Understory development in thinned stands as part of a long-term ecosystem productivity study

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Abstract

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Understory species diversity and composition influences forest ecosystems in a myriad of ways including influencing natural tree regeneration and growth, providing food and habitat for wildlife, creating soil stability, changing soil nutrient availability, and more. The understory is both influencing and being influenced by the overstory layer as they shape the outcomes of one another. In the Long-Term Ecosystem Productivity Study based on the Olympic Peninsula, treatments were implemented in 1995 to assess the effects of species composition, management regimes, and levels of down wood retention on soil productivity and vegetation. Early and mid seral treatments included clearcutting the existing second growth (70-year old forest) and replanting with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plus red alder (*Alnus rubra* Bong.) and purely Douglas-fir respectively. The late seral treatment included selective thinning of the exiting second-growth forest. Finally, control units were left as is. Three levels of woody debris were left on site in each of these treatments and control plots were left unmanaged.

Pre-treatment and multiple post-treatment measurements were taken in 600 understory plots throughout 40 mensuration plots since the study began. I used understory data I collected in 2016 as well as archived data from previous years. The understory species composition, percent

cover, and tree seedling and sapling density were sampled at each plot. These variables were analyzed across treatments and over time. Control and late treatments showed an increase in understory species, but with far less overall cover compared to the early and mid treatments over time. Early and mid treatments showed a substantial increase in evergreen woody shrubs and deciduous ferns in the 20 years post treatment, with salal (*Gaultheria shallon* Pursh) and bracken fern (*Pteridium aquilinum* (L.) Kuhn) being the dominant species in each group. A natural tree regeneration count showed fewer seedlings and saplings growing in the early and mid treatments compared to the late treatments. The late treatments showed a clear pattern of growth over time where smaller seedlings grew to become larger seedlings by the next measurement. Overall species richness and evenness peaked in 2002 and was followed by a decline in 2016. This indicates certain understory species are outcompeting others for nutrients, space, and light. Stands with high densities of understory cover led to far fewer tree regeneration counts, which will in turn change the future of the overstory layer.

The addition of red alder led to greater survival and establishment of Douglas-fir, a highly valued timber product, and fewer western hemlock, a species that often grows in dense patches. This could led to less pre-commercial thinning of western hemlock and the promotion of a target species, overall reducing management costs.

When comparing this study to another Long-Term Productivity Study in southwestern Oregon, the results were very similar (Bormann et al., 2015). Early and mid seral treatment units on both sites saw a pulse of understory growth and a decline in species richness 15 years after treatments were implemented. Control and late treatments had increases in cover over time but not nearly as high as the other treatments. This indicates a pattern is occurring across these ecosystems. Overall, when evaluating any given part of this data, the results appear vastly different than when looking across all years, meaning that these ecosystems are dynamic and we cannot extrapolate beyond the timeframe of studies to understand how the forest will change over time. This creates a need for more long-term studies to fully evaluate best management strategies.

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Introduction

Changes in forest management on the Olympic Peninsula

The Olympic Peninsula, located west of the Puget Sound in Washington State, encompasses dense forested land with a mixture of land ownership including National Park, National Forest, state lands managed by Washington Department of Natural Resources, private, and tribal land. Many different groups of people have an interest in how this area is managed, including local residents, recreational users such as hikers, fishers, and hunters, environmentalists, and large companies focused on timber production.

During the 1970s and 1980s, the Olympic Peninsula's primary industry was timber, providing thousands of jobs to workers in places like Aberdeen, Forks, and Port Angeles, WA. The conversion of most of the original forests, including many old-growth stands, to plantations raised widespread concern, especially for the preservation of the Northern Spotted Owl (*Strix occidentalis caurina*) and the Marbled Murrelet *(Brachyramphus marmoratus)* that relied on these old-growth stands for habitat. In 1990, the Northern Spotted Owl was listed as part of The Endangered Species Act followed by the Marbled Murrelet in 1992 due to a large loss of habitat and a lack of effective regulations around their protection (US Fish and Wildlife, 2011). The owl listing led to a temporary halt on timber sales and the setting aside of over 6 million acres on federal lands in Washington, Oregon, and northern California for late-successional habitat (Dark, 1997). Throughout the 1970s, 1980s, and 1990s, the timber industry was also changing in the Pacific Northwest. Many mills were closing due to recessions, market fluctuations, and mill modernization as well as major restrictions to timber harvesting. As a result, many people lost their jobs and the logging and management approaches began to change on the Olympic Peninsula.

The listing of these species was followed by the adoption of the Northwest Forest Plan in 1994 that designated specific land use categories and regulations on federal land that further restricted timber harvesting on the Olympic Peninsula and throughout the Pacific Northwest. This Plan created reserves for both riparian and old-growth areas with the intention of maintaining important habitat for both wildlife and plant species relying on these ecosystems. The intention was to create one single plan instead of individualized plans for each species. It incorporated adaptive management practices with monitoring so adjustments could be made based on the results of this plan and new scientific knowledge (Haynes et al., 2006). Over the last 20 years, the overall success of the Northwest Forest Plan was complicated by a dynamic environment being altered by natural disturbances as well as the predation of the Northern Spotted Owl by the Barred Owl (*Strix varia*) (Haynes et al., 2006). Although this plan added key protections for late-successional and old-growth habitat, early-successional forests were not represented directly in the reserves created. The Plan assumed that there was an adequate amount of early-successional habitat on private lands. In the resulting bifurcated landscapes– conservation areas and production forests - little emphasis was put on managing land for both ecological values and commodity production at the same time. More importantly, little was investing in learning about the outcome of such approach. This realization prompted the USDA Forest Service, Pacific Northwest Research Station, Washington DNR, and regional universities to began the long-term ecosystem productivity study (LTEP), used as the basis for this thesis. This study was created to evaluate forest dynamics including forest succession, seral stages, woody debris, understory and overstory changes, and more in a comprehensive, long-term ecosystem study.

Forest Succession

The fields of conservation biology and disturbance ecology are both based on the idea that at any one point in time a reasonable distribution of successional stages is important to maintain biodiversity and forest productivity. The ways in which reserve systems and management interact with succession have therefore received much attention. These concepts continue to evolve and guide management. Forest succession is most often represented as a time-driven change in structure, incorporating components like tree size, canopy layers, and stand age (Thomas, 1979). Different labels and definitions have been placed on the various successional stages. Oliver (1980) describes four stages as: stand initiation, stem exclusion, understory reinitiation, and old-growth. These four stages represent a progression of a forest from an initial disturbance to a fully developed forest, each with specific characteristics. Ecosystem dynamics driven by variation in disturbance intensity and its resulting biotic responses complicate how succession concepts are applied in management decisions. Some examples include: minor disturbances during development of a stand alter trajectories (Cissel et al. 1999); major disturbances can sometimes be quickly repeated as in re-burn events (Donato et al. 2009). Such historical artifacts set up highly variable starting conditions for subsequent disturbances. It follows that each stand will have a complex history, thus there are multiple rather than single successional pathways (Turner 1983).

The LTEP study explores plant composition, various underlying processes, and structures associated with different successional stages—all of which can be manipulated in silvicultural prescriptions to achieve ecological diversity and productivity goals.

Plants are naturally adapted to grow more effectively in certain successional stages or in a range of stages based on their light and soil requirements, reproduction, and seed availability. The type and timing of a disturbance and the makeup of the forest post disturbance will greatly impact the types of plant species that will repopulate the area. In the LTEP study, these dynamics have been set and manipulated to understand how the plant composition changes the stand development. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) and red alder (*Alnus rubra* Bong.) have been planted in some experimental plots, while western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and understory species have been removed through mechanisms like harvesting and pre-commercial and commercial thinning.

Plants are also influencing and being influenced by species-specific physiological processes. Some species, like salal (*Gaultheria shallon* Pursh) and bracken fern (*Pteridium aquilinum* (L.) Kuhn), can hold nutrients in their live leaf matter and prevent nearby plants from accessing them (Messer and Kimmins, 1991; Fenn et al., 1996). Others, such as red alder, can fix atmospheric nitrogen and hold it in the soil, increasing its availability to other plants growing nearby (Perakis et al., 2012). These mechanisms are present on the LTEP site, and may be changing how the forest stand develops. Because these plants can drive and impact forest processes, management to change composition is thought to do so as well.

As the forest stand develops, its structure (vertical stratification and horizontal arrangement of trees) changes. Although many studies, including LTEP, have studied the forest structural and composition changes during succession, they rarely consider key ecosystem processes such as nutrient availability, soil development, energy flow, or nitrogen fixation (Bormann et al., 2015). Other studies seek to understand the progression of early-successional to late-successional forests and how to achieve this quicker. Less research has been focused on investigating the early-successional forest and its structure exclusively (Campbell and Donato, 2013). LTEP, set-up to be a 200-year study, explores how both structure and important ecosystem processes are changing in forest stands.

Early- and Late-Seral Stages

The LTEP study investigates aspects of early-, mid- and late-seral forests through its treatments. Early- and mid-seral treatments were both created by clear-cutting and replanting with the intention that over time these units would develop into early- and mid-seral forests. Early-seral forests can be created by both forest management practices like clearcutting and by natural disturbance events such as wildfires, severe flooding, or strong wind storms and result in a total stand replacement.

The early-seral stage occurs after large-scale disturbance events and before the time of canopy closure (Swanson et al., 2011). There is not one clear mold for an early-seral forest. Each will have its own unique composition that is dependent on the cause of the disturbance event and can vary in terms of surviving trees, downed wood, snags, and open spaces. Traditional plantation-style forestry seeks to minimize these attributes by speeding development of mid-seral conifer stands (Franklin et al., 2002). In addition, there has been a shift in the last century from natural disturbances driving change to human manipulation of ecosystems for timber production. This often entailed creating even-aged conifer stands on short rotations (Halpern and Spies, 1995).

Before complete canopy closure can occur in an early-seral forest, there are high light levels reaching the forest floor and this stage is categorized by different species of both flora and fauna than its late seral counterpart (Swanson et al., 2014). Specific early-seral or pioneer plant species can quickly establish in these ecosystems and capitalize on increased light and open spaces. These species may be light dependent or in dormancy until a disturbance event occurs, excluding other late-seral species that require more shade (Connell and Slatyer, 1977). Initially, herbaceous understory species dominate in large openings with high light levels. This can change to a predominantly shrub understory layer when the canopy begins to close and shade increases (Cole et al., 2017).

The understory can often dominate in early-seral conditions and spread horizontally across the stand. The ability of understory species to grow in low-nutrient environments and generate larger and deeper roots give them a competitive advantage over tree seedlings (Bormann, et al., 2015). Although there is variation in understory composition within early-successional forests, that can be due to environmental factors like moisture and nutrients (Halpern and Spies, 1995). Natural regeneration of trees can occur throughout this time if there is a seed source, but competition by understory plants for space and nutrients can kill germinants or seedlings and prevent establishment (Franklin et al., 2002). Research on preferences of wildlife habitat have found that species previously known only to use one successional stage have been also found occupying other successional stages, such as the northern spotted owl in its southern range, using late-seral forests primarily, but foraging for particular prey in early-seral forests (Swanson et al., 2014; Sakai and Noon, 1997). The early-seral forest is dynamic and can provide key habitat for both plant species as well as wildlife.

The late-seral forest occurs after 80 and 100 years and can continue for many decades. Throughout this time period, tree regeneration can occur, giving rise to a future overstory (Powell, 2012). Tree crowns and diameters continue to increase and the primary cause of tree mortality shifts away from competition and towards other things like insect outbreaks and disease (Franklin et al., 2002). The species that defined the early-seral forests, such as deciduous trees like red alder, usually die off. Grasses, forbs, and herbaceous understory species are replaced with a shrub dominated forest floor (Powell, 2012).

Similar to an early-seral forest, a late-seral forest can be influenced by disturbance events that happened previously, which can in turn impact their dominant tree species, tree diameter, soil quality, species interactions, and more (Park and Oliver, 2015). Forest managers interested in the late-seral ecological and economic benefits can implement different management strategies like commercial thinning and fertilizing. This has shown to increase understory biodiversity and promote understory development in old growth and late-successional stands (Sullivan et al., 2009).

Woody Debris

The LTEP study incorporates a woody debris treatment and analyzes the impact of multiple wood levels left on site during initial treatment implementation to understand its influence on the ecosystem. A characteristic of both early- and late-successional naturally-regenerated forests is the presence of woody debris due to tree mortality or forest disturbance. Woody debris can provide long-term benefits for an ecosystem as a habitat structural element and a source of nutrients - depositing key nutrients and organic matter to the soil as it decomposes. These deposits can take decades to fully break down with a half life ranging from 18 to 30 years (Beets et al. 2008). The time frame can change based on environmental factors. High temperatures and moisture levels can accelerate this and result in faster breakdown of woody debris. Although, too much moisture can create anaerobic environments, leading to slower microorganism activity (Yuan et al., 2017). Woody debris can also create habitat for wildlife, including small microclimates that certain wildlife species, like salamanders, can use (Kluber et al., 2009; Dunn and Bailey, 2012; Davis et al., 1983). It can also stabilize soils, retain moisture, and act as nurse logs for both understory and tree species to grow and thrive (Mellen-McLean, 2002).

Understory Growth in a Forest Stand

Although the focus of forest management is often on the overstory trees, the understory plays a key role in forest dynamics and shapes the way the ecosystem will change and develop over time. The LTEP study evaluated understory species over time and compared this to changes in tree seedling and sapling regeneration.

Many factors can influence the types of understory species that are able to establish and grow. This includes canopy gaps, clearcutting, disturbance events, competition for nutrients and space, and herbivory (Roberts, 2004). Understory biodiversity may lead to a healthier overall system with greater nutrient cycling, attraction of diverse wildlife species, and more. The understory can be managed using different methods each with benefits and drawbacks. For example, allowing deer to browse the area has been shown to reduce the density of woody shrubs and lead to greater overall species richness and evenness of ferns, forbs, and shrubs (Royo et al., 2010). Using browsing animals to control dominant understory species can also lead to an ecosystem of understory species that are tolerant to browsing and a decrease of desirable tree species such as red cedar (Royo and Carson, 2006). Each management approach that attempts to control the understory should consider its potential long-term adverse impacts as well.

Understory species have a wide array of adaptations and influence on trees and ecosystems. Forests can be dominated by one or more aggressive and prolifically growing understory species, which may in turn limit biodiversity and space for other species to establish and grow. When disturbances remove the overstory, increased light is available to the forest floor and this pulse allows a burst of growth by the understory vegetation. Tree seedlings are also able to capitalize on this extra light, but can often be outcompeted by a dense understory layer (Finzi and Canham, 2000). This can give rise to prolifically growing species that dominate the forest floor and slow the growth rate of surrounding trees. This can have a substantial impact on the future of the overstory layer and could delay forest succession (Royo and Carson, 2006). In this study, salal and bracken fern are two intensely growing and possibly dominating species.

Salal is an evergreen woody shrub that is known to be aggressive, seemingly dominating some sites. One reason may be because it can reproduce sexually through berries as well as asexually through a network of rhizomes. Its rhizomes allow it to quickly spread through an ecosystem more effectively than species exclusively reproducing sexually. Even when aboveground biomass is removed, its rhizome network can remain intact for long periods of time (Chang et al., 1996). Salal also has the ability to grow in a wide range of light and moisture conditions ranging from partial sun to partial shade and dry soil conditions to high moisture content (Boateng and Comeau, 2002; Cocksedge and Titus, 2004). It also has a competitive advantage underground with the ability to produce tannins that limit the uptake of nitrogen by other plants (Boateng and Comeau, 2002). It can prevent mycorrhizal connections between certain trees growing nearby. It typically takes 5-8 years for salal to establish in an ecosystem after a disturbance event. Once this occurs, it can slow down the growth of nearby trees and cause them to produce less chlorophyll from a lack of nutrients (Boateng and Comeau, 2002). More specifically, salal has been shown to slow and reduce the growth of western hemlock saplings due to its ability to capitalize on nutrients more effectively (Chang et al., 1996; Fraser et al., 1995;). For land managers interested in timber production, an understory of primarily salal can result in fewer trees or smaller yields.

Bracken fern is another species that has the capacity to grow intensively and become dominant on some sites. It is a deciduous fern that can grow up to two meters in height, sprouting from an extensive rhizome system. Similar to salal, it can use these rhizomes to reproduce asexually. Bracken fern also reproduces through spores that can release every year. These spores can live in soil and maintain their viability for up to one year (Boateng and Comeau, 2002). Bracken fern has the ability to uptake nitrogen more effectively (Griffiths and Filan, 2007), limit the growth of other understory and tree species, and hold nutrients like nitrate in their fronds (Fenn et al., 1996). During the growing season, bracken fern blocks light from reaching the forest floor and prevents other species from accessing it due to its expansive fronds. Since it is deciduous, this leaf matter will die and drop, creating a dense mat on the forest floor that could kill seedlings or other plants growing (Boateng and Comeau, 2002).

Figure 1: Images of bracken fern (**Pteridium aquilinum** ***(L.) Kuhn) on the left and salal (*****Gaultheria shallon** ***Pursh) on the right. Image of bracken fern by Washington Native Plant Society.***

A Priori Research Questions & Expectations

The LTEP study aims to understand the dynamics in successional forests and how they change over time by analyzing different components, such as understory plant growth and development and woody debris, and how they interact with one another. The goal of this thesis is to understand how the understory changes throughout time and what impact this has on the rest of the system, including natural tree regeneration and species richness and evenness. This is done through the evaluation of four treatments types: Control, Early, Mid, and Late seral. Each of these represent the seral stage they will become over time as management continues. Controls were untouched. Early and Mid treatments were clear-cut and replanted. Finally, Late treatments were selectively thinned. Table 1 indicates the treatment name that will be used from this point forward and details the treatments and management strategies.

Table 1: Description of treatments implemented and their corresponding management strategy

Name	Treatment	Replanting	Management Strategy
Control	None	None	Allow a 70-year old second-growth conifer stand to develop without management
Early	Clear-cut	Mixed conifer and red alder	Extend the influence of early-seral species
Mid	Clear-cut	Douglas-fir	Speed development of closed canopy Douglas-fir
Late	Thin	None	Speed development of late-seral attributes

The following questions and expectations were posed at the beginning of the study:

1. How has the understory cover and species biodiversity (richness and evenness) changed over time in the Control, Early, Mid, and Late treatments? I expected significant changes with increasing cover and diversity. I expected Controls to have the least amount of cover and species richness followed by the Late treatment. I expected highest cover and species richness in the Early and Mid treatments.

2. Has there been a change in the types of understory species between the pre-treatment and post-treatment measurements? I expected an increase in densities of shrubs and decreases in herbaceous plants.

3. How does a high percent cover of one understory species impact the overall understory biodiversity and cover in each treatment group? I expected an increase in densities of shrubs and decreases in herbaceous plants in the Early and Mid treatments and little change in cover for Controls and Late treatments.

4. Will red alder in the Early treatment increase understory cover and species biodiversity relative to Mid treatment? I expected that increased light and nutrients under red alder would promote more understory cover and diversity.

5. Will Early and Mid treatments produce more seedlings than in Late and Control treatments? I expected tree seedling recruitment to be greatest in Early and Mid treatments presumably because of more light.

6. Is there an interaction between tree seedlings/saplings and understory cover? I had no expectation about this interaction.

7. What influence did low, medium, and high levels of woody debris have on the growth of the understory and seedlings/ saplings? I expected high woody debris plots to have higher understory cover, species richness, and seedling/ sapling regeneration.

8. Do the results suggest changes in forest management practices to increase or decrease understory biodiversity and cover? I expected the Late treatment would need to be thinned more for the recruitment of more understory species. I expected Early and Mid treatments to have high biodiversity and overall cover that may need to be managed if growth was extensive.

Methods

LTEP Site Overview

The LTEP study incorporates four sites representing a range of conditions across western Washington and Oregon (Bormann et al., 2015). All sites at study inception had mature second-growth conifer stands with at least some Douglas-fir in the overstory. Hardwood shrubs and trees and understory were more variable. Each site has similar experimental treatments that were implemented with some site-specific differences. The focus of this thesis and research is on the Sappho site located on the north side of the Olympic Peninsula in Sappho, Washington. The Sappho LTEP site is part of a larger network of research in the Olympic Experimental State Forest (OESF) managed by Washington Department of Natural Resources.

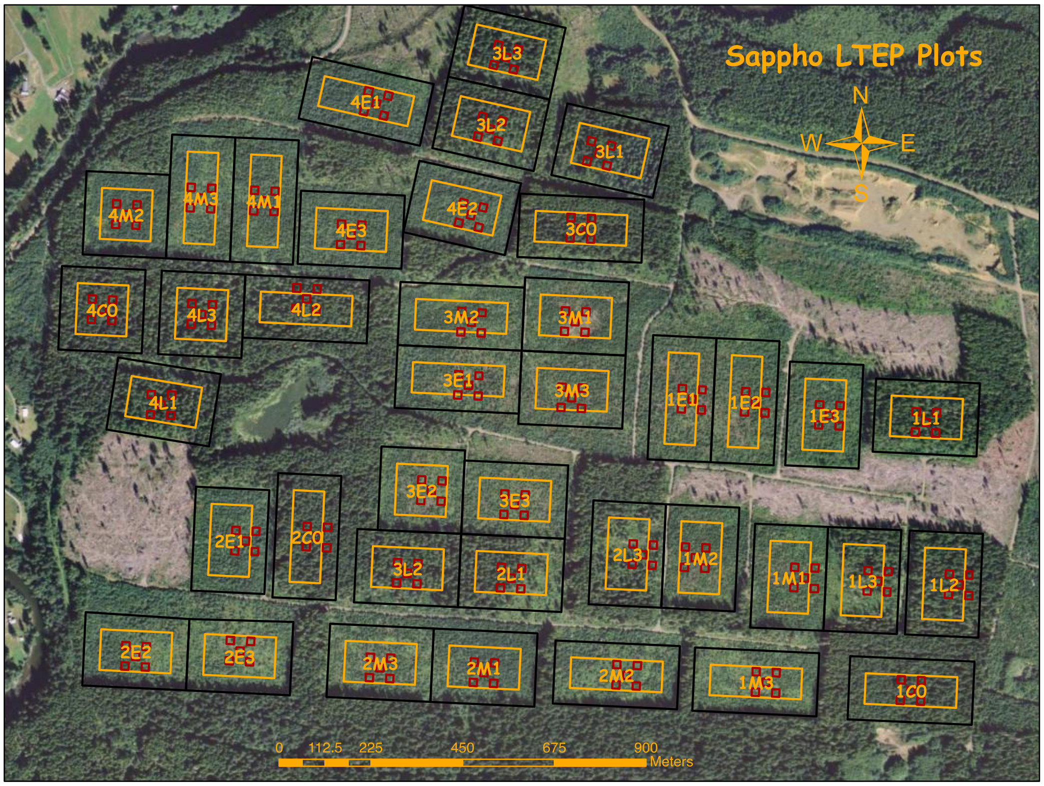

Figure 2: A map of the Sappho LTEP site with each of the 40 mensuration plots shown. Each plot is labeled with its block number, treatment type, and woody debris level. The orange boxes are mensuration plots. Labels are block number, seral treatment, and woody debris level. The red squares are 18 by 18 m tree plots.

The Sappho LTEP site is comprised of four blocks (replicates) of 10 experimental units each totaling forty 6-ha treated units. Within each block are three early-seral, three mid-seral, three late-seral, and one control unit (10 per block). Labeling of treatment was not an indication of the immediate seral type. Instead, the labeling indicates what these treatments will eventually turn into over time.

Woody debris was left on the soil surface in each Early, Mid and Late treatment and was not added to the Control units. Three levels of woody debris were achieved: low (all felled trees, branches, and tops were removed from the site), medium (7.5% of felled trees, branches, and tops were retained), and high (15% of felled trees, branches, and tops were retained). Within each block, each of the three levels of woody debris are represented in the Early, Mid, and Late treatments, making up 9 of the 10 plots with the tenth plot being the control.

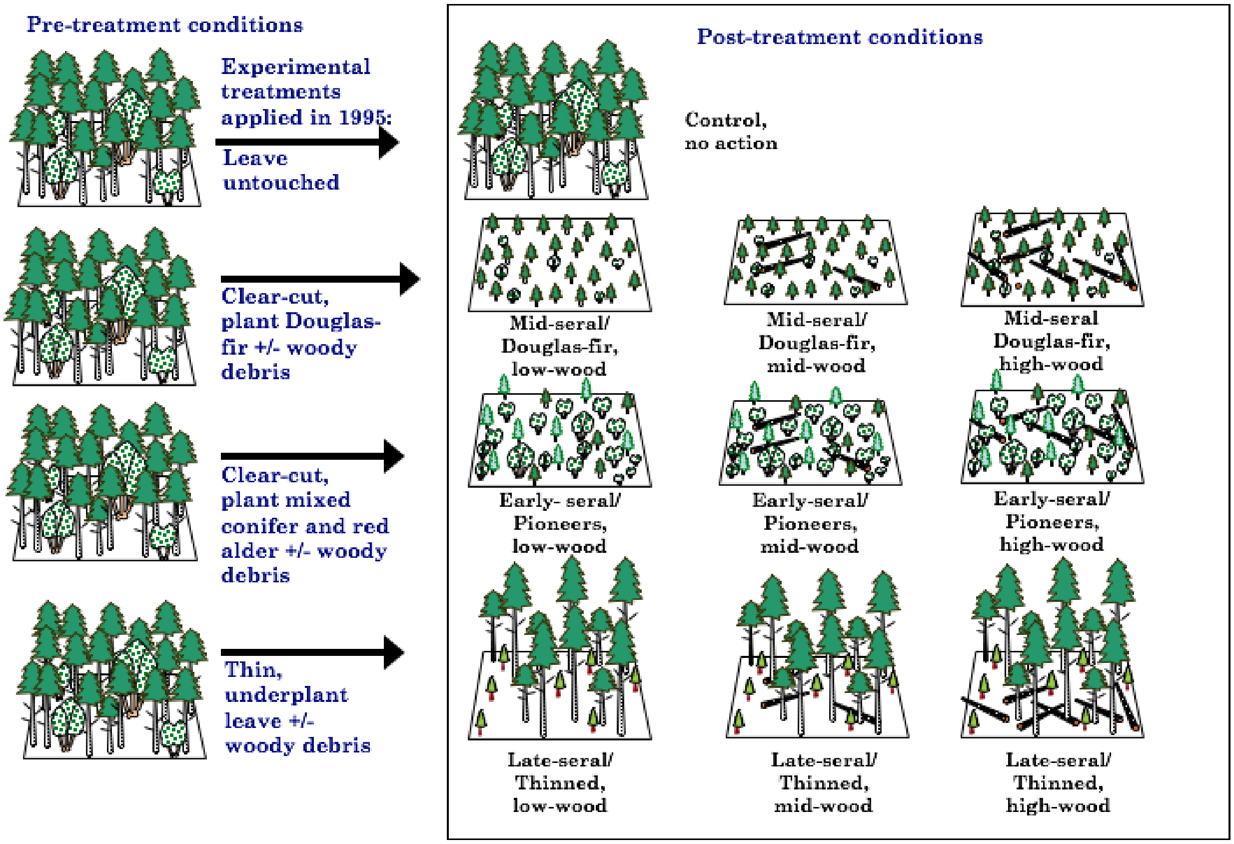

Figure 3: Shows the transition from pre-treatment conditions to post treatment conditions. Early and Mid treatments were clear-cut and replanted. Late seral treatments were selectively thinned Low, medium, and high levels of woody debris was left on site in each treatment.

Pre-treatment measurements were completed in 1993; treatments were implemented in 1995. At this time the Early and Mid treatments were clear-cut. Each Early treatment unit was replanted with Douglas-fir and red alder. The Mid treatment units were replanted with Douglas-fir at even spacing with no gaps (plantation style). In the Late treatment units, the existing mature second-growth, approximately a 70-year-old, predominantly Douglas-fir stand was thinned from about 345 to 185 trees ha^{-1} (350 to 75 trees acre^{-1}) with no additional planting. In the control plots, the mature second growth forest was left untreated. In 2013, pre-commercial thinning took place in the Early and Mid treatment units. This was primarily to remove western hemlock in-growth and restore treatment units to their original composition.

Each mensuration plot has 15 or 16 monumented grid posts that are used as reference points in the plots and are labeled with X_Y coordinates. Grid posts are 25 m apart from one another in every experimental unit arranged in a rectangular or square shape. Each grid post has a corresponding understory plot that is located 10 m away at a designated azimuth, resulting in >600 understory plots total. Each understory plot is 3 by 3 m.

Figure 4: One treatment unit with 15 grid posts (represented with blue crosses) and their corresponding understory plots (represented with teal squares) located northeast of the grid post.

Measurements

Understory cover and species composition, biomass, seedling regeneration, overstory tree diameters, leaf litter, and soil measurements have been taken multiple times on each unit over the last 20 years. Pre-treatment understory measurements were taken in 1993 followed by post-treatment measurements in 1996, 2000, 2002, and 2016; giving a comprehensive look at the changes in understory composition.

The same understory measurement protocol was used for all measurements. Once an understory plot was located, a 3 by 3 m PVC quadrat was laid out to show the plot boundary. First, photos were taken showing a white board with the designated date, mensuration plot number, and understory plot number. The understory cover was measured following the polygon method, where polygons were imagined around the outer portions of the crown of the plant and cover is estimated as if the polygons were solid. For example, the space between each leaf on a plant would be included in the cover measurement. Percent cover was recorded for every vascular plant species present on site to the nearest percent. If there was under 1% cover present, cover was estimated to the nearest tenth of a percent. If an understory species occupies the entire plot, its cover is recorded as 100%. The cover of vertically-overlapping species was counted separately leading to some plots having greater than 100% cover. Plants that were not rooted in the understory plot, but had foliage extending into the plot were measured as well.

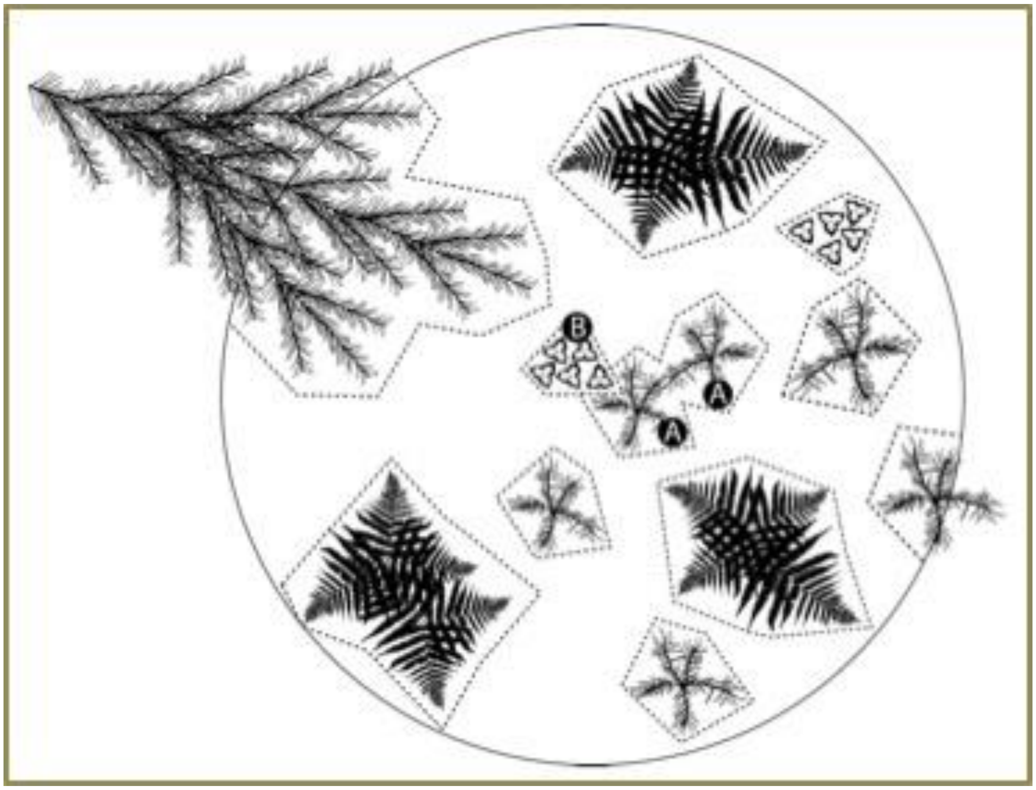

Figure 5: An image of the polygon method used to determine overall percent cover. When plants that are the same species overlap, determine cover using polygons as shown in (A). For plants that are different species, construct separate polygons as shown in (B) (Bigley et al., 2017).

A tree seedling and sapling count was done in each understory plot and was broken down into three height classifications: seedlings <30 cm and a minimum of one-year-old, seedlings >30 cm, and saplings (greater than 136 cm tall with a diameter at breast height of less than 3.5 cm). Seedlings <30 cm were counted only in a 1 by 1m plot based on the closest corner to the corresponding grid post. Seedlings >30 cm and saplings were counted in the entire 3 by 3m understory plot. Each measurement value included the seedling and saplings' species as well. In the 1993 pre-treatment measurement, the understory protocol indicated that once 30 seedlings had been counted, recorders could stop counting and record the value as 30. Therefore, it is unknown what the true value of seedlings were in the 1993 measurement if the value was recorded as 30. The protocol changed after this measurement and in the subsequent measurements all seedlings and saplings were recorded.

Analysis Approach

Using the data collected in 2016 and in the LTEP data archives, overall understory composition was analyzed to determine if there were changes between treatment groups over time. All understory species were put into one of six understory composition groups: graminoid, herb/forb, evergreen fern, deciduous fern, evergreen woody shrub, and deciduous woody shrub. Percent cover of salal and bracken fern were both analyzed independently as well to determine if there were changes in their cover between treatment groups and throughout measurement years.

The quantity of tree seedlings ha^{-1} (i.e. seedling and sapling density) in each treatment group over time was analyzed to determine if there was a statistically significant difference between treatment groups and between measurement years. Each height class was evaluated separately.

Species richness and abundance were calculated using the Shannon diversity index (H) with the following formula:

$$H = -\sum_{i=1}^{S} p_i \ln(p_i)$$

Where H is the Shannon diversity index and p_i is the proportion of species i in relation to the total proportion of species. The resulting values from this formula were summed to get a total number for H. Using this formula, species evenness was determined using Shannon’s equitability (E_H) formula:

$$E_H = H/\ln(S)$$

Where H is the result of the Shannon diversity index and S is the number of different species present in the sample. Species evenness was used to determine if the proportion of species and their corresponding cover was uniform throughout the units.

The distribution of canopy cover of red alder above understory plots was determined using LiDAR (light detection and ranging) point cloud data flown for Washington Department of Natural Resources in 2012 and one-foot resolution color infrared NAIP orthophotography flown in 2015. Known patches of alder and conifers 35 x 35 m were used to develop a 3 band red-green-blue signatures and a 3 band color-infra-red signatures (only the 2 bands were used). These signatures were applied to LiDAR returns 2 to 20 m above the ground to avoid confusion with deciduous understory plants. Fusion software [orsys.cfr.washington.edu/fusion.html] was used to model canopy height and the bare earth terrain model. ArcMap 10.3 was used to generate 4 by 4 m polygons over each 3 by 3 m understory plot with a 1 meter buffer, where percent cover of red alder could be calculated and related to understory data.

Statistical Approach

Two-way ANOVA tests were performed using the R stats package. The value used for alpha for each of these ANOVA tests was 0.05. A Tukey’s honest significance difference post hoc test was performed to determine which pair of means were statistically significant. This was used to determine if there were statistically significant differences between the percent cover of understory species and each treatment group and measurement year. The percent cover of both salal and bracken fern was analyzed in relation to treatment group and measurement year. In addition, the seedling count was analyzed against each treatment group and measurement year. The percent cover of understory species, salal, and bracken fern as well as the seedling counts were used as response variables in this approach. Treatment type (both seral and woody debris treatments) and measurement year were used as predictor variables. The figures in the results section include 95% confidence intervals. Correlation tests were performed between understory species cover and red alder cover also using the stats package in R.

Results

Understory Species Cover

The cover of understory groups (graminoid, herb/forb, evergreen fern, deciduous fern, evergreen woody shrub, and deciduous woody shrub) varied little across experimental units in 1993 before the treatments were applied (Figure 6). Cover was under 11% at this time for all groups with evergreen woody shrubs being the highest cover in Early, Mid and Late treatments and deciduous fern having slightly higher cover than evergreen woody shrub in Controls.

Over the 23 years of measurement, Controls showed small changes in overall cover in understory species. Between the 1996 and 2002 measurements, all understory composition groups showed a decrease in cover except for evergreen ferns which had a 1.6% increase. By 2016, there were increases in cover in all composition groups with the largest increase in evergreen woody shrubs. Early, Mid, and Late treatments were not significantly different from Controls in 1993 ($p>0.05$). By 1996, Early, Mid, and Late treatments with medium woody debris ($p < 0.01$ for all) had significantly different overall cover. In 2002, all Early and Mid treatments ($p < 0.01$ for both) were different than Controls. The Late treatments were not significantly different ($p>0.05$). By 2016 Early and Mid treatments ($p < 0.01$) as well as the Late treatment with high woody debris ($p < 0.01$) were significant.

Thinning in the Late treatments had little effect on total understory cover when compared to Control units. No significant difference was shown for Late units with low and high woody debris in 1996, all units in 2002, and low and medium woody debris units in 2016 ($p > 0.05$). Deciduous fern and evergreen woody shrubs had the highest overall cover from 2000 onwards. Graminoids and forb/herb had low cover since treatment implementation. Evergreen fern and deciduous woody shrub increased from 2002 to 2016.

The Early treatment had an increase in deciduous ferns and evergreen woody shrubs between 1996 and 2016 ($p < 0.01$ for both). Evergreen woody shrubs changed from 3.2% cover in 1996 to 29.9% cover in 2016 on average. Cover of deciduous ferns in 1996 was at 6.5% and increased to 48.3% by 2016 on average. The other understory composition groups did not change substantially from the 1996 to 2016 measurement years with each category having less than 11% cover in the 2016 measurement.

The Mid treatment showed a similar pattern to the Early treatment. Evergreen woody shrubs and deciduous ferns increased significantly from 1996 to 2016 ($p < 0.01$ for both). Graminoids, forbs/herbs, and evergreen ferns showed very little change in cover from 1996 to

2016 with less than 12% cover in each composition group by the 2016 measurement. There was no statistical difference in the amount of understory cover between the Early and Mid treatments for any measurement year (p > 0.05).

The woody debris treatments had no effect on understory cover at any point of measurement (p > 0.05).

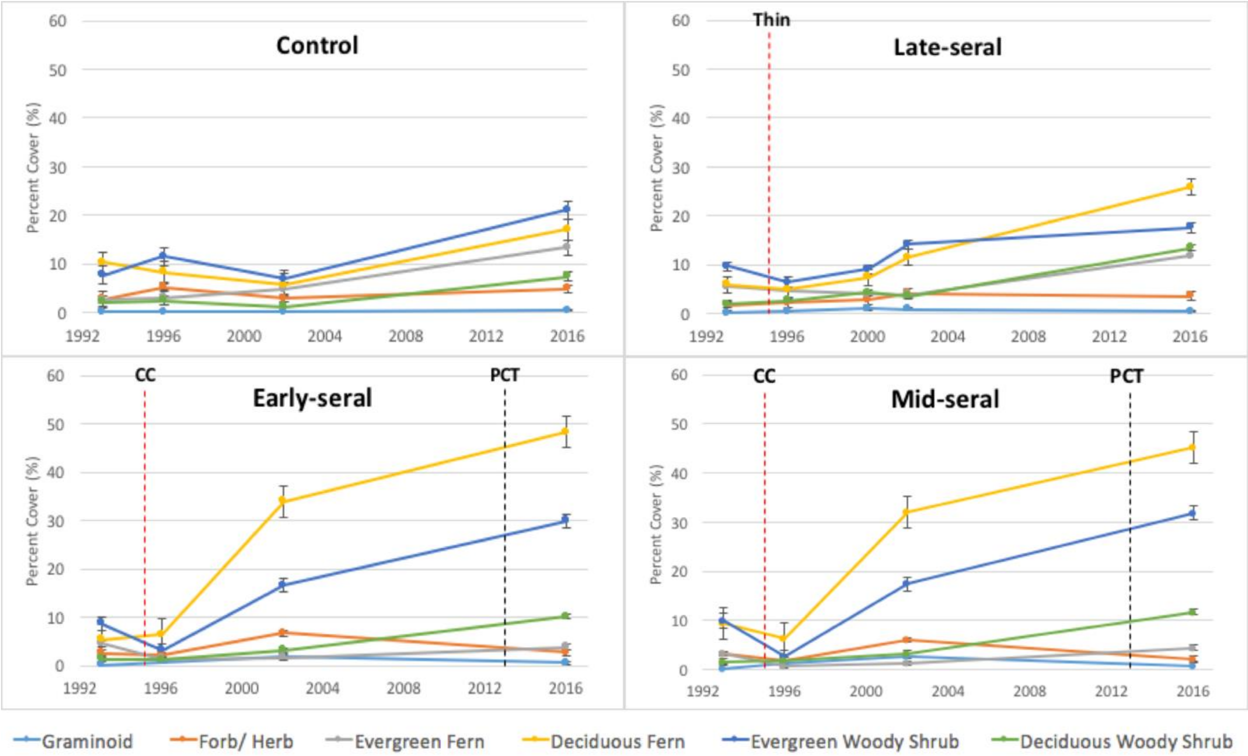

Figure 6: The percent cover of understory species in the Control, Early, Mid, and Late treatments from 1993 to 2016 with 95% confidence intervals. Red dashed line indicates when treatment was implemented, either clear-cut (CC) or thinning (Thin). Black dashed line indicates when pre-commercial thinning took place.

Salal and Bracken Fern Cover:

Salal had by far the highest cover of all members of the evergreen woody shrub group, and bracken fern dominated the deciduous fern group, so we examine them separately. A major surge in salal cover was observed between 2002 and 2016 in Control, Early, and Mid treatments (Figure 7). A much smaller increase was observed in the Late treatment. The increase in the Early and Mid treatments began earlier, after 1996, and later, after 2002, in the Controls. Controls had a three-fold increase in cover from 2002 to 2016 from 11.1% to 36.17% ($p < 0.01$).

In addition to salal growing prolifically, bracken fern also exhibited high overall percent cover throughout the plots. The cover of bracken fern in the control plots and all treatment groups was less than 10% in 1993 and 1996. Late-seral units doubled the cover of bracken fern between 2002 and 2016 ($p <0.01$).

Bracken fern increased in the Early and Mid treatment units from 1996 onwards with the largest increase between 1996 and 2002 ($p < 0.01$ for both). By 2016, cover was at 48% in the Early treatment and 45% in Mid treatment. The cover of bracken fern in Early and Mid units were not significantly different from one another in any measurement year ($p > 0.05$).

Woody debris retention had no significant effect on salal or bracken fern cover across all seral treatments and in each measurement year ($p > 0.05$).

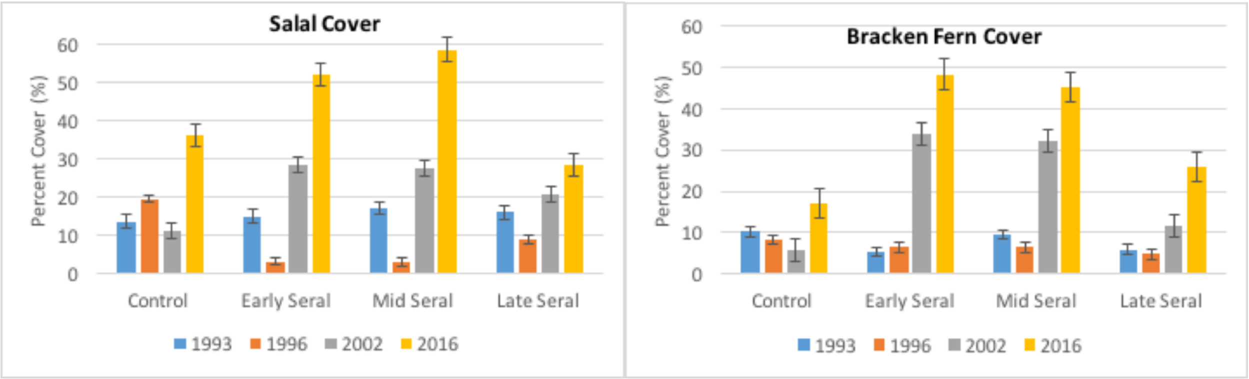

Figure 7: The percent cover of salal and bracken fern in Control, Early, Mid, and Late treatments from 1993 to 2016 with 95% confidence intervals.

Tree Seedlings and Saplings

Control, Early, and Mid treatments were characterized by low seedling and sapling regeneration over time, while Late units experienced high tree regeneration (Figure 10). Pre-treatment measurements showed a large density of small (<30 cm) seedlings followed by a decline in 1996 in Early, Mid, and Late treatments, but also in Controls. The decline in <30 cm seedlings continued from 1996 to 2002. Controls had a net increase in 2016 with an average of nearly 16,000 seedlings ha^{-1}. Seedlings >30 cm and sapling density remained under 600 ha^{-1} through the 2002 measurement (Figure 10). Throughout this time, background tree mortality had increased in the Controls and was 30 times higher than in the Late treatment units (Figure 8).

A major resurgence was observed in Late units by 2000, but not in Controls, Early and Mid treatments. Small (<30 cm) seedlings gave rise to larger (>30 cm) seedlings but with 86% mortality by 2016. >30 cm seedlings gave rise to saplings with 62% mortality by 2016 (Figure

10). Seedling/saplings measured from 1996 to 2016 were 84% western hemlock, 8% Sitka spruce, 4% Douglas-fir, 2% western red cedar, and 2% red alder.

Early treatment units had very low density of all seedlings and saplings throughout all measurement years with no significant change from 1996 to 2016 ($p > 0.05$). By 2016, there was less than 3,500 seedlings/saplings ha^{-1} in all Early treatment units for each height class and woody debris treatment (Figure 11).

The Mid treatment followed a similar pattern as the Early treatment. From 1996 to 2016, there was no significant difference in the number of seedlings <30 cm, >30 cm and saplings ($p > 0.05$). By the 2016 measurement the density of seedlings/ saplings was less than 2,700 seedlings ha^{-1} (Figure 11).

Woody debris was also evaluated to determine if the difference in woody debris levels resulted in different seedling/sapling densities. Low, medium, or high woody debris levels did not result in a statistically significant difference within any treatment group for the number of seedlings <30 cm seedlings, >30 cm, or saplings within any year.

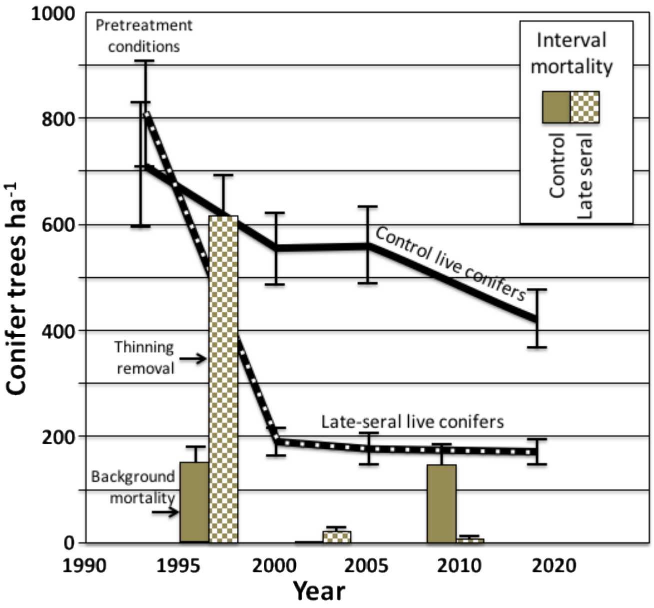

Figure 8: Overall tree mortality in Control and Late treatments from 1995 to 2016.

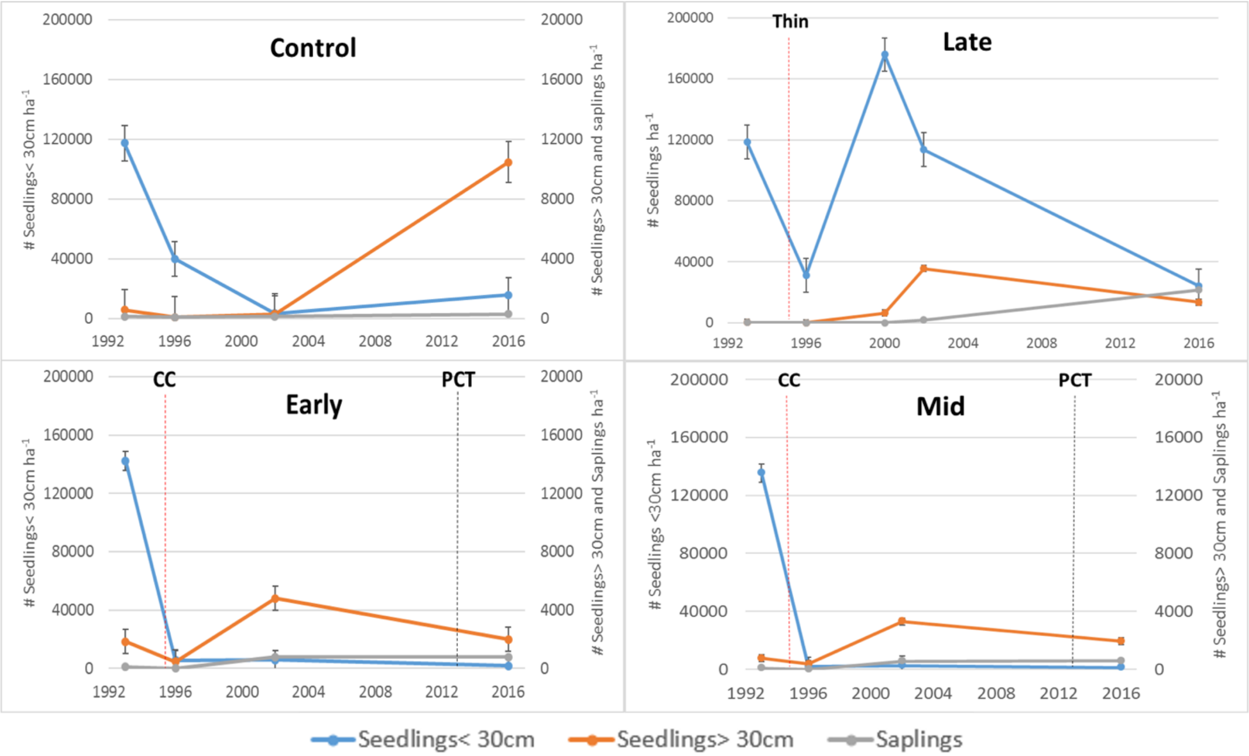

Figure 9: Density of tree seedlings and saplings in Control, Early, Mid, and Late treatments from 1993 to 2016 with 95% confidence intervals. Red dashed line indicates when treatments were implemented. Black dashed line indicates when pre-commercial thinning took place. For all treatments except the Late units, left-hand y-axis corresponds to the number of seedlings <30 cm. Right-hand y-axis corresponds to the number of seedlings >30 cm and saplings. For Late units, left hand y-axis corresponds to all seedlings and saplings. There is no secondary y-axis.

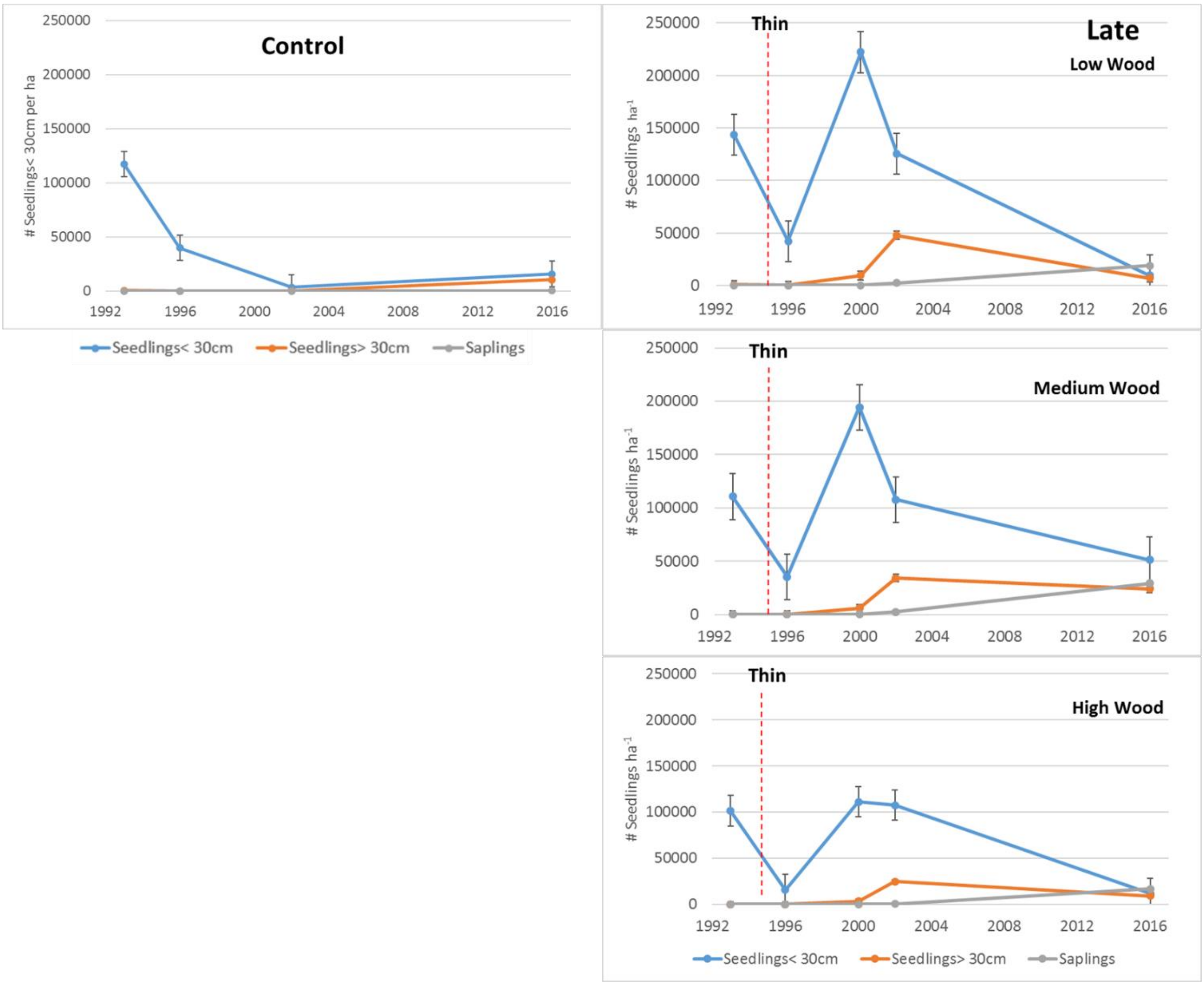

Figure 10: Density of tree seedlings <30 and >30 cm tall and saplings with low, medium, and high woody debris treatments in Control and Late treatment units from 1993 to 2016 with 95% confidence intervals. Red dashed line indicates when treatments were implemented (thinning).

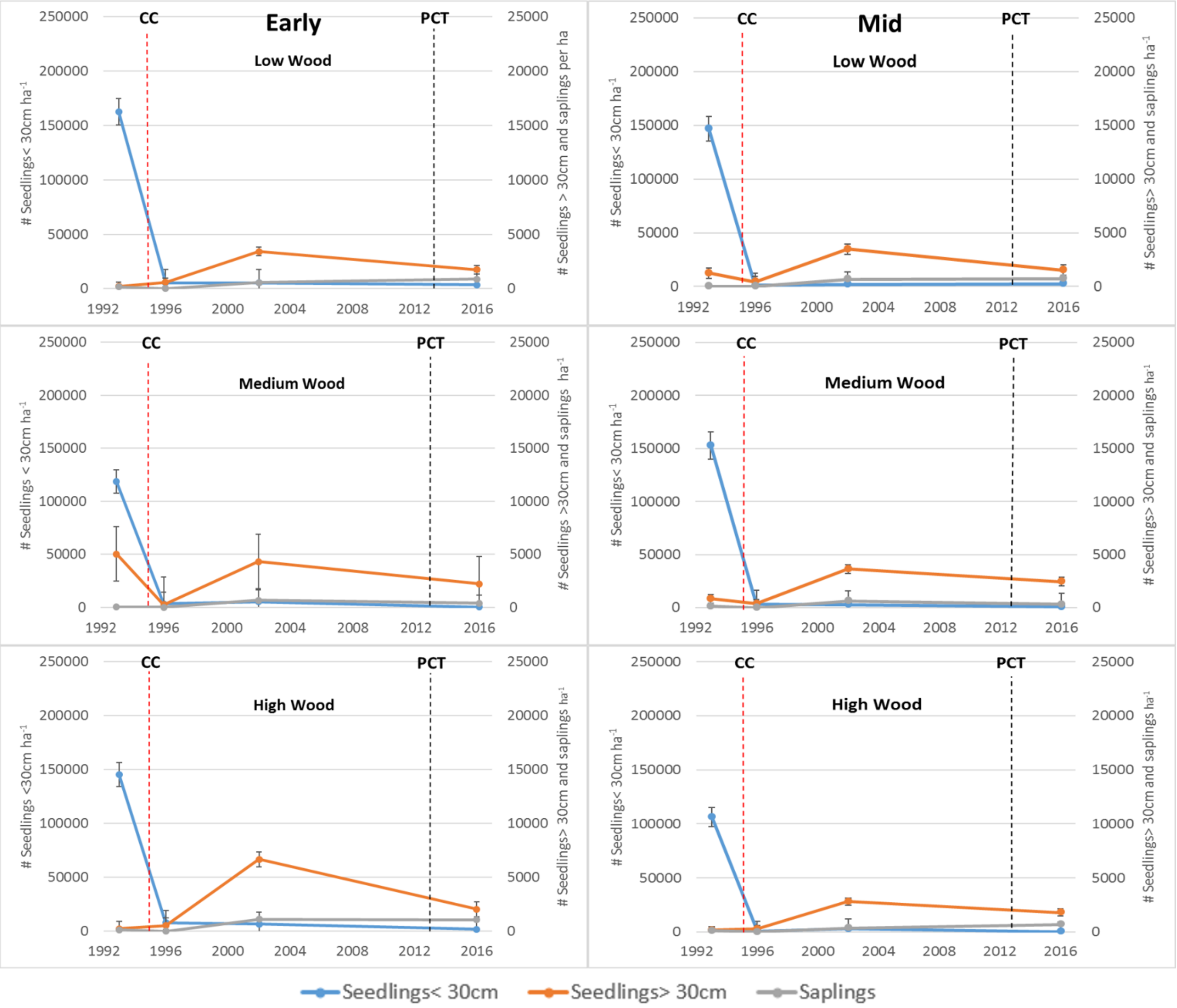

Figure 11: Density of tree seedlings <30 and >30 cm tall and saplings in low, medium, and high levels of woody debris treatments in Early and Mid treatment units from 1993 to 2016 with 95% confidence intervals. Red dashed line indicates when treatments were implemented (clear-cut). Black dashed line indicates when pre-commercial thinning occurred. Left-hand y-axis corresponds to the number of seedlings <30. Right-hand y-axis corresponds to the number of seedlings>30cm and saplings.

Species Richness and Evenness:

Species richness (number of species per experimental unit) was compared between Control, Early, Mid, and Late treatments and the 4 sampling events (Table 2). Richness increased 70-80% 7 years after treatment in 2002 on average, but declined back to near pre-treatment levels 20 years after treatment implementation that ranged from 32 to 41 species. Control plots had the lowest species richness values in each measurement year when compared to the other treatment groups.

Table 2: Species richness (number of species) in control plots, early, mid, and late seral treatment groups between 1993 and 2016

	1993	1996	2002	2016
Control	33	19	29	32
Early Seral	34	33	59	38
Mid Seral	44	39	66	41
Late Seral	40	36	66	34

Species evenness (relative abundance of the different species in an experimental unit) was also compared among treatments and sampling events. The Controls showed similar species evenness from 1993 to 2002. By the 2016 measurement, evenness was highest and species richness was also largest since the 1993 measurement. Early, Mid, and Late units showed similar evenness to one another in each measurement year. Evenness did not change between the 2002 and 2016 measurement for the treatment groups (Figure 12). There was no relationship between species evenness and woody debris treatments in any measurement year.

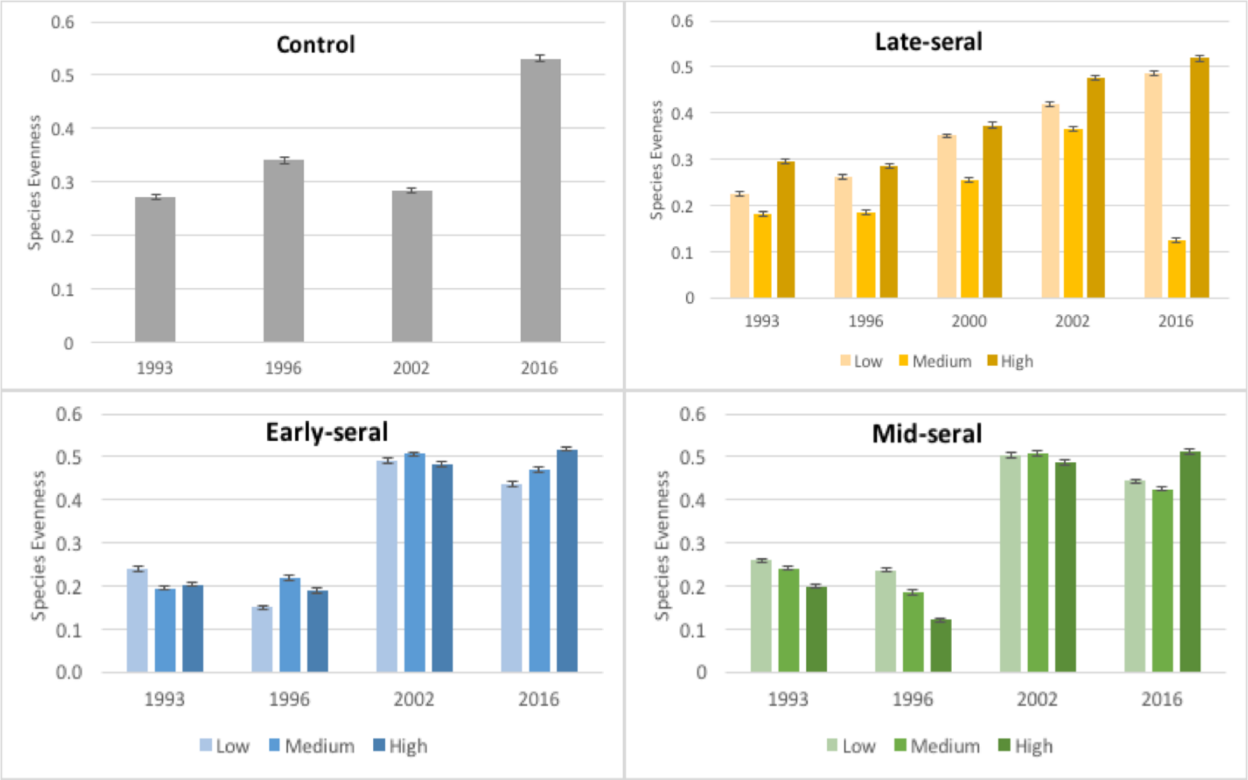

Figure 12: Understory species evenness in control plots, Early, Mid, and Late treatments with low, medium, and high levels of woody debris from 1993 to 2016. All graphs show a 95% confidence interval.

Red Alder's Impact on the Understory and Overstory

The Early treatment was intended to have a 50% alder overstory, but ended up as only 18% in a somewhat patchy pattern. The lack of significant differences between understory in Early and Mid treatments is most likely explained by this implementation discrepancy. Here I examine the effect of alder cover above individual understory plots to evaluate the effect of hardwood trees on understory and tree seedlings and saplings.

Many understory species were statistically related to alder cover ($p < 0.05$), but had low adjusted R^2 values. The herbaceous broadleaf starflower (*Trientalis borealis* Raf. *var. latifolia*

(Hook.) Hulten) had the highest adjusted R^2 (0.50) in the Mid treatment in 2016 with medium woody debris. This positive correlation indicates that red alder and broadleaf starflower grow together in Mid treatment units.

There were several species that increased their association with red alder between the 2002 and 2016 measurements. In the Early treatment with medium woody debris levels both bracken fern and red huckleberry (*Vaccinium parvifolium* Sm.) were significant in 2002 (bracken fern and red huckleberry, $p=0.01$) and again in 2016 (bracken fern and red huckleberry, $p<0.01$) with an increasing positive correlation coefficient value. In the Early units with high amounts of woody debris, bracken fern was significant and had a positive correlation with red alder that increased from 2002 ($p=0.02$) to 2016 ($p=0.01$). In the Mid treatments with high levels of woody debris, salal and bracken fern were both significant and had increasing correlation with red alder over time.

In addition, red alder had significant effects on the overstory layer. In the Early treatment in 2002, the number of Douglas-fir saplings and trees was twice as high as the amount growing in the Mid treatment units, just seven years after treatment implementation and despite more Douglas-fir trees being planted in the Mid treatment units. The Mid treatment had greater amounts of western hemlock in the 2002 measurement when compared to the Early treatment. When adding all tree species, there were twice as many tree stems per hectare in the Early treatment units compared to the Mid treatment plots in 2002.

Discussion

A Priori Questions and Expectations

The questions and expectations of this study are answered individually.

1. **How has the understory cover and species biodiversity (richness and evenness) changed over time in the Control, Early, Mid, and Late treatments? I expected significant changes with increasing cover and diversity. I expected Controls to have the least amount of cover and species richness followed by the Late treatment. I expected highest cover and species richness in the Early and Mid treatments.**

Understory cover increased in each treatment over time. Understory cover in the Control units increased the least, followed by the Late treatments. Controls experienced fluctuations in the amount of understory cover that is most likely explained by tree mortality pulses that created temporary openings, increasing light and water (Pedersen and Howard 2004; Gray et al., 2012). By 2016, the Controls had significantly less understory cover than the Early, Mid, or Late units ($p < 0.01$ for all). Late treatments increased in cover throughout measurement years with highest cover in 2016 ($p < 0.01$). On the other hand, Late units had significantly less understory cover than Early and Mid units in 2016 (p-values of < 0.01 and 0.02 respectively). As expected, Early and Mid units had the highest understory cover that increased over time with largest amounts in 2016. There was no significant difference between the Early and Mid treatments in any measurement year ($p > 0.05$).

Control units had the lowest species richness in each measurement year. Species evenness increased but was still low at a value of 0.53 by 2016 indicating some species are dominating in this ecosystem. Late treatments had similar richness values to the Early and Mids treatments with peaks in 2002 followed by a sharp decline by 2016. Evenness increased between 1996 and 2002 with little change by 2016 in Early, Mid, and Late treatments. Overall evenness was under 0.52 for each treatment group by 2016. These low values for richness and evenness for all treatment groups indicate dominant species are influencing understory cover.

2. **Has there been a change in the types of understory species between the pre-treatment and post-treatment measurements? I expected an increase in densities of shrubs and decreases in herbaceous plants in the Early and Mid treatments and little change in cover for Controls and Late treatments.**

In pre-treatment measurements, all understory composition groups had under 11% cover. In post-treatment measurements, deciduous ferns and evergreen woody shrubs had higher cover than other groups. Controls had increases in most understory composition group by 2016 with evergreen woody shrubs nearly tripling its density. Cover of graminoids and forbs/herbs did not change between measurement years ($p > 0.05$ for both). Lates had similar results with most groups doubling or tripling cover except graminoid and forb/herb.

Early and Mid treatments had large increases in deciduous ferns and evergreen woody shrubs over time. Deciduous ferns increased five fold while forbs/herbs decreased in cover ($p < 0.01$ for both), meeting my expectation. Cover of graminoids did not change over time in both Early and Mids with cover under 3%. Competition for light, nutrients, and space most likely caused certain species and composition groups to increase more than others.

3. **How does a high percent cover of one understory species impact the overall understory biodiversity and cover in each treatment group? I expected an aggressive understory to hinder the growth of minor understory species.**

As salal and bracken fern doubled and tripled respectively in cover in the Early and Mid units, cover of graminoids and evergreen ferns did not change ($p > 0.05$) and forbs/herbs declined ($p < 0.01$) from 2002 to 2016. The Control and Late treatments increased in densities of salal and bracken fern as well but had less cover compared to Early and Mid units. By The 2016 measurement, all treatments had the highest levels of salal and bracken fern than any previous measurement. Other studies have pointed to both salal and bracken fern as having negative impacts on the growth of understory species and seedlings as they outcompete others for space, light, and nutrients (Messer and Kimmins, 1991; Griffiths and Filan, 2007). Understory and overstory growth in LTEP may be affected by this in the future. Species richness declined since the previous measurement with some treatments having half as many species, as expected. Prolifically growing species are having negative impacts on the growth and establishment of other species.

4. **Will red alder in the Early treatment increase understory cover and species biodiversity relative to Mid treatment? I expected that increased light and nutrients under red alder would promote more understory cover and diversity.**

Understory cover, species richness, and evenness was very similar for Early and Mid treatments, indicating that the Early treatment with 18% red alder cover is not influencing the understory overall, which was not what I had expected. Although, some specific understory species do have a correlation with red alder. The herbaceous broadleaf starflower (adjusted $R^2 = 0.50$) has a positive correlation that is stronger than any other understory species relative to red alder. Other species, such as red huckleberry and bracken fern, have a significant correlation as well that has increased throughout measurement years.

Although I did not create a postulate on red alder's impact on the overstory, there was a trend that was apparent after analyzing the data. Early treatments, planted with red alder during treatment implementation, had greater amounts of Douglas-fir and fewer western hemlock saplings and trees than the Mid treatment units by 2002. These results show multiple benefits. Douglas-fir is an important timber tree in the region and finding ways for this tree to successfully grow and thrive is important. Growing red alder and Douglas-fir together has been shown to result in more growth for both species (Radosevich et al., 2006). Red alder's ability to fix nitrogen, leading to higher rates of nitrogen mobilization, could have contributed to higher growth rates for Douglas-fir (Hart et al., 1996). In addition, having a deciduous tree such as red alder will allow more light to the forest floor after its leaves drop. This could benefit the shade intolerant Douglas-fir trees and allow them to grow and establish. On the LTEP site, western hemlock can grow in dense clumps and thickets, leading to less space and light reaching the ground. This could result in limited growth of others tree species as well as understory. Having fewer western hemlock trees could lead to less pre-commercial thinning and overall management costs.

5. **Will Early and Mid treatments produce more seedlings than Late and Control treatments? I expected tree seedling recruitment to be greatest in Early and Mid treatments presumably because of more light.**

Contrary to my expectation, seedling recruitment was far greater in the Late treatments compared to Control, Early, and Mid treatments. Thinning forest stands can result in a greater production and distribution of seeds by trees. This has been shown to lead to far greater amounts of seedling and sapling growth compared to forests left unthinned (Otto et al., 2012). In the Late treatment, the seedlings <30 cm declined in 1996 due to treatment implementation, but then increased by 2000 to densities higher than pre-treatment measurements. This changed again with a decline by 2002. These quick changes in seedling densities suggest these small seedlings are sensitive to environmental conditions and can grow and die quickly. From 2000 to 2002, seedlings >30 cm had increased in density followed by a decline from 2002 to 2016. Between

2002 and 2016, saplings increased in density. This indicates a progression of seedlings where some are growing and becoming part of the next height classification. This treatment is the only one showing a clear growth pattern and has the highest tree regeneration.

Control plots had a steady decline in seedlings <30 cm and little change in larger seedlings and saplings from 1993 to 2002. Overstory analysis in the Controls indicated a 145 tree ha^{-1} pulse of conifer mortality in the Controls during the 1993-2000, lack of mortality from 2000 to 2005, followed by a 154 tree ha^{-1} pulse in 2005 to 2016 (Figure 8). Canopy mortality led to the limited understory growth from 1993 to 2002, but is also associated with a decline in seedlings <30 cm, and no growth of seedlings >30 cm and saplings.

In the Early and Mid treatments, treatment implementation caused a sharp decline in seedlings <30 cm that were present in the 1993 pre-treatment measurement. Seedling growth was limited in all height classes in post-treatment measurements and densities did not return to pre-treatment levels for seedlings <30 cm. Although densities were lower than the Late units, there were still thousands of seedlings and several hundred saplings growing in each measurement year in stands that have an average of 300 trees ha^{-1}.

My results are consistent with other studies where western hemlock seedlings, which represent the vast majority of seedlings/saplings on the LTEP site, can be suppressed by a dominant understory, especially with a high cover of salal (Messier et al., 1991). Bennett et al. (2002) notes the direct competition between salal and hemlock for nutrients with salal dominating. Bracken fern has been shown to negatively impact the growth of nearby seedlings as well (George and Bazzaz, 1999). It follows that the limited growth in seedlings and saplings in the Control, Early, and Mid treatments was most likely caused by competition for nutrients, space, and light from the understory species that were establishing and increasing their growth throughout measurement years.

6. Is there an interaction between tree seedlings/saplings and understory cover? I had no expectation about this interaction.

Yes, in units where understory cover was lower, there were greater densities of seedlings and saplings. This trend occurred exclusively in the Late treatments. Alternately, units with higher overall understory cover had lower tree regeneration. This occurred in the Control, Early, and Mid treatments. After treatments were implemented, declines in seedlings <30 cm occurred in Control, Early, Mid, and Late units. Late units had an increase in these seedlings immediately following. At this time, understory cover did not increase as rapidly as in the Early and Mid treatments, indicating there is competition between seedlings and understory species for space, nutrients, and light.

7. What influence did low, medium, and high levels of woody debris have on the growth of the understory and seedlings/ saplings? I expected high woody debris plots to have higher understory cover, species richness, and seedling/ sapling regeneration.

The woody debris treatment was expected to have an impact on the understory cover, species richness, and seedling/sapling growth, but no statistically significant relationship was found between any components. Other studies have discussed the wide range of factors that play into woody debris break down including species of tree, moisture levels, temperature, and decay class (Kim et al., 2004; Kim et al, 2006; Beets et al. 2008). While some research shows nutrient deposits within several years after treatments began (Kim et al., 2004), others indicate it may take decades for nutrients like nitrogen to be released from woody debris (Lambert et al., 1980). Although a measureable difference was expected at the Sappho LTEP site, it is possible that the woody debris has not deposited enough nutrients yet to see a difference in the data. Also, the woody debris is taking up space on site and could have resulted in less area for other species to occupy. Alternatively, there may be deposits of nutrients that salal and bracken fern are using and preventing other species from accessing. These results were true in the Early, Mid, and Late treatment groups.

8. **Do the results suggest changes in forest management practices to increase or decrease understory biodiversity and cover? I expected the Late treatment would need to be thinned more for the recruitment of more understory species. I expected Early and Mid treatments to have high biodiversity and overall cover that may need to be managed if growth was extensive.**

The results show that regeneration harvesting (i.e. Early and Mid treatments) can result in a surge of understory cover, changes in species richness over time, and some recruitment of seedlings and saplings. The Late thinning treatment resulted in less understory cover and much greater seedling regeneration than the Early and Mid units, indicating that thinning could be used as a management technique to suppress the understory. Clear-cutting and replanting with red alder could be used as a technique to suppress western hemlock regeneration and limit costs of pre-commercial thinning.

Comparisons to Related Literature

The methods used in this study are the same as those used in the Siskiyou LTEP site based in Southwest Oregon (Bormann et al., 2015). The results of Siskiyou LTEP were compared to Sappho LTEP to understand if they were site specific or spanned across both sites

(Figures 13 and 14). Control units in the Siskiyou LTEP site showed similar results to Sappho LTEP with lower overall understory cover than Early and Mid treatments and comparable cover to Late treatments fifteen years after treatment implementation. Also similar to the Sappho LTEP results, species richness remained low in the Control units and was lowest compared to all other treatments (Bormann et al., 2015).

Bormann et al. (2015) also found that Late seral units on the Siskiyou LTEP site had less understory cover and lower richness than Early and Mid treatments, indicating more complete disturbance leads to rapid increase in understory cover more so than thinning. The Siskiyou LTEP site showed a surge of understory growth in the Early and Mid units following treatment implementation. Although different plant species dominate that ecosystem, parallels can be drawn from results found at that site to those observed at the Sappho LTEP site. At the Siskiyou site, shrubs (tanoak, live oak, madrone, etc.) dominated that ecosystem after the initial clear-cut. The areas lacking a dominant shrub had high covers of bracken fern. Fifteen years after treatments were implemented, Early and Mid units had average shrub covers ranging from approximately 50-80% (Bormann et al., 2015). These results mirror the Sappho LTEP site, indicating a pattern despite differing ecosystems and dominant plant species.

Other studies have done similar work to investigate understory growth and development, prolifically growing species, and the influence of woody debris. The Sappho LTEP site showed continuous growth in understory cover through the entire 21-year treatment period. Competition occurred between the understory groups, with certain ones winning and expanding their growth several years after treatment implementation. Deciduous ferns and evergreen woody shrubs had the largest cover while other composition groups did not change or even declined. Species with heavy cover in both of these treatment groups include salal and bracken fern. I observed a similar salal response to the rapid increase in biomass in the first 8 to 15 years after disturbance observed by Messer and Kimmins (1991) in British Columbia. The Knowe et al. (1997) study indicated salal returning to high densities just four years after a disturbance event. Bracken fern, a species also known to hold nutrients and outcompete neighboring plants, greatly increased its cover throughout measurement years as richness declined. Griffiths and Filan (2007) found that bracken fern’s ability to sequester nitrogen gives it a competitive advantage over other species and can result in lower nutrient levels in the soil. This indicates that these species may be having a stronger influence on the ecosystem than others.

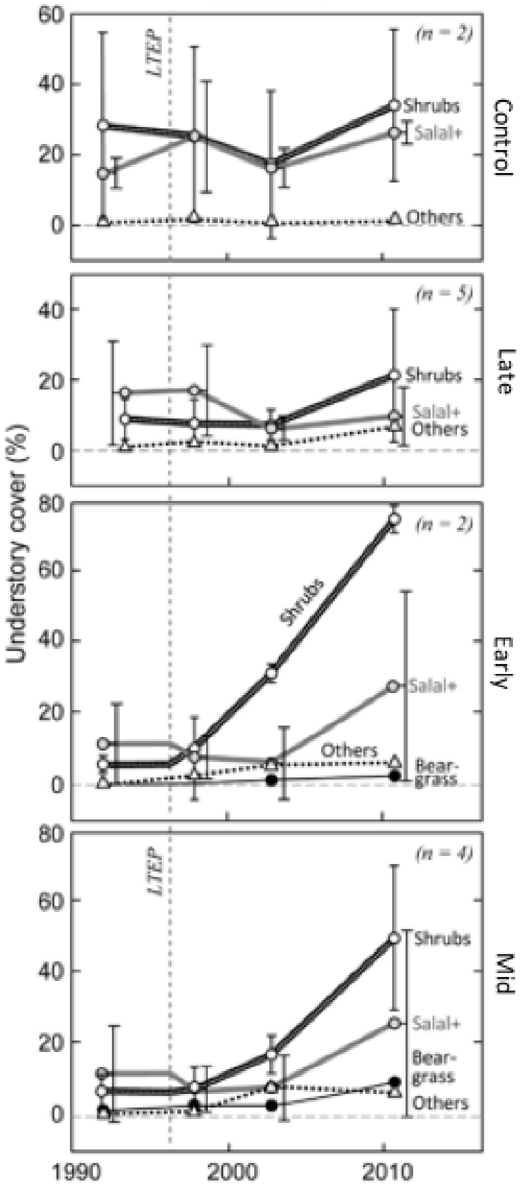

Figure 13: Results from Siskiyou LTEP site based in Southwestern Oregon showing changes in understory cover in Control, Late, Early, and Mid treatments over time (Bormann et al., 2015).

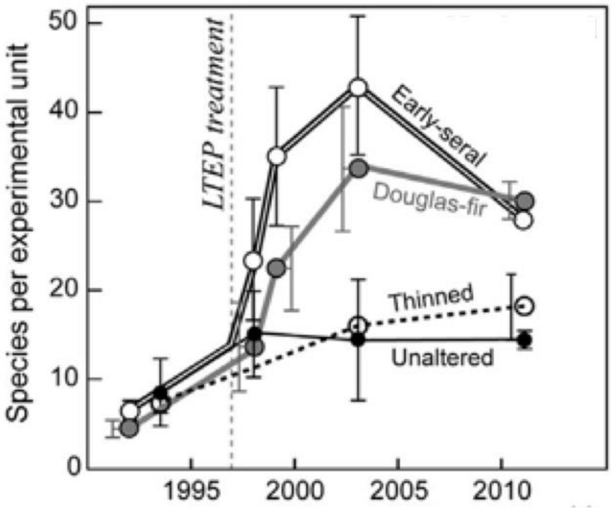

Figure 14: Results from the Siskiyou LTEP site showing species richness in unaltered (Control), thinned (Late), early-seral, and Douglas-fir treatment units over time (Bormann et al., 2015).

Implications for Management

Results from the LTEP study provide several different implications for future management. Disturbance events in the Early and Mid treatments resulted in a pulse of understory growth, especially for salal and bracken fern. Land managers could decide when to control the growth of these plants and other prolifically growing species based on their rate of establishment. Salal, for example, establishes 5-8 years after sprouting and begins to negatively impact surrounding plants after that time period (Boateng and Comeau, 2002). Treatment units with higher understory cover resulted in fewer seedling and sapling regeneration. If natural tree regeneration is a management goal, the understory may need to be removed or reduced in order to achieve this.

The addition of red alder in the Early units resulted in greater densities of Douglas-fir, a quality timber product, and fewer western hemlock, a species that grows densely with less timber value. Therefore, planting red alder could result in less pre-commercial thinning of western hemlock in the stand and therefore reduce overall costs. As the LTEP study continues, more information will provide insight on management techniques.

Future Studies

Many follow up studies could be done on the LTEP project. Future studies could investigate how each individual understory species is responding to the others using a multi-variate statistical approach. This could help show nuisances in the dataset that ANOVA or regression analysis tests would not. In addition, as more measurements are taken in the coming years, researchers could determine if there are plateaus in the cover of salal and bracken fern. Soil samples taken in units with high cover of these species could shed light on nutrient availability in the area. Finally, the influence of woody debris has not been found in the data. Future studies could dive further into its influence on the system.

Conclusion

There are many benefits in working with a long-term ecological study. The ability to analyze a large dataset that spans 25 years allows for a better overall picture of longer-term changes. The LTEP study has shown that results do not stay constant throughout measurement years, but instead are significantly changing over time. Merely looking at changes immediately after treatment does not fully explain the long term effect of these treatments. We therefore can not necessarily extrapolate beyond the time frame of the study to understand what will happen in future years. This indicates a need for more long-term evaluation to better understand how our ecosystems are changing throughout time and the ways in which we can manage them.

Overall, long-term studies are helping scientists understand the interactions occurring in dynamic forest ecosystems. As time passes, it will become even more clear as to how we should proceed with managing our ecosystems for both their ecological and economic values.

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