence intervals calculated from a Tukey HSD multiple comparison test.

Table 3.1. ANOVA table for year 10 seedling heights, basal diameters, height-diameter ratios, and recent height growth rates at McDonald. Bold indicates statistical significance at α=0.05. P, thinning pattern; O, overstory retention level; V, vegetation control; PSME, Douglas-fir; TSHE, western hemlock; THPL, western redcedar; and ABGR, grand fir.

	Df	*Height*		*Basal diam.*		*H-D ratio*		*HGR*	
Effect	*N,D*	*F*	*Pr > F*	*F*	*Pr > F*	*F*	*Pr > F*	*F*	*Pr > F*
Planted									
PSME									
P	1,2	3.86	0.1885	3.48	0.2030	0.09	0.7906	5.39	0.1459
O	3,11	**4.31**	**0.0306**	**13.8**	**0.0005**	**12.0**	**0.0008**	**7.48**	**0.0053**
P*O	3,11	1.12	0.3814	1.04	0.4147	0.45	0.7255	0.14	0.9325
V	1,13[a]	1.55	0.2349	**16.4**	**0.0014**	**27.9**	**0.0001**	1.26	0.2827
P*V	1,13[a]	0.55	0.4722	0.43	0.5258	0.47	0.5053	0.38	0.5497
O*V	3,13[a]	0.57	0.6436	1.77	0.2029	**5.45**	**0.0210**	0.64	0.6035
P*O*V	3,13[a]	1.35	0.3022	3.38	0.0513	0.35	0.7867	2.15	0.1435
TSHE									
P	1,2	2.92	0.2298	3.40	0.2063	3.69	0.1948	8.40	0.1013
O	3,12	**4.80**	**0.0202**	**4.66**	**0.0221**	2.46	0.1129	**6.72**	**0.0065**
P*O	3,12	0.28	0.8416	0.74	0.5497	2.10	0.1540	0.24	0.8702
V	1,14	**6.71**	**0.0214**	**16.5**	**0.0012**	**24.1**	**0.0002**	**6.17**	**0.0262**
P*V	1,14	0.05	0.8290	0.06	0.8164	2.52	0.1344	0.00	0.9693
O*V	3,14	0.28	0.8415	0.63	0.6106	2.25	0.1277	0.29	0.8348
P*O*V	3,14	2.20	0.1335	2.75	0.0817	1.37	0.2936	1.21	0.3431
THPL									
P	1,2	0.94	0.4354	2.35	0.2648	5.47	0.1442	2.42	0.2602
O	3,12	**16.9**	**0.0001**	**17.8**	**0.0001**	**10.2**	**0.0013**	**12.1**	**0.0006**
P*O	3,12	0.07	0.9764	0.09	0.9669	0.13	0.9417	0.25	0.8573
V	1,14	**8.39**	**0.0105**	**11.0**	**0.0043**	**23.4**	**0.0002**	**6.75**	**0.0194**
P*V	1,14	3.33	0.0867	3.28	0.0891	**6.06**	**0.0256**	1.05	0.3198
O*V	3,14	0.98	0.4257	0.66	0.5897	0.81	0.5067	0.98	0.4280
P*O*V	3,14	0.65	0.5961	0.36	0.7846	0.05	0.9831	0.49	0.6927
ABGR									
P	1,2	0.36	0.6111	0.44	0.5738	0.17	0.7201	0.20	0.7018
O	3,12	**6.00**	**0.0097**	**6.42**	**0.0077**	2.83	0.0834	**4.60**	**0.0230**
P*O	3,12	0.57	0.6467	0.52	0.6783	0.36	0.7823	0.65	0.5980
V	1,14	**15.0**	**0.0013**	**32.2**	**0.0000**	**48.8**	**0.0000**	**32.7**	**0.0000**
P*V	1,14	0.13	0.7224	1.00	0.3315	3.47	0.0811	1.23	0.2836
O*V	3,14	0.85	0.4860	0.97	0.4310	0.81	0.5071	**4.07**	**0.0251**
P*O*V	3,14	1.81	0.1862	2.41	0.1052	2.9	0.0649	1.84	0.1808
Natural									
PSME									
P	1,2	1.03	0.4175	3.00	0.2252	10.2	0.0853	1.03	0.4175
O	2,8	2.85	0.1164	2.15	0.1788	1.01	0.4055	2.85	0.1164
P*O	2,8	0.63	0.5579	0.38	0.6939	3.14	0.0984	0.63	0.5579
V	1,8[b]	0.05	0.8358	2.33	0.1656	5.13	0.0534	0.05	0.8358
P*V	1,8[b]	0.06	0.8106	0.02	0.8842	0.14	0.7175	0.06	0.8106
O*V	2,8[b]	1.19	0.3535	0.49	0.6321	0.05	0.9514	1.19	0.3535
P*O*V	2,8[b]	1.47	0.2861	0.74	0.5083	1.14	0.3677	1.47	0.2861

[a] Lower df for planted Douglas-fir due to lack of regeneration in one subplot.
[b] Lower df for natural Douglas-fir due to lack of regeneration in four subplots.

Table 3.2. Comparison of median heights (cm) of planted and dominant naturally-regenerated conifers across treatment levels ten years after thinning. Values for each treatment type within a given row with different letters are significantly different ($p<0.05$). PSME, Douglas-fir; TSHE, western hemlock; THPL, western redcedar; and ABGR, grand fir.

	Thinning Pattern		Overstory Retention Level				Vegetation Control	
	Gappy	Uniform	Low	Medium	High	V. High	Yes	No
McDonald								
Planted								
PSME	165 *a*	123 *a*	174 *a*	152 *ab*	137 *ab*	113 *b*	150 *a*	135 *a*
TSHE	270 *a*	234 *a*	309 *a*	257 *ab*	255 *ab*	198 *b*	279 *a*	227 *b*
THPL	227 *a*	202 *a*	282 *a*	231 *a*	222 *a*	145 *b*	230 *a*	199 *b*
ABGR	172 *a*	164 *a*	206 *a*	184 *a*	158 *ab*	130 *b*	188 *a*	149 *b*
Natural								
PSME	98 *a*	86 *a*	109 *a*	94 *a*	75 *a*	----	93 *a*	91 *a*
Blodgett								
Planted								
PSME	203 *a*	188 *a*	227 *a*	192 *b*	171 *b*	----	209 *a*	182 *b*
TSHE[1]	256 *a*	265 *a*	331 *a*	267 *b*	200 *c*	----	306 *a*	221 *b*
THPL[2]	55	58	70 *a*	53 *b*	48 *b*	----	57	56
Natural								
PSME	118 *a*	96 *a*	140 *a*	107 *ab*	81 *b*	----	114 *a*	100 *a*
TSHE	251 *a*	238 *a*	312 *a*	250 *ab*	187 *b*	----	254 *a*	236 *a*

[1] A thinning pattern x overstory retention level x vegetation control interaction technically prohibits the interpretation of main treatment effects (see Figure 3.2). However, removal of an unusual outlying data point eliminated the interaction and revealed strong correlations between planted hemlock heights and overstory retention level and vegetation control.

[2] A thinning pattern x vegetation control interaction technically prevents the interpretation of the main effects of these two treatments. However, no combination of these treatments is significantly different from the other three combinations, and any differences that did exist would be minor.

Table 3.3. Comparison of heights, basal diameters, H:D ratios, and recent average annual height growth rate of planted and dominant naturally-regenerated conifers between gaps and the surrounding matrix within gappy treatments. Heights, basal diameters, and recent height growth rates are back transformed from log scale and represent medians. Values with different letters are significantly different ($p<0.05$). PSME, Douglas-fir; TSHE, western hemlock; THPL, western redcedar; and ABGR, grand fir.

	Height (cm)		BD (mm)		H:D Ratio		AHGR (cm)	
	Gap	Matrix	Gap	Matrix	Gap	Matrix	Gap	Matrix
McDonald								
Planted								
PSME	201 *a*	138 *b*	25.3 *a*	16.3 *b*	82.8 *a*	86.8 *a*	20 *a*	9 *b*
TSHE	313 *a*	242 *a*	40.0 *a*	29.3 *a*	84.5 *a*	85.3 *a*	34 *a*	26 *b*
THPL	298 *a*	208 *b*	45.1 *a*	29.0 *b*	74.6 *a*	75.5 *a*	26 *a*	18 *b*
ABGR	199 *a*	163 *a*	27.8 *a*	22.8 *a*	73.2 *a*	73.4 *a*	14 *a*	12 *a*
Natural								
PSME	122 *a*	95 *a*	20.3 *a*	19.0 *a*	89.4 *a*	79.1 *a*	17 *a*	16 *a*
Blodgett								
Planted								
PSME	251 *a*	183 *b*	31.3 *a*	20.3 *b*	83.2 *a*	94.4 *b*	26 *a*	16 *b*
TSHE	371 *a*	237 *b*	41.1 *a*	22.2 *b*	95.8 *a*	110.3 *b*	47 *a*	26 *b*
THPL	69 *a*	52 *b*	7.1 *a*	5.0 *b*	101.2 *a*	108.8 *b*	7 *a*	5 *b*
Natural								
PSME	135 *a*	110 *a*	15.7 *a*	10.7 *a*	96.7 *a*	113.5 *a*	18 *a*	14 *a*
TSHE	361 *a*	242 *b*	37.2 *a*	21.0 *b*	104.5 *a*	121.9 *b*	51 *a*	32 *b*

Table 3.4. ANOVA table for year 10 seedling heights, basal diameters, height-diameter ratios, and recent height growth rates at Blodgett. Bold indicates statistical significance at α=0.05. P, thinning pattern; O, overstory retention level; V, vegetation control; PSME, Douglas-fir; TSHE, western hemlock; and THPL, western redcedar.

	Df	*Height*		*Basal diam.*		*H-D ratio*		*HGR*	
Effect	*N,D*	*F*	*Pr > F*	*F*	*Pr > F*	*F*	*Pr > F*	*F*	*Pr > F*
Planted									
PSME									
P	1,2	1.91	0.3007	1.25	0.3800	0.14	0.7447	0.23	0.6802
O	2,8	**10.1**	**0.0066**	**11.3**	**0.0046**	4.19	0.0568	**13.2**	**0.0029**
P*O	2,8	0.78	0.4912	0.17	0.8442	0.72	0.5151	0.41	0.6747
V	1,12	**6.76**	**0.0233**	**16.9**	**0.0014**	**14.1**	**0.0027**	**14.7**	**0.0024**
P*V	1,12	0.75	0.4048	1.13	0.3090	0.25	0.6229	1.03	0.3298
O*V	2,12	0.08	0.9219	0.27	0.7703	0.86	0.4479	0.41	0.6739
P*O*V	2,12	0.23	0.7962	0.04	0.9567	0.14	0.8733	0.33	0.7278
TSHE									
P	1,2	0.04	0.8548	0.00	0.9790	0.06	0.8316	0.00	0.9671
O	2,8	**36.9**	**0.0000**	**38.6**	**0.0000**	4.46	0.0501	**43.3**	**0.0000**
P*O	2,8	2.87	0.1149	3.57	0.0781	1.61	0.2579	3.49	0.0811
V	1,12	**58.7**	**0.0000**	**76.2**	**0.0000**	**51.5**	**0.0000**	**65.7**	**0.0000**
P*V	1,12	0.29	0.6022	0.61	0.4490	1.49	0.2457	0.50	0.4912
O*V	2,12	1.95	0.1844	2.25	0.1485	1.73	0.2191	1.51	0.2606
P*O*V	2,12	**4.19**	**0.0416**	3.17	0.0785	1.25	0.3217	2.91	0.0932
THPL									
P	1,2	0.72	0.4863	3.80	0.1907	1.78	0.3142	0.72	0.4863
O	2,8	**14.7**	**0.0021**	**38.2**	**0.0000**	0.57	0.5877	**10.5**	**0.0059**
P*O	2,8	0.55	0.5973	1.90	0.2116	0.48	0.6334	1.35	0.3123
V	1,12	0.38	0.5498	**11.1**	**0.0059**	**7.37**	**0.0188**	**4.83**	**0.0483**
P*V	1,12	**9.35**	**0.0099**	3.80	0.0750	1.28	0.2804	2.42	0.1461
O*V	2,12	0.16	0.8515	0.52	0.6064	0.61	0.5602	0.04	0.9593
P*O*V	2,12	0.11	0.8992	1.85	0.1996	0.48	0.6276	0.46	0.6401
Natural									
PSME									
P	1,2	2.95	0.2278	3.15	0.2181	0.43	0.5775	1.62	0.3310
O	2,8	**6.61**	**0.0202**	**6.47**	**0.0213**	1.68	0.2457	**5.18**	**0.0360**
P*O	2,8	0.47	0.6387	0.47	0.6392	0.11	0.9009	1.08	0.3832
V	1,10[a]	1.23	0.2926	1.80	0.2096	**6.05**	**0.0337**	2.89	0.1198
P*V	1,10[a]	0.76	0.4026	0.76	0.4028	2.33	0.1582	0.17	0.6915
O*V	2,10[a]	0.61	0.5621	0.35	0.7105	0.03	0.9669	0.69	0.5258
P*O*V	2,10[a]	0.17	0.8464	0.41	0.6729	3.70	0.0628	0.07	0.9343
TSHE									
P	1,2	0.12	0.7602	0.15	0.7386	0.76	0.4749	0.00	0.9509
O	2,8	4.20	0.0567	**5.01**	**0.0389**	1.43	0.2938	**6.11**	**0.0245**
P*O	2,8	1.26	0.3348	1.45	0.2907	2.37	0.1559	1.44	0.2923
V	1,12	0.61	0.4509	0.27	0.6109	0.08	0.7812	4.39	0.0580
P*V	1,12	0.09	0.7730	0.00	0.9670	0.50	0.4923	0.05	0.8301
O*V	2,12	0.78	0.4820	0.85	0.4526	0.46	0.6440	0.71	0.5130
P*O*V	2,12	0.07	0.9354	0.24	0.7892	2.64	0.1122	0.21	0.8153

[a] Lower df for natural Douglas-fir due to lack of regeneration in two subplots.

Table 3.5. Comparison of recent annual height growth rates (cm) over the past three years for planted and dominant naturally-regenerated seedlings across treatment levels. Growth rates are back transformed from natural log scale and represent medians. Values for each treatment type within a given row with different letters are significantly different ($p<0.05$). PSME, Douglas-fir; TSHE, western hemlock; THPL, western redcedar; and ABGR, grand fir.

	Thinning Pattern		Overstory Retention Level				Vegetation Control	
	Gappy	Uniform	Low	Medium	High	V. High	Yes	No
McDonald								
Planted								
PSME	15 *a*	8 *a*	18 *a*	13 *ab*	10 *bc*	7 c	12 *a*	10 *a*
TSHE	29 *a*	20 *a*	33 *a*	27 *a*	26 *a*	15 *b*	28 *a*	21 *b*
THPL	20 *a*	16 *a*	27 *a*	20 *a*	19 *a*	9 *b*	20 *a*	15 *b*
ABGR	13 *a*	12 *a*	16 *a*[1]	13 *ab*	13 *ab*	8 *b*[1]	15 *a*[2]	10 *b*[2]
Natural								
PSME	16 *a*	13 *a*	15 *a*	17 *a*	11 *a*	----	16 *a*	12 *a*
Blodgett								
Planted								
PSME	19 *a*	18 *a*	25 *a*	18 *b*	14 *b*	----	22 *a*	15 *b*
TSHE	29 *a*	29 *a*	40 *a*	30 *a*	20 *b*	----	37 *a*	23 *b*
THPL	5 *a*	5 *a*	6 *a*	5 *b*	5 *b*	----	6 *a*	5 *b*
Natural								
PSME	15 *a*	11 *a*	18 *a*	13 *ab*	8 *b*	----	15 *a*	11 *a*
TSHE	33 *a*	33 *a*	45 *a*	34 *ab*	23 *b*	----	36 *a*	30 *a*

[1] Difference between low and very high is only significant in subplots where vegetation was not controlled.

[2] Difference is only significant in the medium and ultra high retention levels.

Table 3.6. Comparison of median basal diameters (mm) of planted and dominant naturally-regenerated conifers across treatment levels ten years[1] after thinning. Values for each treatment type within a given row with different letters are statistically significantly different ($p<0.05$). PSME, Douglas-fir; TSHE, western hemlock; THPL, western redcedar; and ABGR, grand fir.

	Thinning Pattern		Overstory Retention Level				Vegetation Control	
	Gappy	Uniform	Low	Medium	High	V High	Yes	No
McDonald								
Planted								
PSME	20 *a*	14 *a*	22 *a*	19 *a*	18 *a*	11 *b*	20 *a*	15 *b*
TSHE	33 *a*	27 *a*	36 *a*	31 *ab*	32 *ab*	22 *b*	36 *a*	25 *b*
THPL	32 *a*[2]	26 *a*[2]	42 *a*	32 *a*	32 *a*	17 *b*	33 *a*[3]	25 *b*[3]
ABGR	24 *a*	23 *a*	28 *a*	26 *a*	23 *ab*	17 *b*	28 *a*	19 *b*
Natural								
PSME[1]	19 *a*	14 *a*	19 *a*	17 *a*	12 *a*	----	17 *a*	14 *a*
Blodgett								
Planted								
PSME	23 *a*	21 *a*	27 *a*	21 *b*	18 *b*	----	25 *a*	19 *b*
TSHE[4]	26 *a*	26 *a*	34 *a*	27 *b*	19 *c*	----	33 *a*	21 *b*
THPL	5 *a*	6 *a*	7 *a*	5 *b*	5 *b*	----	6 *a*	5 *b*
Natural								
PSME	12 *a*	9 *a*	14 *a*	10 *ab*	8 *b*	----	12 *a*	10 *a*
TSHE	22 *a*	21 *a*	28 *a*	22 *ab*	15 *b*	----	22 *a*	21 *a*

[1] Basal diameters for natural Douglas-fir at McDonald were measured 13 years after thinning.
[2] Difference is significant when vegetation was not controlled.
[3] Difference is only significant in the uniform pattern.
[4] A thinning pattern x overstory retention level x vegetation control interaction confounds the interpretation of main effects. However, trends are very similar to those shown for height in Figure 6.

Table 3.7. Comparison of average H:D ratios of planted and dominant naturally-regenerated conifers across treatment levels ten years[1] after thinning. Values for each treatment type within a given row with different letters are statistically significantly different ($p<0.05$). PSME, Douglas-fir; TSHE, western hemlock; THPL, western redcedar; and ABGR, grand fir.

	Thinning Pattern		Overstory Retention Level				Vegetation Control	
	Gappy	Uniform	Low	Medium	High	V. High	Yes	No
McDonald								
Planted								
PSME	86.1 *a*	88.1 *a*	77.9 *a*[2]	84.3 *a*	79.6 *a*	106.6 *b*[2]	78.4 *a*[3]	95.8 *b*[3]
TSHE	84.6 *a*	90.3 *a*	89.9 *a*	84.1 *a*	83.4 *a*	92.4 *a*	80.7 *a*	94.2 *b*
THPL	75.2 *a*[4]	81.4 *a*[4]	71.2 *a*	76.9 *a*	74.5 *a*	90.6 *b*	71.9 *a*[5]	84.8 *b*[5]
ABGR	73.3 *a*	74.0 *a*	73.5 *a*	72.7 *a*	70.7 *a*	77.7 *a*	67.6 *a*	79.8 *b*
Natural								
PSME[1]	82.3 *a*	95.7 *a*	85.3 *a*	92.8 *a*	88.8 *a*	----	84.2 *a*	93.7 *a*
Blodgett								
Planted								
PSME	91.9 *a*	94.2 *a*	86.8 *a*	94.1 *ab*	98.2 *b*	----	86.9 *a*	99.2 *b*
TSHE[2]	107.8 *a*	108.9 *a*	105.6 *a*	106.9 *a*	112.5 *a*	----	101.1 *a*	115.6 *b*
THPL	107.0 *a*	101.1 *a*	101.1 *a*	104.3 *a*	106.8 *a*	----	99.1 *a*	109.1 *b*
Natural								
PSME	105.4 *a*	112.0 *a*	101.8 *a*	109.8 *a*	114.5 *a*	----	113.0 *a*	104.4 *b*
TSHE	120.4 *a*	124.5 *a*	118.3 *a*	121.3 *a*	127.7 *a*	----	121.8 *a*	123.1 *a*

[1] H:D Ratio for natural Douglas-fir is based on measurements taken 13 years after thinning.
[2] Difference is only significant when vegetation was not controlled.
[3] Difference is only significant in subplots thinned to a high or very high retention level.
[4] Difference is significant when vegetation was not controlled.
[5] Difference is only significant in uniformly thinned subplots.

Table 3.8. Percentage of recorded seedlings suffering damage. Browsing damage is separated by percentage of all seedlings browsed and percentage of seedlings less than 1.5 meters tall browsed. Percentage for other is for the next most prevalent damage type, which is listed afterwards.

	Overall	**Browsed** All (<1.5 m)	**Top Dieback**	**Other**	**Other Type**
McDonald					
Planted					
Douglas-fir	73.1	42.5 (51.8)	21.0	4.5	Rodent girdling
Western hemlock	32.0	3.9 (2.2)	10.0	7.6	Antler rubbing
Western redcedar	57.0	37.8 (63.6)	7.1	9.5	Antler rubbing
Grand fir	34.8	2.2 (2.0)	12.0	5.3	Rodent girdling
Natural					
Douglas-fir	63.3	50.8 (55.9)	1.9	4.8	Rodent girdling
Blodgett					
Planted					
Douglas-fir	47.6	29.1 (38.5)	7.2	3.0	Loss of terminal bud
Western hemlock	35.7	0.2 (0.5)	11.9	10.7	Lateral dieback
Western redcedar	71.2	60.8 (61.3)	4.6	2.7	Top clipping
Natural					
Douglas-fir	46.2	28.3 (28.8)	4.0	4.6	Mechanical damage
Western hemlock	12.1	0.0 (0.0)	1.3	2.6	Top clipping

Table 3.9. Comparison of recent annual height growth rates between undamaged seedlings and either seedlings suffering from any type of damage or seedlings suffering specifically from browsing damage. Values are back transformed from the natural log scale, and represent the median. Letters indicate significantly different growth rates for undamaged and damaged or undamaged and browsed seedlings ($p<0.05$).

	Annual Height Growth (cm)		
	Undamaged	**Damaged**	**Browsed**
McDonald			
Planted			
Douglas-fir	20 *a*	7 *b*	9 *b*
Western hemlock	25 *a*	19 *b*	----
Western redcedar	22 *a*	12 *b*	9 *b*
Grand fir	13 *a*	8 *b*	----
Natural			
Douglas-fir	19 *a*	10 *b*	9 *b*
Blodgett			
Planted			
Douglas-fir	22 *a*	15 *b*	15 *b*
Western hemlock	31 *a*	24 *b*	----
Western redcedar	6 *a*	5 *b*	5 *b*
Natural			
Douglas-fir	12 *a*	12 *a*	13 *a*
Western hemlock	33 *a*	26 *a*	----

CHAPTER 4: CONCLUSIONS

The overall objective of our study was to determine the extent to which different levels and patterns of overstory thinning accompanied by vegetation control would result in an understory conifer layer that, after 10-13 years, is on a trajectory to contribute to the first stages of development of a multilayered canopy. Within this overall objective, we also wanted to (1) evaluate whether natural regeneration alone may result in the development of an understory conifer layer or whether underplanting would be necessary to improve seedling distribution and/or growth and (2) determine how the development of the understory conifer layer differs between a moister site with a substantial component of western hemlock in the overstory and a drier site with a mostly pure Douglas-fir overstory.

Findings from our study indicate that thinning to overstory retention levels below those commonly associated with maximizing timber production has the potential to create a productive understory conifer layer after 10-13 years. Seedling growth generally increased under lower overstory densities, and at the drier site, establishment and survival of understory conifers was also higher under lower overstory densities. Shade-tolerant species generally outperformed the moderately shade-intolerant Douglas-fir in terms of establishment, survival, and growth across the range of overstory retention levels used in our study (RD 2.5-5.0); however, Douglas-fir remained a component in the understory of stands thinned to the lower end of this range. Western hemlock exhibited the greatest potential for growth in an understory environment. Western redcedar performed comparably to western hemlock when browsing pressure was relatively low, demonstrating the potential for growing this commercially valuable species under thinned stands if damage from browsing can be minimized.

An overstory thinning regime with the creation of small gaps (0.06- and 0.1-ha) across 20 percent of the stand did not result in significant differences in the establishment, survival, or growth of understory conifers at the stand-level relative to the use of uniform thinning. However, the highest seedling growth at both study sites was generally observed in gaps. Furthermore, large differences in growth occurred between gaps and the surrounding forest matrix within the “gappy” thinning pattern, suggesting the creation of a more heterogeneous understory. In the absence of future thinnings, the importance of gaps in the maintenance of a productive understory conifer layer would be expected to increase over time, especially under higher overstory retention levels.

The use of vegetation control in conjunction with overstory thinning showed promise for expediting the creation of an understory conifer layer under thinned stands in our study. In most cases, vegetation control led to an increase in the survival rate and size of underplanted seedlings after ten years, and these larger seedlings continued to exhibit greater annual height growth rates than seedlings found in unsprayed stands. Vegetation control also resulted in significantly higher establishment of naturally-regenerated Douglas-fir. While growth gains for dominant naturally-regenerated seedlings were generally not as large as those for underplanted seedlings, vegetation control appeared to lead to a higher rate of recruitment into larger height classes for both naturally-regenerated Douglas-fir and western hemlock. Vegetation control also led to decreased or modified shrub cover.

The potential role of natural conifer regeneration in the eventual creation of a multilayered canopy differed between the two sites used in our study. Where western hemlock comprised a significant portion of the overstory (averaging 45% across the site) alongside Douglas-fir, prolific regeneration of western hemlock occurred in the understory. Because the growth of dominant naturally-regenerated western hemlock seedlings rivaled that of planted hemlock and exceeded that of planted Douglas-fir and western redcedar at this site, natural regeneration alone has the potential to contribute significantly to the development of an understory conifer layer. However, because dense “thickets” of natural hemlock regeneration often overtopped naturally-regenerated Douglas-fir and excluded shrubs and herbaceous vegetation in many areas, objectives related to understory biological diversity might not be met. Thinning within the understory conifer layer may be required to enhance species diversity in addition to promoting the development of additional canopy layers.

Where Douglas-fir dominated the overstory stand with a few grand fir and hardwoods intermixed, natural regeneration consisted of sporadic Douglas-fir with isolated patches of grand fir. Although natural regeneration establishment increased under decreasing levels of overstory retention (and in the presence of vegetation control), even at the lowest level of overstory retention (RD 2.6), naturally-regenerated Douglas-fir seedlings (and grand fir seedlings where they occurred) were relatively small compared to their underplanted counterparts and much smaller than underplanted western hemlock and western redcedar. As a result, in thinned stands with nearly pure Douglas-fir overstories, underplanting may be considered desirable to improve the distribution and/or increase growth rates within the understory conifer layer.

While our study demonstrates the potential for overstory thinning accompanied by vegetation control to promote the eventual development of a multilayered canopy, at least four caveats exist. First, vigorous young overstories in our study exhibited rapid crown closure following thinning. As a result, future thinnings would be required to maintain adequate levels of survival and growth within the understory conifer layer. Even if done carefully, harvesting operations associated with each thinning would kill or damage some understory conifers (Newton and Cole 2006). Second, the slow growth of conifers under thinned stands relative to growth rates often achieved in full sunlight suggests that the achievement of a multilayered canopy may require 30 years or more plus additional entries after initial thinning, even in more heavily thinned stands. Third, heavier thinnings that create more suitable conditions for understory conifer growth may also increase the likelihood of windthrow in the overstory and invasions by exotic plant species in the understory (Bailey et al. 1998, Thysell and Carey 2000, Chan et al. 2006). Finally, the opportunity costs associated with management towards late-successional forest structure (Latta and Montgomery 2004) and the uncertainty of achieving desired outcomes must be acceptable to the landowner. It is unlikely that two-aged or multi-aged management in the Oregon Coast Range has the potential to generate similar financial returns to even-aged management of Douglas-fir; however, if management objectives favor the creation of a multilayered canopy comprised of multiple species and age classes, the use of overstory thinning, understory vegetation control and in some cases planting, may provide the means for achieving these objectives. Pre-commercial thinning of the understory conifer layer may also be required if the initial understory conifer layer excludes other desirable vegetation or prohibits the establishment of additional canopy layers over time.

Results and conclusions in our study are based on development of an understory conifer layer 10-13 years after it was created. Further research is required to evaluate the longer-term development of multilayered canopies in thinned, second-growth Douglas-fir stands as overstory-understory interactions continue to evolve. Research would also be required to determine whether the structural development of these stands actually meets the needs of wildlife it was intended to benefit.

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