Long-Term Forest Restoration Effectiveness Monitoring in the Fort Clatsop Unit

Lewis and Clark National Historical Park

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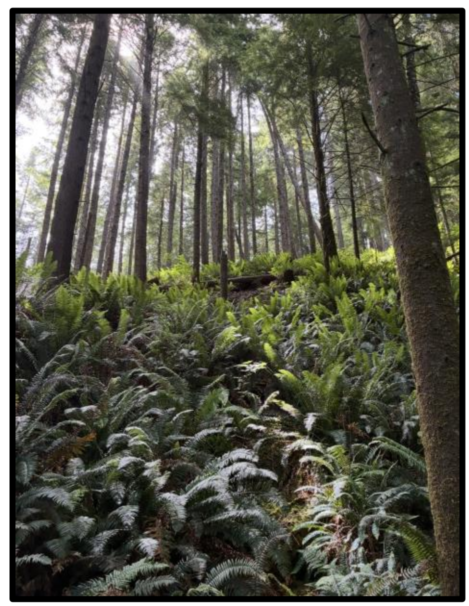

Project Introduction & Scope:

The Lewis and Clark National Historical Park (LEWI) was established as a National Memorial in 1958 to commemorate the history of the Lewis and Clark Expedition and its winter encampment at Fort Clatsop. In 2004, the site was redesignated as a National Historical Park. In 1995, the park drafted its General Management Plan (GMP) and Environmental Impact Statement (EIS) designed to guide park efforts related to preserving the history and natural landscapes surrounding Fort Clatsop. Within the GMP, a key area of focus was the purchasing of forest lands adjacent to the fort site, with the goal of restoring them to more closely reflect the historic conditions experienced by the Corps of Discovery.

> *"The proposed boundary expansion would provide protection of the forested and agricultural landscape now surrounding the Fort area and, by practicing forest management on some of the land included, would allow a return to a forest landscape representative of that experienced by the Corps of Discovery." (p. 46)*

In 2002, following the publication of the GMP, Congress passed the Fort Clatsop Memorial Expansion Act, adding approximately 963 acres of surrounding forest land to the Fort Clatsop Unit. The acquired lands were largely industrial second and third growth forests which had been cut and replanted several times to support the area's timber industry. As a result, the acquired land parcels differed greatly in both appearance, structure and ecology, from the natural, unmanaged stands present during the Lewis and Clark Expedition.

The acquired industrial plantations were characterized by densely stocked stands of young, small trees, a management strategy designed to maximize timber production. As a result, very little light reached the forest floor in these stands, essentially eliminating the understory vegetation, rich soils, downed trees and snags that are characteristic of Pacific Northwest forests. The historic stands experienced by the Corps of Discovery featured a much lower stem density, as well as larger, older trees and varying tree ages. Additionally, these unmanaged forests supported a structurally dense forest floor, teeming with vegetation, shrubs and fallen logs (Means et al, 1996). Literature suggests that active intervention is often necessary when converting industrial plantations toward more natural, self-sustaining forest conditions (Bailey & Tappeiner, 1998). Without disturbance or management intervention, these stands may remain in relatively static, simplified developmental stages for decades, with limited progression toward late successional or old-growth structure (Franklin et al., 2002).

In an effort to accelerate the development of acquired timber lands towards historic old-growth conditions, LEWI developed a restoration plan that implemented variable density restoration thinning, snag creation and native species planting to promote structural and ecological complexity across formerly managed stands. These treatments were designed to reduce stand density, increase structural heterogeneity, and reintroduce key ecological components such as large, downed wood, snags, and understory diversity. Collectively, the actions outlined in the restoration plan aim to shift previously simplified, plantation style forests toward more complex, late successional conditions that more closely resemble those historically present in the Pacific Northwest.

Literature Review:

Historically, Pacific Northwest forests were characterized by complex, multi-aged stands with large trees, diverse canopy layers, and abundant coarse woody debris. However, extensive industrial logging has transformed much of the region into simplified, even-aged second growth forests with reduced structural complexity. The Pacific Northwest's timber industry expanded rapidly during the late nineteenth and twentieth centuries, driven largely by high demand for Douglas-fir and other conifer species, as timber inventory in the previously logged Great Lakes and Southern states dwindled (Wall, 1972). The shift in timber industry attention from other parts of the country to the Pacific Northwest coupled with advances in logging technology and transportation infrastructure created a perfect storm for rapid and large-scale extraction of old growth forests across the region. Innovations such as interconnected railways, and logging roads made previously inaccessible parcels of land available to timber companies. Additionally, early selective logging practices were gradually replaced by large-scale clearcutting systems that enabled rapid extraction and regeneration of commercially valuable timber (Rajala, 1993). Following World War II, federal and private forest lands were increasingly managed under intensive production forestry regimes, which emphasized short rotation cycles, even aged stands, and high yield plantations aimed at maximizing profits (Wall, 1972).

Over time, the combined effects of intensified logging, improved extraction technologies, and industrial forest management practices led to a profound decline in old growth forest cover across the Pacific Northwest. Since the time of European settlement, roughly 72 percent of original old growth conifer forest in the region has been lost, largely due to the timber industry (Strittholt, Dellasala, & Jiang, 2006). This widespread loss has resulted in the hyper fragmentation of remaining old growth stands and the near elimination of continuous late successional forest across much of the landscape, fundamentally altering regional ecosystem structure and function. Given this widespread loss, understanding the ecological importance of old growth forests is essential for evaluating why their restoration and conservation remain a central goal in Pacific Northwest Forest management.

Old growth forests in the Pacific Northwest Region are critically important for sustaining biodiversity, water cycling, ecosystem resiliency, carbon sequestration, nutrient cycling and soil productivity (Rapp, 2003). Characterized by multilayered canopies, large and structurally diverse trees, and abundant coarse woody debris, absent in industrial stands, these forests create a wide range of ecological niches and microhabitats that support high levels of species diversity (Carey 1998). This structural complexity which develops over centuries allows many species with different habitat requirements to coexist within the same forest, making old growth ecosystems among the most biologically diverse environments in the region. The upper canopy, featuring large, thick branches provides unique habitat for threatened bird species such as the Northern Spotted Owl (*Strix occidentalis caurina)* and the Marbled Murrelet (*Brachyramphus marmoratus)* which rely on late successional forest structure for nesting, roosting, and foraging (Carey, 1998). Large canopy trees also support epiphytic communities of mosses, lichens, and ferns that provide food, nesting material, and shelter for numerous invertebrates and vertebrates (Carey, 1998). Lower canopies, consisting of smaller developing trees, further increase vertical habitat complexity, supporting overstory vegetation such as lichens and mosses and a diverse range of arboreal wildlife across multiple trophic levels. This variation in canopy heights and spacing produce heterogeneous light conditions on the forest floor, which in turn promotes understory plant diversity and tree regeneration (Spies, 1998). In this way, both shade tolerant and intolerant plants are able to grow and thrive in unique environmental niches, increasing diversity, structural complexity and habitat variability (Stewart, 1998). This diversity in groundcover creates a wide range of food, resources and shelter, providing rich feeding grounds for terrestrial mammals such as elk, deer and other herbivores. Groundcover also provides important habitat for pollinators, songbirds, and small mammals that contribute to seed dispersal, pollination, and other ecological processes (Stewart, 1998). Beyond this, the high volume of standing dead wood and coarse woody debris present in late successional forests, absorb and hold water, making them unique habitats for a variety of organisms including cavity nesting birds, small mammals, amphibians and reptiles as well as fungi, invertebrates, and decomposer communities that play a critical role in nutrient cycling and ecosystem functioning (Rose et al, 2001).

Beyond support of biodiversity and habitat, old growth forests in the Pacific Northwest are critical for water cycling and carbon sequestration processes as well as ecosystem resiliency. Long term ecological research demonstrates clear differences in how young and old forests regulate these processes. Compared to old growth stands, young forests, typical of industrial/plantation stands, exhibit lower water use efficiency and greater sensitivity to summer drought, with tree growth rates declining sharply during periods of water limitation, such as warm summer months (Farinacci, Jones & Silva, 2024). Conversely, late succession stands tend to exhibit greater resistance to drought and climatic variability, with more stable growth patterns and sustained carbon uptake even during periods of water stress. Large, mature trees are particularly important in this regard, as their deep rooting systems and established physiological regulation allow them to access and retain water more effectively, reducing sensitivity to drought conditions (Farinacci, Jones & Silva, 2024). In other words, late successional forests sequester carbon and store water much more effectively than younger stands, while also buffering ecosystems against the increasing impacts of climate change. These differences in physiological function scale up to influence watershed level processes, with old growth forests promoting more stable streamflow, greater groundwater recharge, and more consistent regulation of seasonal water availability compared to younger, simplified stands (Grant, Tague & Allen, 2013).

The structural complexity characteristic of old growth forests further enhances their resilience by regulating microclimatic conditions, maintaining higher humidity, and reducing environmental stress during periods of drought. These same structural attributes contribute to greater fire resilience, as old growth forests often develop varying stand structures, higher canopy moisture, and spatial discontinuity that can reduce fire spread and severity compared to dense, even aged industrial plantations (Farinacci, Jones & Silva, 2024). These water regulating functions also reinforce long term carbon sequestration, since stable soil moisture conditions support continuous photosynthesis, reduce drought induced carbon loss, and enhance long term biomass accumulation in both above and belowground pools. In addition to living vegetation, the abundance of coarse woody debris in late successional forests plays an important role in regulating forest hydrology and resilience. These forests are rich with woody debris, which absorbs and retains the frequent rainfall characteristic of the Pacific Northwest region. Having a high moisture holding capacity, coarse woody debris acts as a critical moisture reservoir particularly during the warmer, drier summer months (Harmon et al., 1986). By slowly releasing stored water back into surrounding soils, coarse woody debris helps maintain soil moisture, moderates soil temperatures, protect against drought and wildfires and creates favorable conditions for seedling establishment and ecosystem recovery following disturbance (Harmon et al., 1986).

Beyond moisture retention, habitat and ecosystem resiliency, the coarse woody debris found in late successional forests of the Pacific Northwest also acts as a critical contributor to nutrient cycling and soil productivity. The productivity of forest ecosystems is largely determined by the availability and cycling of key limiting nutrients, particularly nitrogen, phosphorus, potassium, calcium, and magnesium, which are essential for processes such as photosynthesis, root development, and cellular function. In forested systems, these nutrients are primarily introduced and recycled through atmospheric deposition, mineral weathering of parent material, biological fixation, and the decomposition of organic matter, including leaf litter, roots, and woody debris (Edmonds et al., 1989). Among these pathways for introduction, the decomposition of organic material plays a central role in maintaining long term soil fertility, as it gradually returns stored nutrients back into the soil and makes them available for plant uptake. In late successional forests of the Pacific Northwest, coarse woody debris is a particularly important component of this process, acting as both a physical substrate for decomposition and a long-term reservoir of nutrients. Historically, these forests had thick layers of organic matter and biomass coating the forest floor, largely consisting of woody debris, dropped pine needles and other forms of leaf litter. As industrial plantation stands have become more pervasive across the region, these biomass layers have been substantially reduced through intensive harvesting, slash removal, and shorter harvest rotations (Krankina, et al, 2014). Consequently, fewer organic materials remain on the forest floor to decompose and replenish soil nutrient pools, disrupting the slow, continuous cycling of nutrients that characterizes old growth ecosystems. The reduction in organic biomass and woody debris within industrial forest stands has contributed to declining soil productivity throughout the Pacific Northwest. Linked with tree growth and development, soil productivity is a critical determinant of long-term ecosystem health, influencing the capacity of forests to support rapid tree growth, sustain biodiversity, and recover following natural disturbances (Jurgensen et al., 1997).

In addition to their role in nutrient cycling, coarse woody debris also serve as "nurse logs," providing stable, nutrient rich surfaces that facilitate seed germination and tree establishment. By retaining moisture, moderating soil temperatures, and supporting communities of fungi, bacteria, and other decomposers, decaying logs create favorable microsites for seedling survival, particularly for many conifer species native to the Pacific Northwest (Woods, Maleta & Ortmann, 2021). This process promotes natural forest regeneration while maintaining the structural diversity characteristic of late-successional ecosystems. Since coarse woody debris accumulates over centuries through natural mortality and disturbance, it is widely recognized as a defining structural feature and ecological indicator of old-growth forests. Consequently, the retention and reintroduction of coarse woody debris in managed forests is essential for restoring key late-successional features such as efficient nutrient cycling, high soil productivity, natural tree regeneration, and reestablishing the ecological functions and structural complexity that distinguish old-growth forests in the region.

In order for industrial timberland forest stands to begin the process of developing old growth characteristics, management and intervention is often necessary to accelerate structural complexity, restore ecological processes, and reestablish long-term nutrient cycling and habitat heterogeneity. Without active intervention, these second growth industrial stands remain characterized by densely stocked trees, little sunlight reaching the forest floor, and limited structural complexity that constrains understory development and biodiversity. (Carey, 2003). In these conditions, intense competition among densely packed trees limits diameter growth, reduces vertical potential, and suppresses the development of understory vegetation, resulting in simplified forest structure that persists over long time periods without disturbance or management (Franklin et al, 2002). As a result, natural successional processes alone may not be enough to restore the diversity of habitat conditions, nutrient cycling pathways, and microclimatic variation that define late-successional forests. To address these structural and functional limitations, forest managers often rely on active silvicultural interventions designed to accelerate ecosystem development toward old-growth conditions. These management approaches commonly include density thinning treatments that reduce stem concentration within a stand. Density thinning treatments involve selectively and methodically cutting down trees within the forest stand in order to simulate natural disturbances. In doing so, forest managers are able redistribute available light and resources and promote increased heterogeneity in tree spacing and growth rates (Carey, 2003). Additionally, many intervention efforts will utilize a combination of gaps and skips to simulate natural disturbance and preserve existing ecological features. Gaps refer to areas within a restoration area in which trees are removed in a patch to mirror historically occurring natural disturbances. In this way, these areas increase light availability at the forest floor, reduce competition for water and nutrients, and create favorable conditions for understory vegetation, tree regeneration, and the establishment of a more diverse age and size structure (Brodie & Harrington, 2020). The resulting variation in canopy cover promotes the development of heterogeneous microclimates and habitat conditions that more closely resemble those found in naturally disturbed, late-successional forests (Carey, 2003). Conversely, skips are patches intentionally left untreated during thinning operations to retain favorable existing habitat features, maintain canopy continuity, and preserve structural elements such as large trees, snags, and coarse woody debris (Brodie & Harrington, 2020).

In addition, retention-based practices may be incorporated to preserve or introduce key structural elements such as standing dead wood, and coarse woody debris, which are essential for supporting habitat diversity and nutrient cycling processes. For example, many forest managers attempt to reintroduce these unique habitat features by leaving thinned trees and logging byproducts on the forest floor where they function as future coarse woody debris, gradually decomposing to contribute to soil organic matter, moisture retention, and long-term nutrient cycling. In some cases, selected trees are also girdled to disrupt nutrient flow, resulting in standing deadwood, useful for maintaining vertical structure and providing habitat continuity for cavity nesting species and other wildlife (Franklin et al., 2002) (Bunnel, Kremsater, & Wind, 1999). In certain cases, native species that have become rare under previous management regimes may also be replanted in the treatment areas to help re-establish historical habitat conditions and ecological equilibrium. Together, these interventions are intended to guide second growth industrial forests toward more complex, resilient, and functionally diverse conditions that more closely resemble late-successional ecosystems.

Objectives for Fort Clatsop's Restoration Efforts:

These variable thinning strategies are ultimately guided by broader forest restoration objectives aimed at accelerating the development of late-successional structure and ecosystem function. Within the Fort Clatsop Unit, LEWI elected to implement a combination of variable density thinning, retention of logging debris on the forest floor, snag creation, and native species planting in their restoration efforts. Together, these actions were intended to mimic key elements of natural disturbance regimes and old-growth forest structure by increasing habitat heterogeneity, enhancing nutrient cycling through the addition of coarse woody debris, and promoting long-term forest development of more complex and resilient ecological conditions. Within the parks 2011 Environmental Assessment (EA), LEWI established eight main objectives designed to guide restoration efforts and inform subsequent monitoring and management decisions.

LEWI Forest Restoration Objectives

Objective 1.1	*Enhance forest structural complexity through application of variable density thinning (applying a variety of thinning treatments and untreated areas across the landscape to create heterogeneity on a landscape scale) and other techniques designed to accelerate stand development by truncating the competitive exclusion stage of forest development.*
Objective 1.2:	*Reintroduce the range of plant species made rare under previous management.*
Objective 1.3	*Increase diameter growth rates to speed development of large trees and reduce windthrow risk by decreasing the ratio between tree height and trunk diameter (H: D ratio)*
Objective 1.4	*Encourage the development of multiple canopy layers.*
Objective 1.5	*Increase the number and size of snags, downed logs and forest floor biomass.*
Objective 1.6	*Stimulate the re-initiation of understory plants through overstory thinning.*
Objective 1.7	*Retain existing snags and downed wood where possible to preserve existing habitat structures.*
Objective 1.8	*Create additional snags and downed wood to recruit these structures where they are lacking or underrepresented.*

Table 1. Forest restoration objectives outlined in 2011 Environmental Assessment. Used to guide management and monitoring decisions within the Fort Clatsop Unit.

Using these objectives as guiding principles, LEWI's restoration efforts focused on accelerating natural forest development processes that would otherwise occur over much longer time periods, by initiating the structural and ecological changes necessary for second growth stands to progress toward late-successional conditions. By reducing stand density, increasing canopy variability, promoting native vegetation recovery, and enhancing the abundance of deadwood habitat such as snags and coarse woody debris, the project aimed to restore the fundamental processes that support old-growth forest function. These objectives also provided a framework for evaluating restoration success over time by establishing measurable indicators of forest development, including changes in tree growth, canopy structure, understory composition, dead wood abundance, and overall habitat complexity.

Methods:

Forest Monitoring: Sampling Design:

Using these objectives, LEWI created a forest monitoring protocol in 2012, the summer before initial thinning treatments. LEWI staff determined that 20 x 20-meter square plots would be the most appropriate size to accurately and efficiently sample the forest characteristics of interest. The general layout for each plot features wooden stakes marking each outer plot corner, a rebar and cap indicating plot center, and five 1.5-meter square plots at center, established using a combination of wooden stakes and red pin flagging.

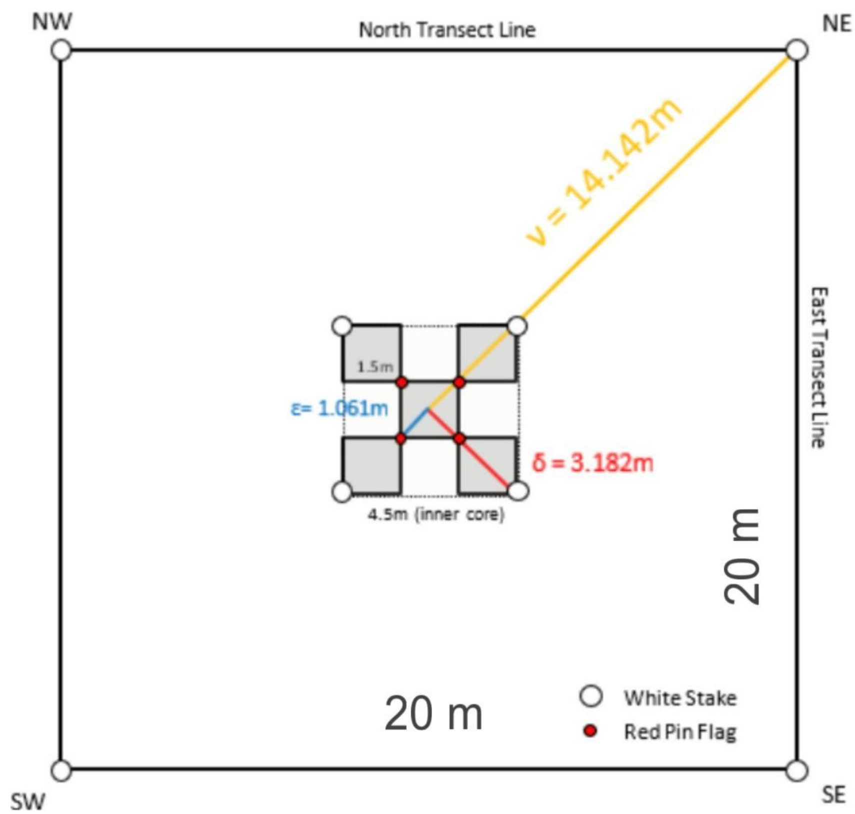

Figure 1. Sample 20x20 meter forest plot layout used for data collection and forest monitoring within the Fort Clatsop Unit at the Lewis and Clark National Historic Park.

At present, a total of 57 forest plots have been established within the Fort Clatsop Unit to assess the effectiveness of the park's restoration efforts, including thinning, snag creation and native species planting. Plots were either co-located with existing elk pellet survey locations (systematically distributed throughout the park) or randomly placed using GIS software. Each plot is ideally established and measured within the year before density thinning treatments and revisited every five years for remeasurement. Due to differences in monitoring and thinning seasons, the 5-year return timelines have a range of 4.5-5.5 years. (See Appendix Figure A1. for individual plot establishment/revisit schedule). Each plot included in analysis was visited a total of 3 times following establishment. Of the 57 established plots, the plot count by stand type is:

- 45-year-old Sitka Spruce *(Picea sitchensis)* (45 PICSIT) = 43 plots
- 35-year-old Sitka Spruce *(Picea sitchensis)* (35 PICSIT) = 5 plots
- 15-year-old Sitka Spruce *(Picea sitchensis)* (15 PICSIT) = 5 plots
- 45-year-old Red Alder *(Alnus rubra)* (45 ALNRUB) = 4 plots

The number of plots established within each stand type was proportional to the area designated for treatment. Within each 20-meter square plot, the following data was collected at the time of each visit using physical data sheets:

Within the square plot	Interior tree species and diameter at breast height (DBH).
	Standing dead wood species and DBH.
	Total height and height to base of canopy of the four trees closest to each respective corner stake.
Along the North and East boarders of the plot	Line intersect sampling of coarse woody debris, recording; species, length, DBH and decay class.
Within the five 1.5-meter square interior plots	Woody tree recruitment, stem count & species.
	Herbaceous species and percent cover.
At plot center	Forest overstory density (added summer 2017).

Table 2. Data collected and collection location for forest monitoring metrics within a 20x20 meter forest plot.

Of the 57 forest plots, 10 (7 = 45 PICSIT, 2 = 35 PICSIT, 1= 45 ALNRUB) were selected as controls and received no restoration treatments throughout the study period. The purpose of these plots was to measure the effectiveness of LEWI's treatments in terms of tree growth, understory development and deadwood habitat against untreated areas within the forest. This allowed LEWI to gauge the effectiveness of management intervention in propelling stand development from industrial timberland toward a late-successional forest.

Analysis:

Prior to analysis, the dataset underwent quality assurance and quality control (QA/QC) within the Forest Monitoring Microsoft Access database to ensure the completeness, consistency, and accuracy of the final dataset. Data were reviewed for missing values, duplicate records, and potential entry errors, including impossible or biologically implausible measurements. Variables such as interior tree DBH, coarse woody debris dimensions, understory percent cover, and event dates were screened for missing or impossible values and cross checked against original field records when discrepancies were identified. Any errors identified during the QA/QC process were corrected where possible or documented. These procedures helped ensure that all analyses were conducted using a complete and reliable dataset. See Appendix for a list of QA/QC actions performed.

After performing QA/QC, a total of 7 plots were excluded from subsequent analysis due to not meeting study criteria. Some plots were not revisited during all scheduled monitoring periods, while others had been compromised by the construction or presence of recreational trails, reducing their suitability for evaluating restoration outcomes. Thus, the total number of forest plots examined during analysis was 50. Of the 50 plots analyzed, count by stand type is:

- 45-year-old Sitka Spruce *(Picea sitchensis)* treated (45 PICSIT treated) = 31 plots
- 45-year-old Sitka Spruce *(Picea sitchensis)* control (45 PICSIT control) = 6 plots
- 35-year-old Sitka Spruce *(Picea sitchensis)* treated (35 PICSIT treated) = 3 plots
- 35-year-old Sitka Spruce *(Picea sitchensis)* control (35 PICSIT control) = 2 plots

- 15-year-old Sitka Spruce (*Picea sitchensis)* treated (15 PICSIT treated) = 5 plots
- 45-year-old Red Alder *(Alnus rubra)* treated (45 ALNRUB treated) = 2 plots
- 45-year-old Red Alder *(Alnus rubra)* control (45 ALNRUB control) = 1 plots

Following QA/QC procedures and finalization of the dataset, data analysis was conducted in R Studio (version 4.5.2) to evaluate differences in forest structure, composition, and development among stand types and treatment conditions. Analyses focused on evaluating patterns in variables associated with forest development and restoration outcomes, including stand density, tree diameter at breast height (DBH), understory vegetation cover, coarse woody debris characteristics, and tree recruitment. Statistical analyses and visualizations were used to assess variation among stand types as well as treatment vs control groups and ultimately evaluate stand development across the monitoring period.

Results:

Changes in Stem Density

The most direct structural effect of LEWI's thinning treatments is a reduction in overall stem density within treated stands. Stem density was evaluated as an indicator of treatment effectiveness and early stand development following restoration thinning. Because thinning selectively removed densely planted trees, primarily Douglas Fir (*Pseudotsuga menziesii*) and Western Hemlock (*Tsuga heterophylla*), treated stands were expected to exhibit an immediate reduction in stem densities compared to control stands. However, control stands were also expected to exhibit a gradual reduction in stem density due to density dependent mortality and competition among trees. Stem density (number of trees per hectare) was calculated for each plot at the time of each of the three revisits. Figure 2 illustrates changes in stem density among stand types and treatment conditions across the monitoring period, with values indexed to the initial visit for each plot to evaluate changes in density over time. Both treatment types in the 45 PICSIT stand type displayed extreme outliers that dramatically impacted overall trends. As a result, 45 PICSIT control and 45 PICSIT treated groups are each displayed twice, once including the outlier and once excluding the outlier.

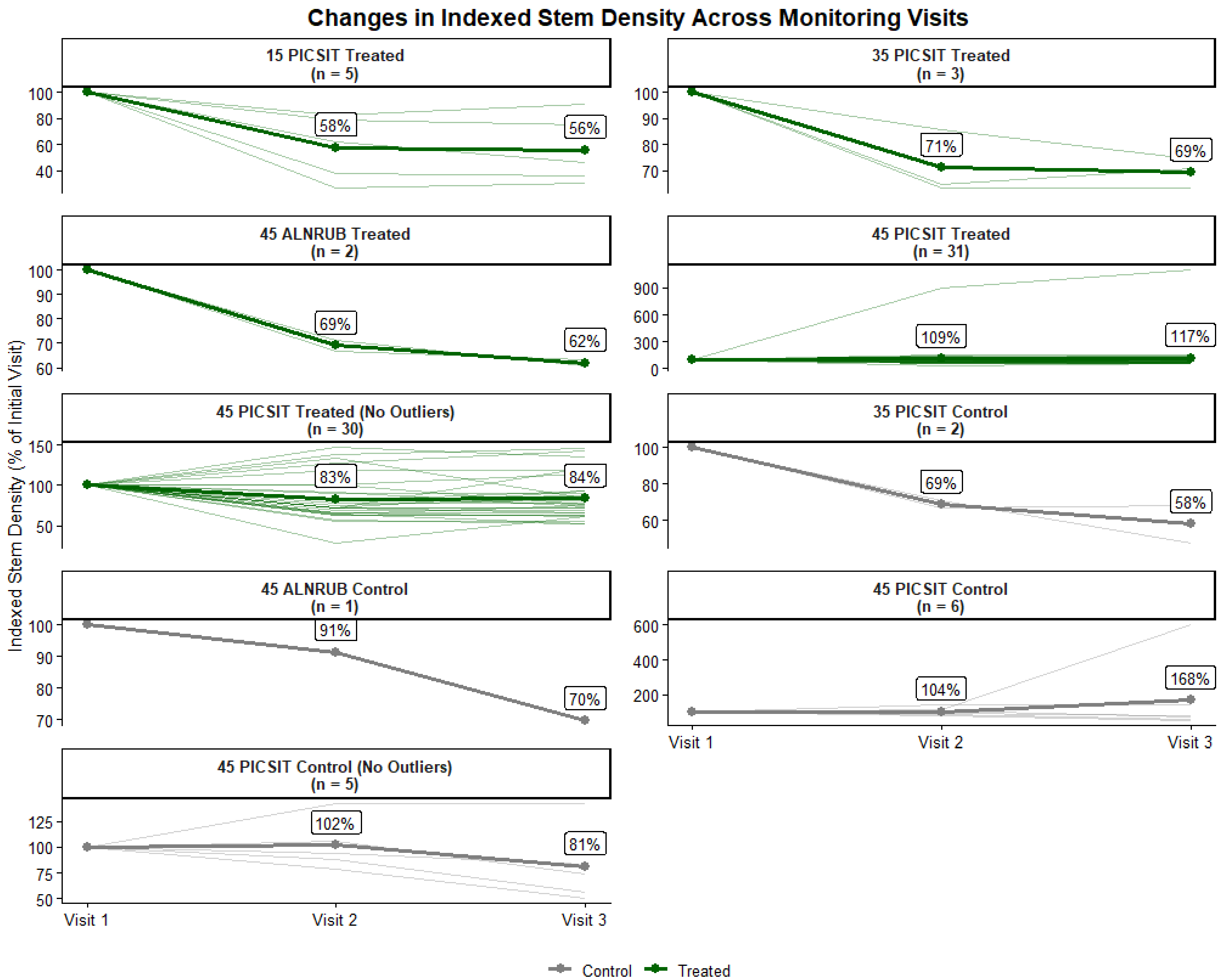

Figure 2. Indexed stem density across monitoring visits by stand type and treatment condition. Stem density values are expressed relative to initial plot conditions (Visit 1 = 100%). Individual lines represent individual plots, while thicker lines represent mean trends within each treatment group.

Based on Figure 2, stem density generally decreased throughout the monitoring period across stand types, with variation in magnitude of change among treatment conditions. Treated plots generally showed an initial reduction in stem density because of thinning treatments followed by a period of relatively stable stem densities in later monitoring visits. This trend suggests that immediate structural changes from thinning occurred early in the monitoring period, followed by a period of density stabilization with less competition for resources allowing established trees to thrive. One 45 PICSIT treated plot exhibited an unusually high indexed stem density value due to a large proportional increase relative to its initial measurement. Because indexed values are calculated relative to baseline conditions, plots with low initial stem counts can produce disproportionately large changes. This outlier increased variability within the 45 PICSIT treated group and influenced the overall treatment trend; however, when excluded, the remaining plots generally followed the broader pattern of initial decline followed by density stabilization observed across treated stands.

Conversely, the control plots generally exhibited gradual downward trajectories in stem density throughout the monitoring period. This is consistent with density dependent mortality and competition in overcrowded, untreated stands. An exception was observed in the 45 PICSIT Control treatment, where one plot exhibited a substantial increase in indexed stem density that influenced the overall trend for that treatment group, possibly due to low initial stem density at the first visit. Excluding this plot, the remaining 45 PICSIT Control plots exhibited declining trajectories more consistent with the patterns observed in other control stands.

Changes in DBH

Changes in diameter at breast height (DBH) were evaluated among stand and treatment types to evaluate the impact of LEWI's thinning treatments on tree size distribution over time and structural development towards late-successional forest characteristics. Violin plots were used to visualize the distribution of individual tree DBH measurements across three monitoring visits, with wider sections representing greater concentrations of trees within a given diameter range. Comparisons were made between treated and control stands within each stand type and age class. Data were cleaned to include only conifer and alder species commonly associated with the study stands, including *Picea sitchensis*, *Pseudotsuga menziesii*, *Tsuga heterophylla*, *Thuja plicata*, *Pinus contorta*, and *Alnus rubra*. Smaller understory hardwoods such as Cascara (*Rhamnus purshiana*) and Pacific Crabapple (*Malfus fusca*) were excluded to prevent naturally smaller DBH values from skewing overall patterns in stand development.

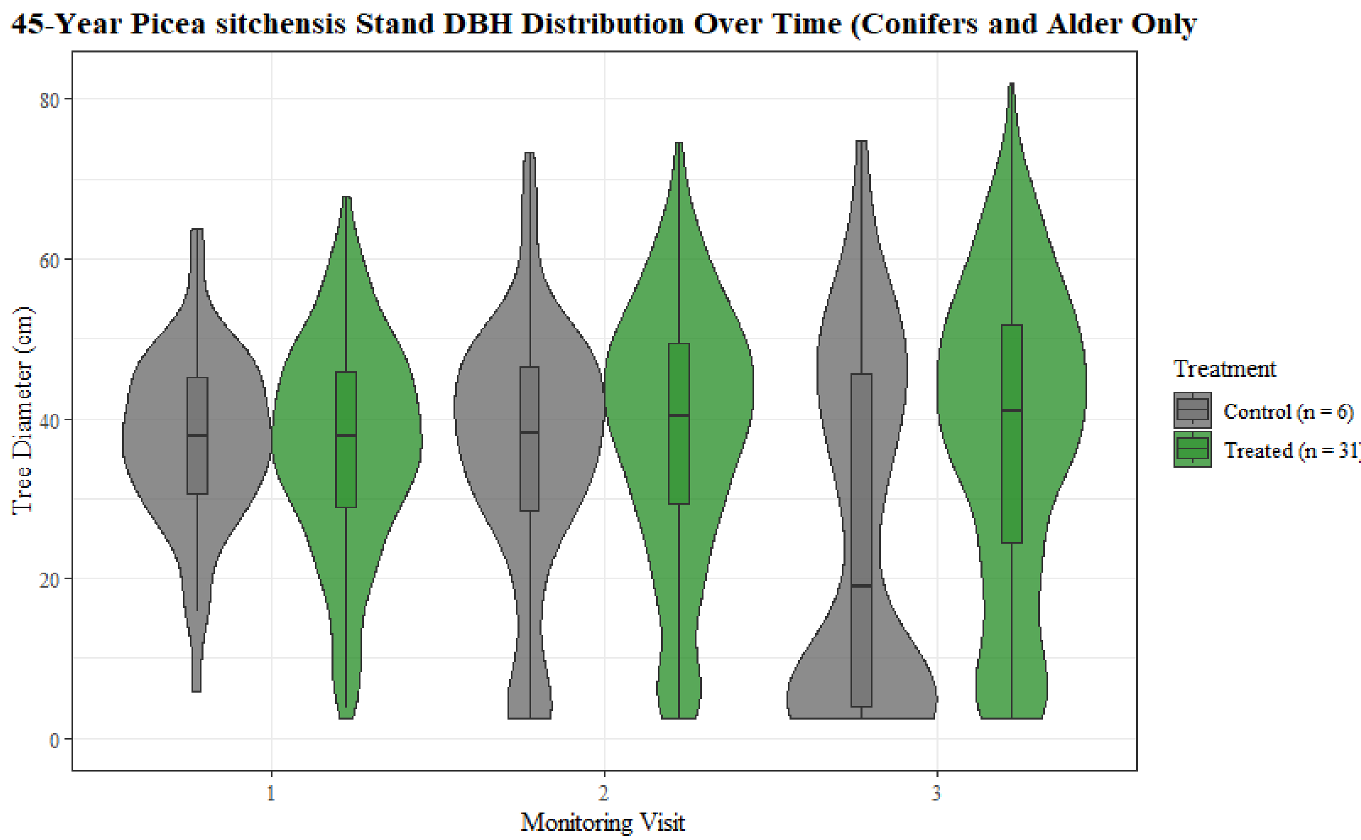

Figure 3. Distribution of individual tree diameter at breast height (DBH) measurements across three monitoring visits for treated and control 45-year-old Picea sitchensis stands. Violin width represents the relative concentration of trees within each DBH range. Only dominant conifer and alder species were included to represent changes in overstory stand structure.

The 45 PICSIT stands generally started with a similar DBH range among treatment and control plots. Throughout the monitoring period, treated stands showed a greater representation of large diameter trees in the distribution when compared with control stands. Control stands saw an overall decrease in representation of large trees across the monitoring period coupled with an increase in smaller DBH class trees. These results are consistent with thinning treatments reducing stand competition allowing trees to grow larger at the individual level. Control stands increase in representation of smaller DBH class trees may reflect the continued presence of suppressed understory trees heavily competing for light and resources, leading to repetitive patterns of mortality and regeneration. Without thinning, these trees may be less likely to reach larger diameter classes, contributing to the continued dominance of smaller stems within untreated stands.

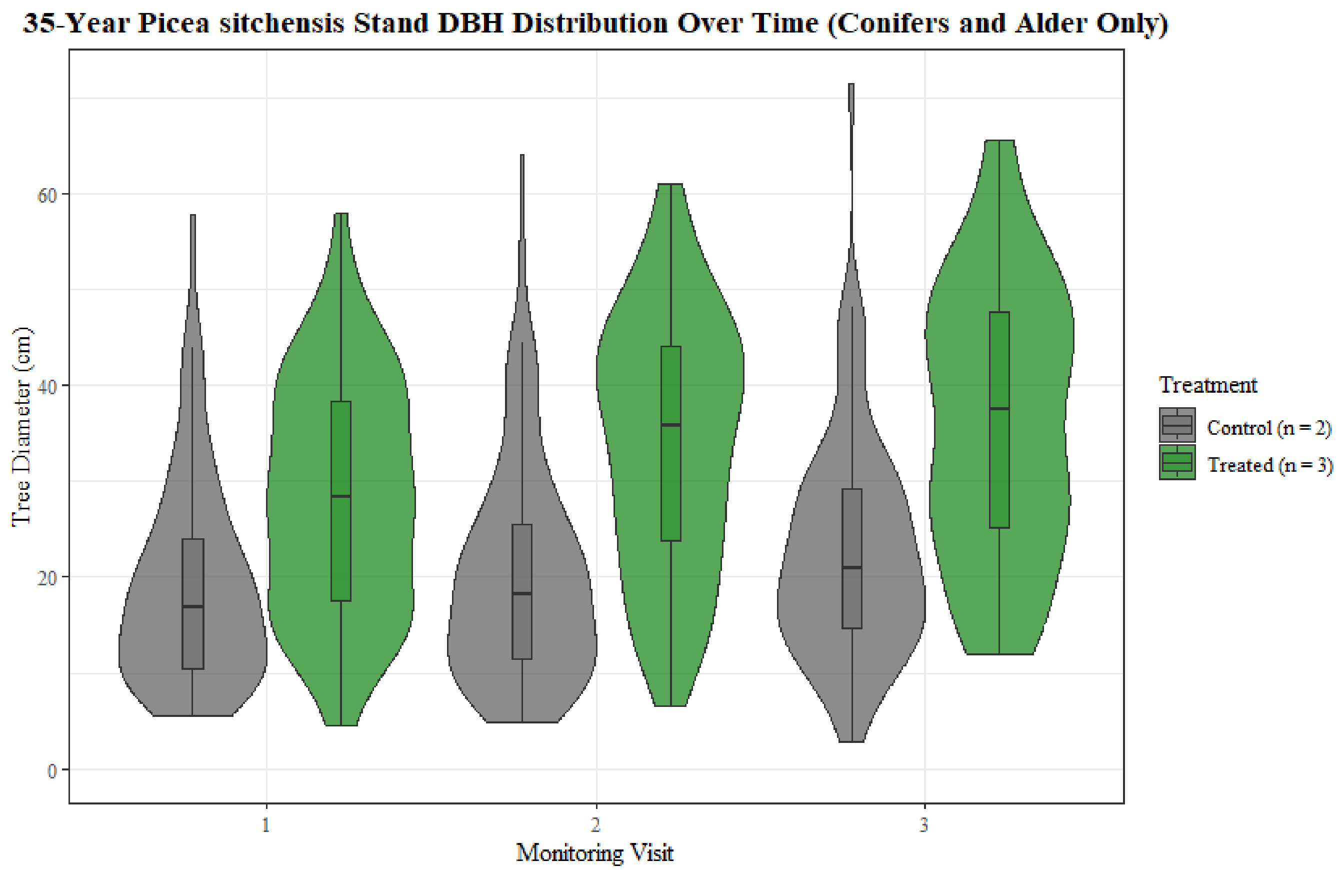

Figure 4. Distribution of individual tree diameter at breast height (DBH) measurements across three monitoring visits for treated and control 35-year-old Picea sitchensis stands. Violin width represents the relative concentration of trees within each DBH range. Only dominant conifer and alder species were included to represent changes in overstory stand structure.

The 35 PICSIT stands displayed an initial disparity in DBH distributions, with control plots being dominated by smaller diameter trees, while the treated plots had a much more evenly distributed DBH range. Throughout the monitoring period, treated plots displayed an increased representation of large DBH class trees. Control plots experienced slow and marginal growth in large DBH trees, with most representation remaining concentrated among smaller diameter trees. These patterns suggest that thinning treatments may have reduced competition among trees, promoting greater development of larger diameter stems, while untreated stands continued to retain a higher proportion of smaller diameter trees, unable to develop due to competition and scarce resources.

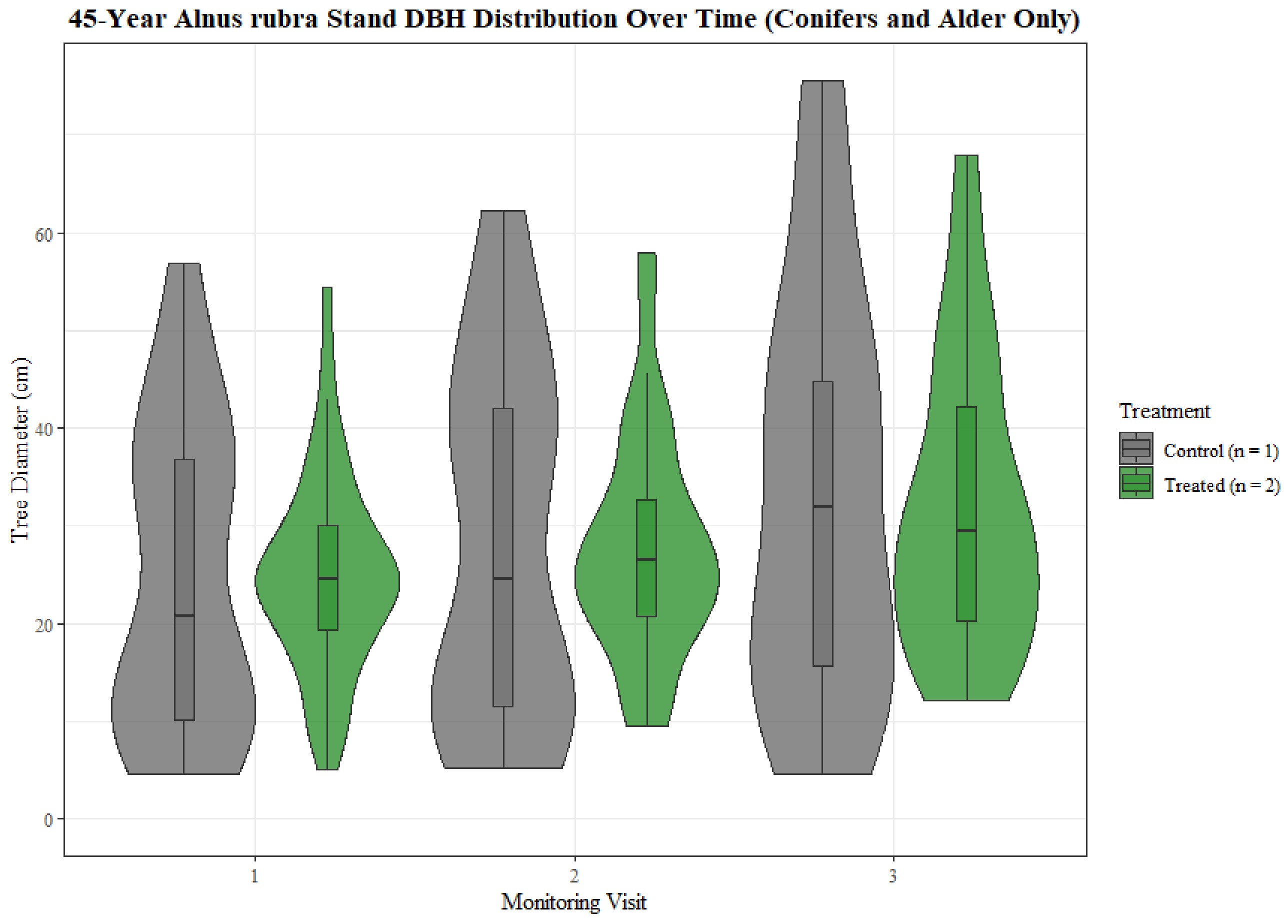

Figure 5. Distribution of individual tree diameter at breast height (DBH) measurements across three monitoring visits for treated and control 45-year-old Alnus Rubra stands. Violin width represents the relative concentration of trees within each DBH range. Only dominant conifer and alder species were included to represent changes in overstory stand structure.

The 45 ALNRUB stands displayed pronounced differences between initial DBH distribution between control and treated plots. The control plot had a broader DBH range, with representation across a wide range of DBH classes. In contrast, treated plots showed a more concentrated DBH distribution, with most trees occurring within a narrower diameter range. Throughout the monitoring period, control plot maintained a broad DBH distribution while also increasing representation of larger diameter trees, suggesting continued development across multiple size classes. Treated plots similarly showed an increase in the representation of larger diameter trees over time, while maintaining a more concentrated distribution compared to the control. Development in the initially well-distributed control stand suggests that this plot continued its natural pattern of stand development without major structural changes from management intervention. Treated plots also showed increased representation of larger diameter trees over time, consistent with reduced competition following thinning treatments.

Changes in Herbaceous Cover

Changes in herbaceous species ground cover was evaluated to measure the effectiveness of LEWI's thinning treatments on promoting understory development and restoration. A summary table was used to visualize changes in mean percent cover of 10 key herbaceous species selected in consultation with LEWI staff based on their ecological importance, native status, and relevance to restoration goals. Species of primary interest were Deer fern *(Blechnum spicant)*, Wood rush *(Luzula sp.),* Sword fern *(Polystichum munitum),* Himalayan blackberry *(Rubus bifrons),* Salmonberry *(Rubus spectabilis),* Pacific blackberry *(Rubus ursinus),* Red elderberry *(Sambucus racemosa),* Evergreen huckleberry, *(Vaccinium ovatum),* Red huckleberry *(Vaccinium parvifolium),* and Salal *(Gaultheria shallon).* Changes in species cover were evaluated across monitoring visits and stand treatment types to identify trends in desirable native species and non-native species response following thinning treatments. Changes in the ten key species throughout the monitoring period can be seen in Table 3.

This information was complemented by calculating the mean Simpson's Diversity Index for each stand and treatment type. Simpson's Diversity Index was calculated using all recorded herbaceous species and their corresponding percent cover values to evaluate overall changes in understory community diversity. Unlike individual species trends from Table 3., which highlight changes in specific taxa, Simpson's Diversity Index incorporates both species richness and evenness by measuring the distribution of cover among all species within each plot. Higher index values indicate a more diverse and evenly distributed herbaceous community, while lower values indicate greater dominance by fewer species. Plot level diversity values were averaged by stand type and monitoring visit to evaluate whether thinning treatments contributed to increased understory complexity and biodiversity over time. Simpson's Diversity Index results can be found in Table 4.

Changes in Herbaceous Species Ground Cover

Mean percent cover across monitoring visits

Species	Native	15 PICSIT Treated				35 PICSIT Control				35 PICSIT Treated				45 ALNRUB Control				45 ALNRUB Treated				45 PICSIT Control				45 PICSIT Treated			
		V1	V2	V3	Δ	V1	V2	V3	Δ	V1	V2	V3	Δ	V1	V2	V3	Δ	V1	V2	V3	Δ	V1	V2	V3	Δ	V1	V2	V3	Δ
Deer fern *(Blechnum spicant)*	Native	2.8%	3.8% (+0.9)	6.6% (+2.8)	+3.7%	0.0%	0.0% (+0.0)	4.0% (+4.0)	+4.0%	2.0%	4.5% (+2.5)	3.0% (-1.5)	+1.0%	5.0%	0.0% (-5.0)	0.0% (+0.0)	-5.0%	3.0%	2.0% (-1.0)	0.0% (-2.0)	-3.0%	9.8%	7.1% (-2.6)	8.5% (+1.4)	-1.3%	5.3%	9.8% (+4.5)	11.4% (+1.6)	+6.2%
Wood rush *(Luzula sp.)*	Native	0.0%	0.0% (+0.0)	1.3% (+1.3)	+1.3%	0	0	0	0	0.0%	1.0% (+1.0)	2.2% (+1.2)	+2.2%	0	0	0	0	0	0	0	0	0.0%	3.7% (+3.7)	3.9% (+0.2)	+3.9%	1.0%	3.8% (+2.8)	2.3% (-1.5)	+1.3%
Sword fern *(Polystichum munitum)*	Native	14.2%	12.2% (-2.1)	15.1% (+3.0)	+0.9%	11.1%	17.1% (+6.1)	22.2% (+5.1)	+11.2%	33.9%	26.1% (-7.8)	40.2% (+14.1)	+6.3%	32.0%	30.0% (-2.0)	60.2% (+30.2)	+28.2%	55.8%	60.6% (+4.8)	66.4% (+5.8)	+10.6%	24.1%	42.1% (+18.0)	47.7% (+5.6)	+23.6%	31.9%	45.0% (+13.0)	49.1% (+4.1)	+17.2%
Himalayan blackberry *(Rubus bifrons)*	Non-native	0.0%	0.0% (+0.0)	4.0% (+4.0)	+4.0%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	5.6% (+5.6)	10.2% (+4.7)	+10.2%
Salmonberry *(Rubus spectabilis)*	Native	4.9%	8.8% (+3.9)	5.8% (-2.9)	+1.0%	0	0	0	0	31.0%	7.9% (-23.1)	17.5% (+9.6)	-13.5%	32.5%	29.4% (-3.1)	29.5% (+0.1)	-3.0%	7.0%	10.5% (+3.5)	2.0% (-8.5)	-5.0%	6.5%	14.7% (+8.2)	5.8% (-8.9)	-0.7%	4.5%	12.6% (+8.1)	13.9% (+1.3)	+9.4%
Pacific blackberry *(Rubus ursinus)*	Native	15.8%	19.2% (+3.5)	5.7% (-13.5)	-10.0%	7.0%	4.2% (-2.8)	4.7% (+0.4)	-2.3%	0.0%	0.0% (+0.0)	1.0% (+1.0)	+1.0%	0	0	0	0	0.0%	7.8% (+7.8)	0.0% (-7.8)	+0.0%	18.2%	8.9% (-9.4)	9.8% (+1.0)	-8.4%	3.5%	5.6% (+2.1)	7.1% (+1.6)	+3.6%
Red elderberry *(Sambucus racemosa)*	Native	17.1%	13.6% (-3.5)	11.3% (-2.3)	-5.8%	0	0	0	0	62.0%	63.6% (+1.6)	15.0% (-48.6)	-47.0%	0	0	0	0	3.0%	19.5% (+16.5)	26.8% (+7.2)	+23.8%	19.0%	9.2% (-9.8)	4.0% (-5.2)	-15.0%	7.7%	12.4% (+4.7)	12.9% (+0.5)	+5.2%
Evergreen huckleberry *(Vaccinium ovatum)*	Native	0.0%	0.0% (+0.0)	3.3% (+3.3)	+3.3%	2.0%	0.0% (-2.0)	0.0% (+0.0)	-2.0%	0	0	0	0	0	0	0	0	1.0%	3.5% (+2.5)	6.0% (+2.5)	+5.0%	1.0%	1.2% (+0.2)	2.7% (+1.5)	+1.7%	10.2%	18.5% (+8.3)	11.2% (-7.3)	+1.0%
Red huckleberry *(Vaccinium parvifolium)*	Native	18.0%	5.3% (-12.7)	1.8% (-3.6)	-16.2%	2.5%	4.8% (+2.3)	2.8% (-2.1)	+0.2%	0.0%	0.0% (+0.0)	1.8% (+1.8)	+1.8%	0	0	0	0	5.0%	1.5% (-3.5)	0.0% (-1.5)	-5.0%	2.2%	2.6% (+0.4)	6.3% (+3.7)	+4.0%	4.3%	8.2% (+3.9)	8.5% (+0.3)	+4.2%
Salal *(Gaultheria shallon)*	Native	0	0	0	0	15.0%	22.2% (+7.2)	13.2% (-9.0)	-1.8%	7.7%	8.0% (+0.3)	3.3% (-4.7)	-4.3%	0	0	0	0	6.3%	12.9% (+6.6)	23.2% (+10.3)	+16.9%	9.7%	10.1% (+0.4)	8.9% (-1.2)	-0.8%	9.3%	13.5% (+4.2)	16.3% (+2.8)	+7.0%

Table 3. Mean percent cover of selected herbaceous species across monitoring visits and stand treatment types. Values represent average cover across monitoring plots. Positive values indicate increases in species cover relative to previous monitoring visits.

Based on Table 3., changes in herbaceous species ground cover varied among stand types and treatments, with several native understory species showing increases in cover following restoration treatments. Sword fern (*Polystichum munitum*) demonstrated the strongest and most consistent increase across stand types, with total changes ranging from +0.9% in 15-year PICSIT treated stands to +28.2% in 45-year ALNRUB control stands and +23.6% in 45-year PICSIT control stands. While sword fern increased more drastically in control plots, it is important to note that control plots generally began with lower levels of herbaceous cover when compared to treated plots. Sword fern increased in all stand types, suggesting that this species remained a dominant and persistent component of the understory throughout monitoring.

Other native understory species showed more variable responses. Salal (*Gaultheria shallon*) increased in several stand types, particularly in 45-year PICSIT treated stands (+7.0%) and 45-year ALNRUB treated stands (+16.9%), indicating potential expansion of native shrubs over time following thinning. Salmonberry (*Rubus spectabilis*) showed mixed responses, increasing in some treated stands but declining in others, suggesting that species-specific responses and initial stand conditions influenced understory trajectories. Similarly, red elderberry (*Sambucus racemosa*) displayed large fluctuations, including a substantial decline in 35-year PICSIT treated stands (-47.0%) but increases in 45-year ALNRUB treated stands (+23.8%). More research may be required to understand these discrepancies. Changes in blackberry varied between native and non-native taxa species. Trailing blackberry (*Rubus ursinus*) generally declined in PICSIT stands, including a decrease of -10.0% in 15-year PICSIT treated stands and -8.4% in 45-year PICSIT control stands, although small increases occurred in some treatment groups. In contrast, Himalayan blackberry (*Rubus bifrons*) remained absent or low in most stand types but increased in 45-year PICSIT treated stands (+10.2%), indicating localized establishment of this non-native species following restoration activities. Overall, the selected indicator species showed increases in several native understory species following thinning treatments, particularly sword fern and salal, although responses varied among stand ages and forest types. Species specific trends suggest that restoration treatments influenced understory composition differently depending on initial stand conditions, species ecology, and competitive interactions.

Changes in Herbaceous Species Diversity				
Mean Simpson's Diversity Index across monitoring visits				
Stand Type	Visit 1	Visit 2 (Change)	Visit 3 (Change)	Total Change
15 PICSIT Treated	0.613	0.733 (+0.120)	0.619 (-0.114)	+0.006
35 PICSIT Control	0.378	0.433 (+0.055)	0.432 (-0.001)	+0.054
35 PICSIT Treated	0.316	0.458 (+0.142)	0.413 (-0.045)	+0.097
45 ALNRUB Control	0.712	0.674 (-0.038)	0.641 (-0.033)	-0.071
45 ALNRUB Treated	0.245	0.631 (+0.386)	0.587 (-0.044)	+0.342
45 PICSIT Control	0.517	0.641 (+0.124)	0.597 (-0.044)	+0.080
45 PICSIT Treated	0.521	0.677 (+0.156)	0.651 (-0.026)	+0.130

Table 4. Mean Simpson's Diversity Index by stand and treatment type across monitoring visits. Simpson's Diversity Index was calculated using species level percent cover data from all recorded herbaceous species. Values represent mean plot level diversity within each stand type and treatment group across monitoring visits, with higher values indicating greater species diversity and more even distribution of herbaceous cover.

By including all recorded herbaceous species, the Simpson's Diversity Index (SDI) explored in Table 4. provides a more comprehensive view of understory changes during the monitoring period. Generally, changes in understory diversity were relatively small. However, all stand and treatment types exhibited increases over the monitoring period, with the exception of the 45 ALNRUB Control group (n=1). Groups experiencing the biggest jumps in SDI were the 45 ALNRUB treated (+0.342) and 45 PICSIT treated (+ 0.130) stands. Notably, all treated groups experienced more substantial increases in diversity when compared to their corresponding control groups. These patterns suggest that LEWI's restoration thinning treatments may have contributed to increases in understory diversity by creating conditions that promote the establishment and persistence of additional herbaceous species. Although the magnitude of change varied among stand types, the overall trend of increasing diversity across treated stands indicates movement toward a more diverse understory community consistent with restoration objectives. However, the relatively short monitoring period and differences in initial stand conditions should be considered when interpreting these changes, as fluctuations can occur due to environmental variability, species availability, and site-specific factors.

Average percent cover of herbaceous species by plot treatment and stand type was also evaluated to assess overall understory response following thinning treatments. Mean herbaceous cover was summarized across monitoring visits for each stand and treatment type and visualized using a bar chart. This analysis incorporated all recorded herbaceous species and provided a broader assessment of changes in understory vegetation structure and recovery over time. This figure is valuable in LEWI's assessment of the effectiveness of thinning treatments on understory regeneration.

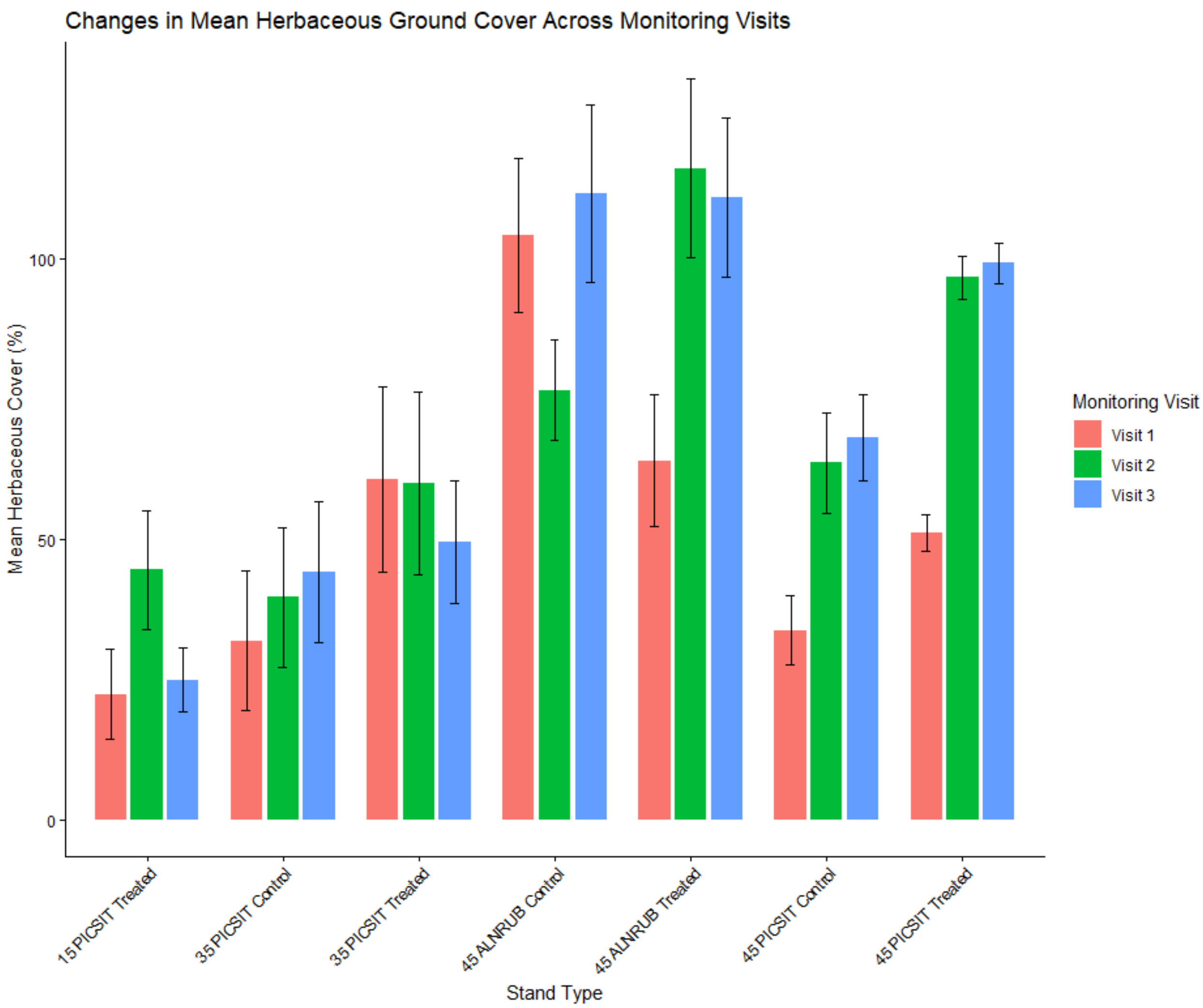

Figure 6. Changes in mean herbaceous ground cover across monitoring visits by stand and treatment type. Mean total herbaceous percent cover was calculated at the subplot level using all recorded herbaceous species across monitoring plots and averaged within stand and treatment type. Bars represent mean percent cover for each stand and treatment type during each monitoring visit. Error bars represent standard error of the mean and illustrate variability among subplots within each stand and treatment type.

Based on Figure 6., the 45 PICSIT and 45 ALNRUB treated groups experienced the largest increases in understory cover throughout the monitoring period. Also increasing were the 45 PICSIT, 45 ALNRUB, and 35 PICSIT control groups, although less dramatically than the 45 PICSIT and 45 ALNRUB treated groups. This suggests that within older forest stands, thinning treatments may be particularly valuable in promoting understory development. Corresponding increases in control plots within the same stand type suggest that stand specific conditions and features may also play a role in in natural development rates of herbaceous species. The 15 PICSIT treated group exhibited an initial increase in understory cover between the first and second monitoring visits, followed by a decline during the third visit to levels comparable with initial conditions. This increase in cover followed by a sharp decrease indicates potential environmental conditions outside of thinning treatments that may be impacting observed patterns. For instance, factors such as changing weather patterns, animal activity or outside disturbance could have contributed to the abnormal pattern observed within this stand type. Interestingly, the 35 PICSIT treated groups saw a slight decrease in understory cover over the course of the monitoring period. Overall, the stronger response observed in 45 PICSIT and 45 ALNRUB treated stands suggests that thinning treatments may be more effective at promoting understory development in older, more established forest stands where existing vegetation communities and stand structure may be better positioned to respond to increased resource availability.

While changes in herbaceous cover over time provide insight into understory response following LEWI's restoration treatments, overstory structure is an important factor influencing understory development. Canopy density directly affects the availability of light, moisture, and other resources reaching the forest floor, which can influence the establishment and persistence of herbaceous species. Because LEWI's thinning treatments were designed to reduce stand density and increase structural complexity, the relationship between overstory density and understory cover was evaluated to determine whether variation in canopy conditions was associated with differences in understory vegetation response. A linear regression analysis was conducted to assess the relationship between overstory density and total herbaceous percent cover at the plot-visit level. Because forest overstory density measurements were first collected in 2017, only monitoring visits from 2017 and 2026 were included in this analysis.

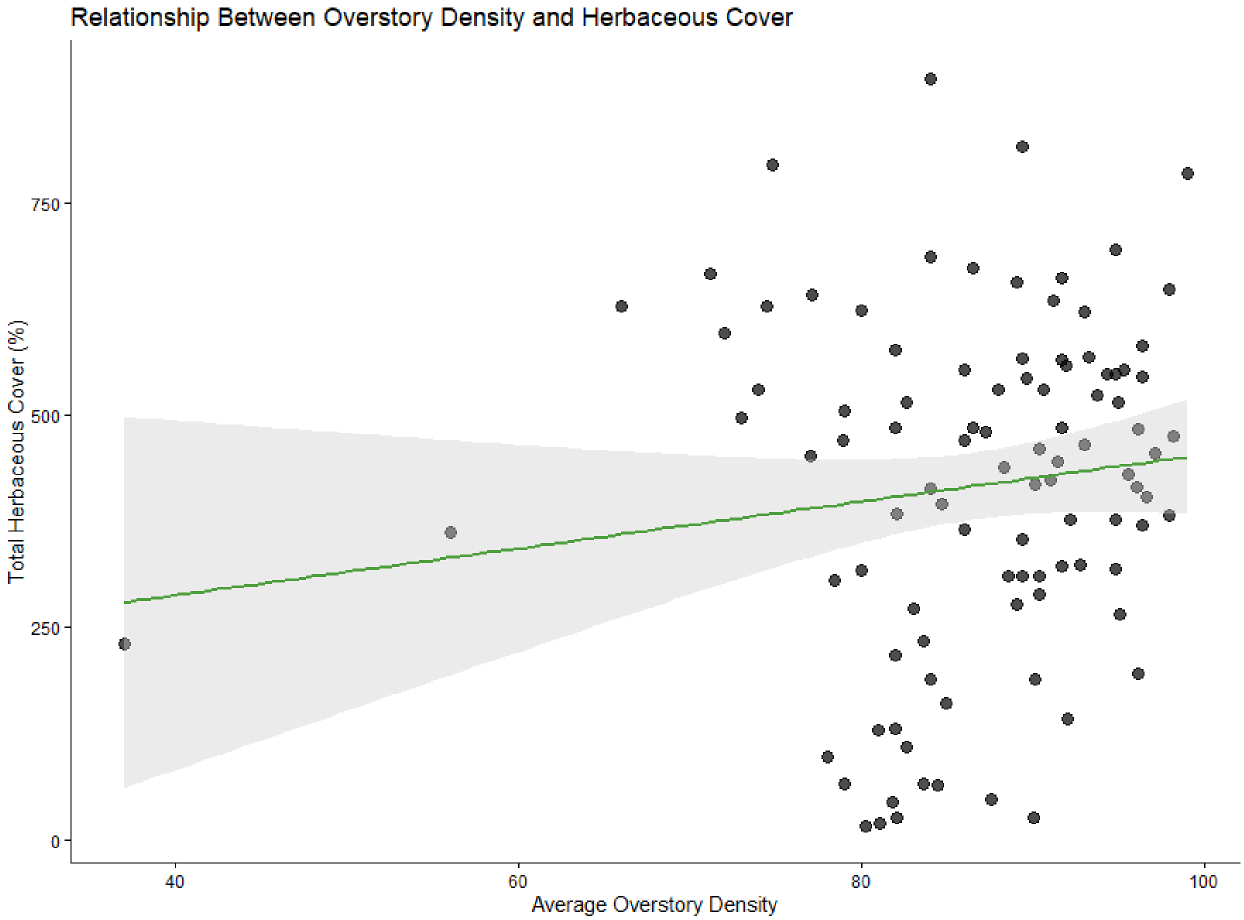

Figure 7. Relationship between overstory density and percent cover of herbaceous species across monitoring plots. The relationship between overstory density and understory cover was evaluated at the plot-visit level using data from summer 2017 onwards. Each point represents the overstory density and overall percent cover of center subplots within an individual plot during a monitoring visit. The solid line represents the fitted linear regression model, and the shaded area represents the 95% confidence interval of the predicted relationship.

Based on Figure 7., no significant relationship was observed between forest overstory density and herbaceous cover. Although the regression model indicated a slight positive trend between overstory density and percent herbaceous cover, the relationship was not statistically significant ($R^2 = 0.016$, $p = 0.209$). It is important to note that the majority of monitoring plots exhibited relatively high levels of overstory density, resulting in limited variation in canopy conditions across plots. Consequently, overstory density explained little of the observed variation in herbaceous cover, suggesting that canopy density alone was not a strong predictor of understory development during the monitoring period. Instead, other factors, including stand age, treatment history, site conditions, and species composition, likely contributed more substantially to patterns in understory vegetation. Although thinning treatments appeared to promote increases in understory cover in several older treated stands (Figure 6), these results suggest that the relationship between canopy density and understory response is more complex than canopy cover alone. More data and variance in canopy density may be required to better understand this relationship. Restoration treatments may influence understory development through multiple interacting mechanisms, including increased light availability, altered resource competition, and changes in microsite conditions.

Changes in Coarse Woody Debris and Recruitment

Coarse woody debris (CWD) was surveyed and measured at the plot level during each of the three revisits throughout the monitoring period. This allowed LEWI to gauge the effectiveness of thinning treatments, which emphasized the retention and creation of downed logs, to develop structural complexity and increase CWD within restored forest stands. Changes in CWD abundance and volume provide an important indicator of progress toward late-successional forest conditions, as downed wood contributes to wildlife habitat, nutrient cycling, moisture retention, and long-term ecosystem resilience. Results were visualized in a bar chart to explore differences in CWD abundance between treated and control stands within the same stand type/age class, as shown in Figure 8.

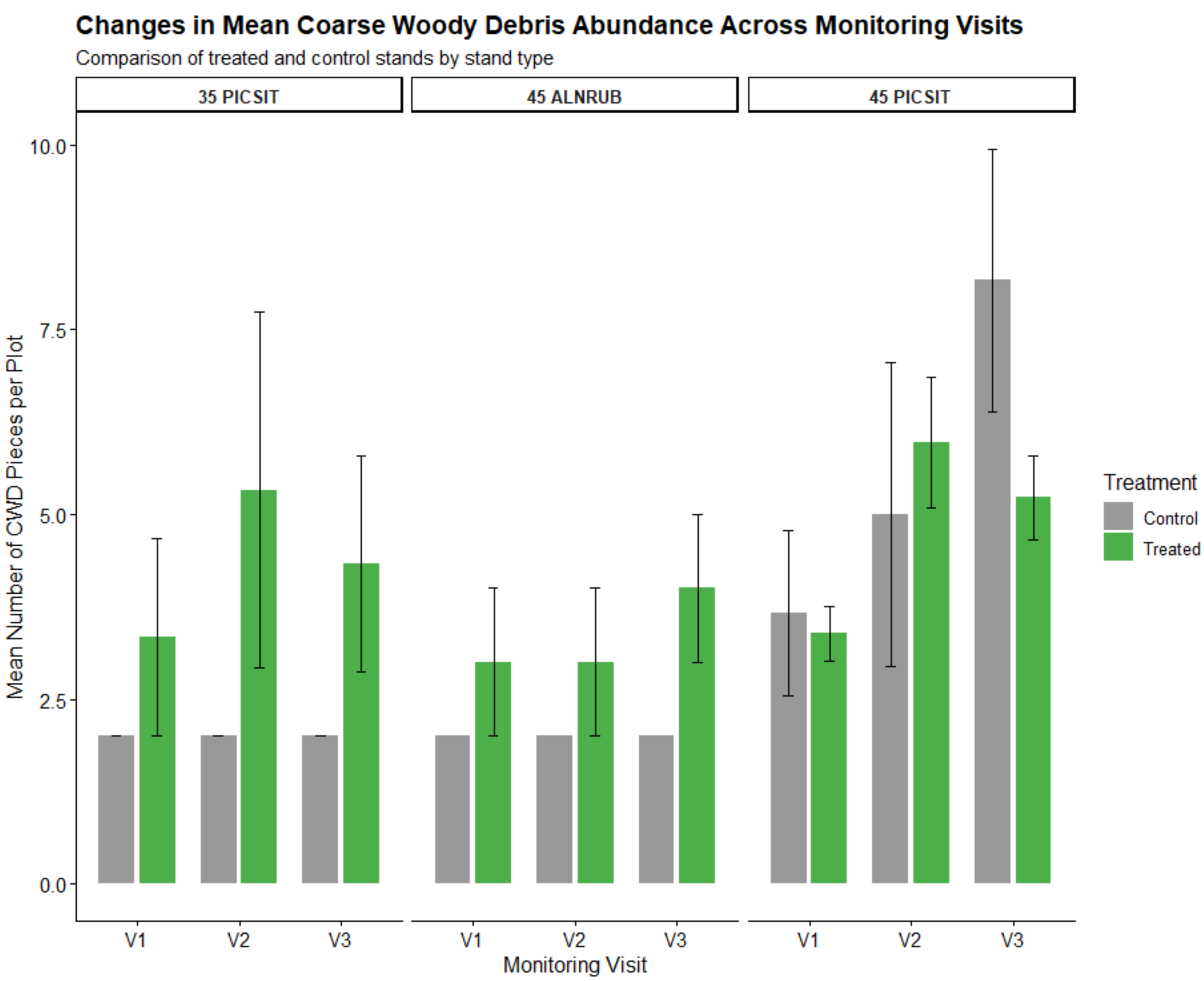

Figure 8. Changes in mean coarse woody debris abundance across monitoring visits by stand and treatment type. Mean CWD abundance was calculated as the number of CWD pieces recorded per plot during each monitoring visit and averaged within stand and treatment type. Bars represent mean CWD pieces per plot for each stand/treatment type during each monitoring visit. Error bars represent standard error of the mean and illustrate variability among plots within each stand and treatment type.

Based on Figure 8., coarse woody debris (CWD) increased following treatment in the 35 PICSIT and 45 ALNRUB treated stands, with both stand types showing greater increases than their corresponding control plots, which remained relatively constant throughout the monitoring period. The accumulation of CWD in these treated plots suggests that restoration activities, including variable density thinning and the retention of downed woody material, may have contributed to increases in forest floor structural complexity. In contrast, the 45 PICSIT control group showed the largest increase in coarse woody debris abundance, surpassing its treated counterparts. Although 45 PICSIT treated plots also increased over time, the greater increase observed in controls suggests that factors beyond treatment alone influenced CWD dynamics. Differences in initial stand structure, existing CWD at the time of treatment, natural tree mortality, and variance in decomposition rates may have impacted the observed patterns among treatment groups. Since CWD accumulation can occur both naturally and through management intervention, the more dramatic increase in the 45 PICSIT control plots compared to treated plots does not necessarily indicate management ineffectiveness but rather highlights the role that stand specific characteristics can have on the accumulation of CWD.

Importantly, all treated stands saw an increase in CWD throughout the monitoring period. This suggests that LEWI's treatments were effective in promoting the accumulation of downed woody material and increasing structural complexity within restored forests stands. The retention of existing logs and the creation of new woody debris as a result of thinning likely contributed to the observed increases in CWD abundance over time. This suggests that variable density thinning treatments may be a valuable tool for developing important habitat features associated with late-successional forest stands, contributing to overall habitat enhancement and diversity. Additionally, this increase in CWD can be critical for supporting ecosystem functions such as moisture retention, nutrient cycling and vegetation regeneration, all of which are key components of late successional forests. Ultimately, Figure 8., suggests that treatments were effective in initiating CWD accumulation in the Fort Clatsop Unit, aligning with LEWI's goals of restoring key late-successional feature.

Beyond an assessment of abundance, the role of coarse woody debris in promoting woody tree recruitment was also evaluated. Also known as nurse logs, CWD are a critical feature of late successional ecosystems that function by providing stable, moist, nutrient rich surfaces that facilitate seed germination and tree establishment. Tree recruitment is an essential component of forest restoration because the establishment of new trees promotes future stand development, increases vertical and horizontal structural complexity, and contributes to the development of late-successional forest characteristics over time. In previously simplified forest systems, such as dense plantation stands, increasing recruitment is particularly important for restoring multi-aged forest conditions and maintaining long-term ecosystem resilience. Therefore, the relationship between CWD abundance and woody tree recruitment was evaluated to determine whether plots with greater quantities of downed woody material also supported higher levels of regeneration. Results were visualized using a linear regression model to assess the relationship between CWD abundance and woody tree recruitment across all monitoring plots and revisit periods.

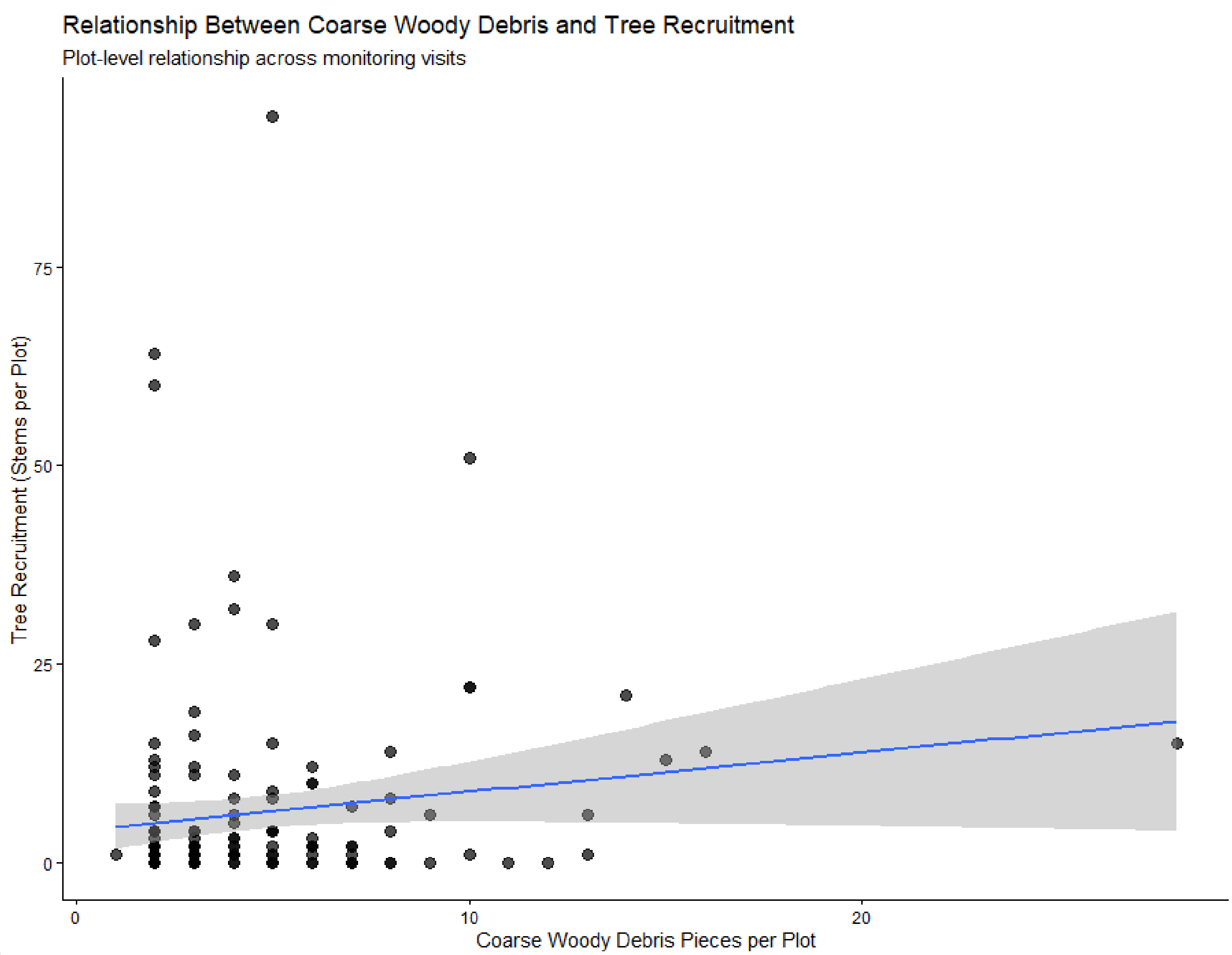

Figure 9. Relationship between coarse woody debris abundance and woody tree recruitment across monitoring plots. The relationship between CWD abundance and woody tree recruitment was evaluated at the plot-visit level using data from all three monitoring periods. Each point represents the number of CWD pieces and recruited woody stems recorded within an individual plot during a monitoring visit. The solid line represents the fitted linear regression model, and the shaded area represents the 95% confidence interval of the predicted relationship. Recruitment values were log-transformed prior to regression analysis to account for skewed distribution.

According to Figure 9., a weak positive relationship was observed between CWD abundance and woody tree recruitment. Because woody recruitment tree values were highly skewed due to many plots with low recruitment and a small number of plots with high recruitment, recruitment values were log-transformed prior to regression analysis to improve model fit and meet linear regression assumptions. Results indicated a significant positive relationship between CWD abundance and recruitment ($\beta = 0.078$, $p = 0.003$), with CWD abundance explaining approximately 5.7% of variation in woody tree recruitment ($R^2 = 0.057$). This suggests that plots containing greater quantities of CWD tended to support slightly higher levels of tree recruitment, although additional factors likely also played an important role in contributing to overall recruitment patterns.

In order to better understand woody tree recruitment trends in the Fort Clatsop Unit, recruitment share by species was evaluated across all forest plots by stand and treatment type at the time of each plot's final revisit. This allowed for analysis of changes in recruitment as the monitoring period progressed. By understanding which species are being recruited, LEWI can evaluate whether restoration treatments are effective in promoting the establishment of a more diverse and structurally complex forest consistent with late-successional forest characteristics. Increased recruitment of shade tolerant conifer species, such as western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*), would indicate progression toward more complex forest conditions by promoting multiple canopy layers and increasing species diversity over time. Conversely, continued dominance by one species or limited conifer recruitment may suggest that additional management actions are needed to support long term restoration goals. Results regarding share of recruitment by species across stand and treatment types were visualized in Figure 10.

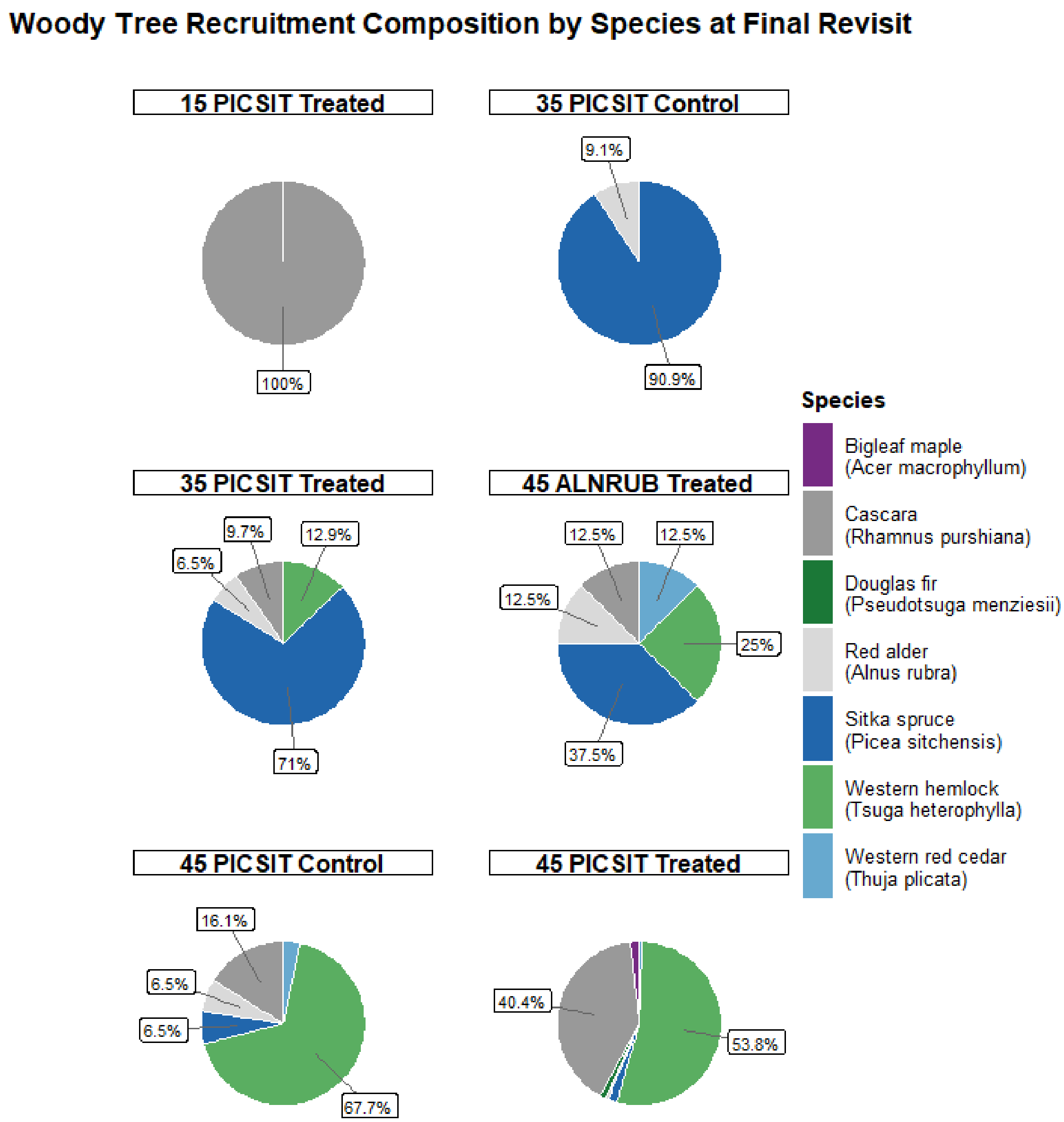

Figure 10. Share of woody tree recruitment by species at Visit 3. Recruitment stem counts were collected at the plot level and combined among plots within the same stand and treatment type. The proportion of each species represents its contribution to total woody tree recruitment within each stand and treatment group at the time of the final revisit. Species with unknown identification codes were excluded from analysis. The 45 ALNRUB control stand had no recruitment at Visit 3 and was excluded from the figure.

Based on Figure 10, recruitment appears to vary among stand types, with treatment generally being associated with increases in recruited species diversity. In the 35 PICSIT stand type, both control and treated plots recruit primarily Sitka Spruce (logical in a spruce stand), however the treated stands display lower levels of Sitka Spruce recruitment in favor of other woody tree species such as Red Alder, Western Hemlock, and Cascara. In the 45 PICSIT stand type, both treated and control groups recruit mainly Western Hemlock, suggesting that this species continues to establish successfully across both management conditions. Interestingly, the treated plots also experience a large share of recruitment from Cascara, whereas remaining distribution in control plots is more evenly divided among multiple species. The 45 ALNRUB treated stand displays the most diversity, with fairly equal recruitment representation among multiple species. The 15 PICSIT treated group showed the least diversity, with Cascara representing 100 of recruitment within the stand type.

Discussion and Implications

The monitoring metrics evaluated in this study provided a comprehensive assessment of LEWI's restoration objectives by capturing changes in forest structure, ecosystem function, and biological complexity. Together, measurements of stem density, tree diameter growth, understory vegetation, coarse woody debris, and woody tree recruitment addressed multiple components of late-successional forest development identified within the park's restoration objectives. While no single metric fully captures the complexity of LEWI's forest ecosystem recovery, the combination of structural and ecological indicators provided valuable insight into whether restoration thinning treatments are effective in moving second growth industrial stands toward conditions more representative of Pacific Northwest old growth forests.

Reflecting on LEWI's restoration objectives as outlined in the park's 2011 Environmental Assessment, variable density thinning treatments throughout the Fort Clatsop Unit appear to have advanced Objective 1.1, which aims to enhance forest structural complexity and accelerate stand development. With the exception of a single 45 PICSIT outlier plot, Figure 2 shows that treated stands consistently exhibited reduced stem density followed by density stabilization after restoration, indicating that thinning treatments successfully moved treated plots away from the dense, homogeneous stand conditions characteristic of industrial plantations. By reducing competition among trees and creating a more heterogeneous stand structure, these treatments represent an important first step toward the development of the structurally diverse conditions characteristic of late-successional forests. In addition to reductions in stem density, increases in tree diameter distributions within treated stands further suggest that thinning has begun to promote more structurally complex forests, directly aligning with EA Objective 1.3. Larger diameter trees are a defining characteristic of late-successional ecosystems, and the greater representation of larger DBH classes observed in treated stands as the monitoring period progresses indicates that reduced competition may be allowing residual trees to allocate newly accessible resources toward growth.

Results also show advancement on Objectives 1.5, 1.7, and 1.8, all of which relate to increasing structural complexity within treated stands through the creation and retention of deadwood and coarse woody debris habitat. Based on Figure 7, all treated stands exhibited an increase in the amount of CWD present per plot (on average). This suggests that thinning treatments and the associated creation and retention of downed wood have contributed to introducing increased structural complexity into restored stands throughout the monitoring period. With higher levels of CWD, treated stands are better equipped to carry out critical ecosystem functions associated with late-successional stands such as; providing wildlife habitat, nutrient cycling, water retention, and vegetation regeneration support. The accumulation of CWD was also linked to increased structural heterogeneity based on correlation with woody tree recruitment. Figure 9 showed a weak positive relationship between woody tree recruitment and amount of CWD present in the plot. Plots with a higher amount of CWD tended to have higher levels of woody tree recruitment. Multiple canopy layers is a key facet of old growth and late successional ecosystems and is often achieved through consistent and gradual accumulation of new trees. Given this important link, results suggest that LEWI's deadwood retention strategies may be valuable not only for the ecosystem services provided by CWD, but also as a tool for the development of multiple canopy layers and eventual overstory heterogeneity.

Additionally, data regarding understory development indicates advancement on objectives 1.2 and 1.6 which center around restoring herbaceous groundcover in treated stands. While specific species response varied by stand type (Table 3.), changes in Simpson's Diversity Index suggest that treatment was successful in increasing diversity of herbaceous cover in the understory. Based on Table 4., the observed increase in SDI was higher in treated groups when compared to their corresponding control groups, suggesting that thinning treatments may have promoted the establishment of a diverse range of groundcover species at a faster rate than untreated stands. This increase in groundcover diversity is particularly important in the development process from industrial to late-successional stands. A well developed and diverse understory is a key component of a late-successional forests in the Pacific Northwest. Functioning by providing habitat within a wide range of ecological niches, providing a variety of foraging sources for wildlife, and supporting nutrient cycling and biomass accumulation in the soil, the understory in critical for ecological balance and long-term ecosystem resilience. Results suggest that LEWI's restoration efforts have advanced the development of a diverse understory, consistent with restoration objectives.

Collectively, results from monitoring efforts indicate that LEWI's restoration treatments have initiated measurable changes in forest structure and ecological function consistent with the park's long term restoration goals. Although restoration efforts cannot immediately transform a second growth industrial stand into a developed stand with old growth characteristics, early responses observed in stem density, tree growth, coarse woody debris accumulation, understory diversity, and woody tree recruitment suggest that variable density thinning is effectively accelerating key processes associated with late-successional forest development in the Fort Clatsop Unit. By reducing stem density, increasing growing space and resource access for retained trees, promoting structural heterogeneity, and encouraging the establishment of a more diverse understory and tree recruitment distribution, restoration treatments appear to be shifting second growth stands away from simplified plantation conditions and toward more complex forest trajectories.

Despite the observed advancement of the treated forest stands in the Fort Clatsop Unit, old growth characteristics such as including large diameter trees, multilayered canopies, abundant standing and downed deadwood, and diverse understory communities develop over thousands of years and require many years in stand development in order to be fully expressed. Therefore, the observed changes in LEWI's forest should be viewed as early indicators of recovery from an ecosystem that was dramatically changed by the timber industry, rather than a complete transition to old growth conditions. Continued monitoring will be essential moving forward for determining whether these early structural and ecological changes persist and continue to move restored stands toward more complex, resilient forest ecosystems.

Moving forward, monitoring efforts at LEWI should continue to better assess change over time and differences in control vs treated stands. At the current state, each forest plot has data spanning roughly 15 years of development following thinning (or lack thereof for controls). Since old growth forests develop over the course of thousands of years, 15 years is an extremely small sampling period and as a result developing trends and forest trajectories may not be accurately captured in the existing dataset. With a larger dataset spanning a broader period, overarching trends may become more apparent, providing greater insight into whether restoration treatments are consistently moving stands toward desired late-successional conditions. Continued monitoring will also improve the ability to distinguish short term responses to thinning from longer term ecological changes associated with forest maturation. Some restoration objectives, such as reductions in stem density and increases in diameter growth, may occur relatively quickly following treatment, while other characteristics, including complex canopy development, accumulation of large woody material, and shifts in species composition, are expected to develop more gradually over much longer time periods. Maintaining consistent monitoring protocols will allow LEWI to track these varying rates of ecosystem change and evaluate whether initial restoration responses persist as stands continue to mature.

The current monitoring metrics provide an effective framework for evaluating the outcomes of LEWI's thinning treatments and tracking progress toward the park's long-term restoration objectives. Measurements of trees per plot, tree size, coarse woody debris, understory vegetation, and woody tree recruitment collectively capture many of the key structural and ecological changes expected during the transition from industrial plantations to late-successional forest conditions. As a result, the existing monitoring protocol should be maintained to ensure consistency and allow for meaningful comparisons across future monitoring periods. By maintaining a consistent monitoring protocol, future research can build upon a robust long-term dataset that captures forest development from its earliest stages, rather than introducing changes in sampling methods that may limit comparisons over time. However, as restored stands continue to mature, additional monitoring variables could further improve understanding of restoration outcomes. Metrics related to canopy structure and vertical complexity, snag abundance and decay, wildlife use, and regeneration success beyond seedling recruitment could provide a more complete assessment of ecosystem recovery. Expanding monitoring to include these indicators, while maintaining the current protocol, would allow LEWI to continue building a long-term dataset capable of evaluating both early restoration responses and the gradual development of late-successional forest characteristics.

Conclusions

The results of this long-term monitoring effort demonstrate that LEWI's variable density thinning treatments have initiated measurable changes consistent with the park's goal of accelerating late-successional forest development within the Fort Clatsop Unit. Across multiple indicators of forest structure and ecosystem function, treated stands showed evidence of movement away from simplified industrial plantation conditions and toward more complex forest characteristics. Reductions in stem density, increases in tree diameter growth, greater accumulation of coarse woody debris, and improvements in understory diversity collectively suggest that restoration treatments are successfully promoting conditions associated with older, more resilient Pacific Northwest forests.

Although these early responses represent important progress, the development of old growth characteristics requires hundreds to thousands of years and cannot be fully achieved within the relatively short timeframe represented by the current monitoring dataset. Instead, the observed changes should be viewed as early indicators that restoration treatments are altering stand trajectories and creating conditions that may support continued ecological development over time. Continued monitoring will be critical for determining whether these initial responses persist and whether treated stands continue progressing toward the structural complexity and ecological functions characteristic of late-successional forests. Maintaining LEWI's existing monitoring protocol will be essential for building upon the robust long-term dataset established over the past 15 years. Consistent measurements across future monitoring periods will allow the park to distinguish short term treatment responses from longer term forest development processes and provide valuable insight into the effectiveness of restoration strategies. As stands mature, incorporating additional indicators of ecosystem complexity, such as canopy structure, snag dynamics, wildlife use, and regeneration success, may further strengthen evaluations of restoration outcomes. Through continued monitoring and adaptive management, LEWI can continue to assess progress toward restoring more diverse, resilient, and functionally complex forest ecosystems.

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Appendix A: Supplementary Figures

Monitoring Plot	Date Installed	Year thinned	Re-visit Year 1	Re-visit Year 2
FP 000	31-Jul-12	2013	2017	2022
FP 001	31-Jul-12	2013	2017	2022
FP 002	1-Aug-12	2013	2017	2022
FP 003	30-Jul-12	2013	2017	2022
FP 007	18-Jul-12	2013	2017	2022
FP 015	1-Aug-12	2013	2017	2022
FP 033	18-Jul-12	2013	2017	2022
FP 041	19-Jul-12	2018	2017	2022
FP 050	24-Sep-12	2013	2017	2022
FP 051	26-Sep-12	2013	2017	2022
FP 067	24-Jul-12	2013	2017	2022
FP 069	24-Jul-12	2013	2017	2022
FP 078	25-Jul-12	2013	2017	2022
FP 097	27-Jul-12	2013	2017	2022
FP 134	28-Jun-12	2018	2017	2022
FP 135	27-Jun-12	2018	2017	2022
FP 146	9-Jul-12	2018	2017	2022
FP 147	9-Jul-12	2018	2017	2022
FP 159	22-Oct-12	control	2017	2022
FP 160	11-Jul-12	2013	2017	2022
FP 161	23-Oct-12	2013	2017	2022
FP 162	10-Jul-12	2013	2017	2022
FP 164	10-Jul-12	2013	2017	2022
FP 173	6-Nov-12	2013	2017	2022
FP 175	5-Nov-12	2013	2017	2022
FP 176	5-Nov-12	2013	2017	2022
FP 177	2-Aug-12	2013	2017	2022
FP 028	18-Nov-13	2014	2018	2023
FP 057	16-Jan-14	2014	2018	2023
FP 158	17-Jul-12	2014	2018	2023
FP 171	13-Jul-12	2014	2018	2023
FP 172	16-Jul-12	2014	2018	2023
FP145	12-Nov-13	2014	2018	2023
FP157	13-Nov-13	2014	2018	2023
FP 133	17-Jul-12	2016	2020	2025
FP 004	24-Jan-17	2017	2021	2026
FP 034	29-Nov-16	2017	2021	2026
FP 130	7-Nov-16	2017	2021	2026
FP 139	3-Oct-16	2017	2021	2026
FP 142	7-Nov-16	2017	2021	2026
FP 144	12-Dec-16	control	2021	2026
FP 149	2-Dec-16	control	2021	2026
FP 152	5-Oct-16	2017	2021	2026
FP 153	4-Oct-16	2017	2021	2026
FP 166	4-Oct-16	control	2021	2026
FP 202	3-Jan-17	control	2021	2026
FP 225	8-Nov-16	2017	2021	2026
FP143	14-Jan-14	2017	2021	2026
FP 012	6-Apr-17	2018	2022	2027
FP 064	26-Jan-17	2018	2022	2027
FP 066	25-Jan-17	2018	2022	2027
FP 088	5-Jan-17	2018	2022	2027
FP 148	30-Jan-17	2018	2022	2027
FP 156	6-Apr-17	2018	2022	2027
FP 292	11-Apr-17	control	2022	2027
FP 293	11-Apr-17	2018	2022	2027

Figure A1. Establishment and revisit schedule for the 57 established forest plots within the Fort Clatsop Unit at the Lewis and Clark National Historic Park (LEWI).

Access Database Query	**Result**	**Action Taken**
Visits per plot	Plots 028, 057, 143 & 157 were included in the dataset, yet had < 3 visits	Plots were excluded from the dataset for consistency in analysis.
Missing plot information (Location ID, Coordinates, Stand Type, Age, Establishment Year, Control/Non-Control)	No missing values	None
Duplicate plot visits	None	None
Impossible Dates	None	None
Missing interior tree DBH	No missing values	None
Missing corner tree DBH	Plot 177 missing SW corner tree DBH (2022)	Cross checked with original data sheet, DBH was not recorded, left as is.
Impossible DBH values	None	None
Missing/impossible coarse woody debris values	Large/small diameter not recorded pre summer 2017, no other missing diameters, No missing lengths, No impossible lengths, No impossible DBH	None
Missing/impossible standing deadwood values	No missing DBH, a few extremely large DBH values	Cross referenced large DBH values with original datasheet to confirm accuracy, all values correct.
Missing/impossible herbaceous cover data	None	None
Missing overstory density values	None	None
Check marker notes	Nothing of concern	None

Table A1. Quality control, quality assurance (QA/QC) checks performed, result of checks and resulting actions taken.

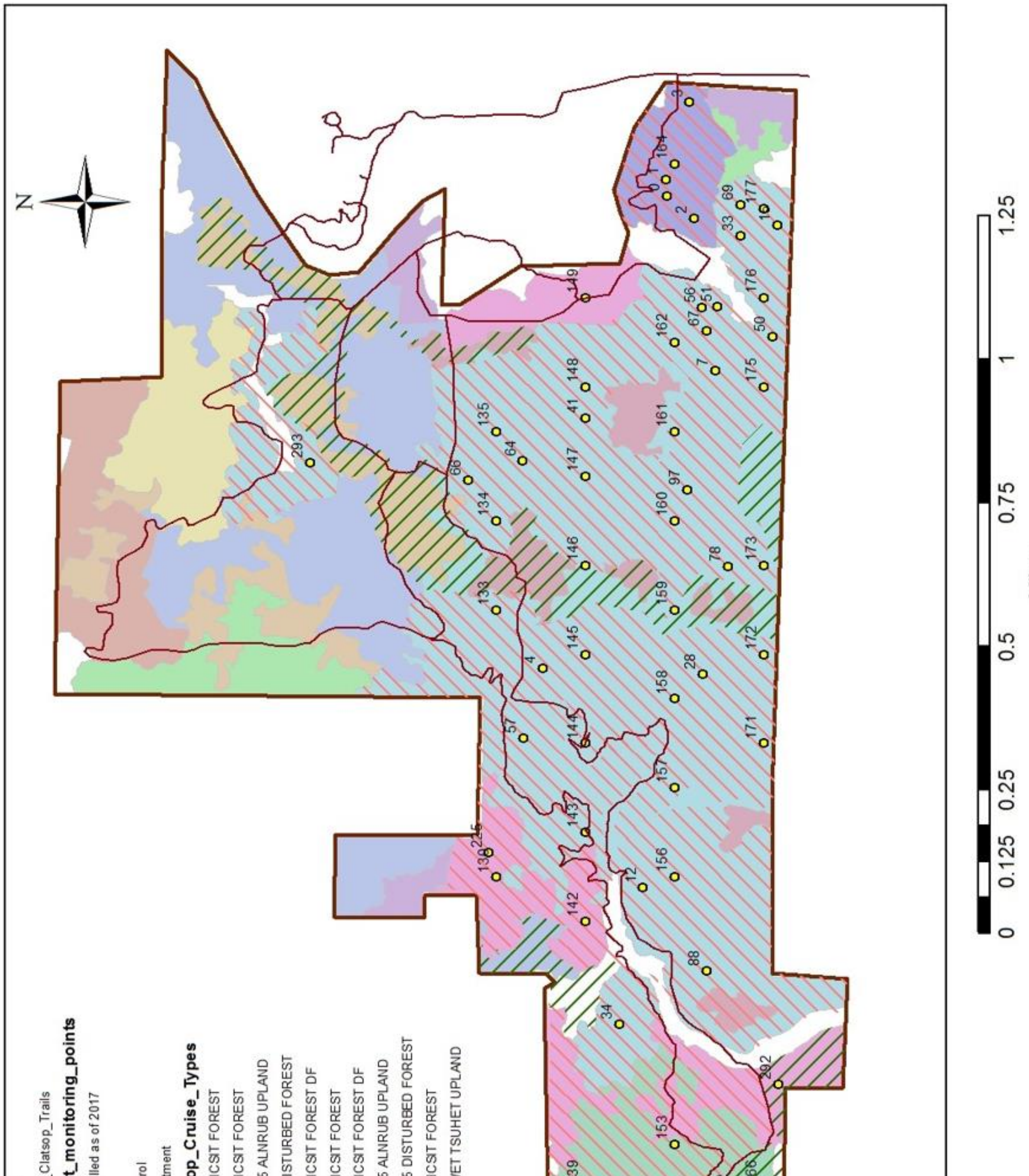

Figure A2. Forest monitoring plot locations and corresponding forest type within the Fort Clatsop Unit.

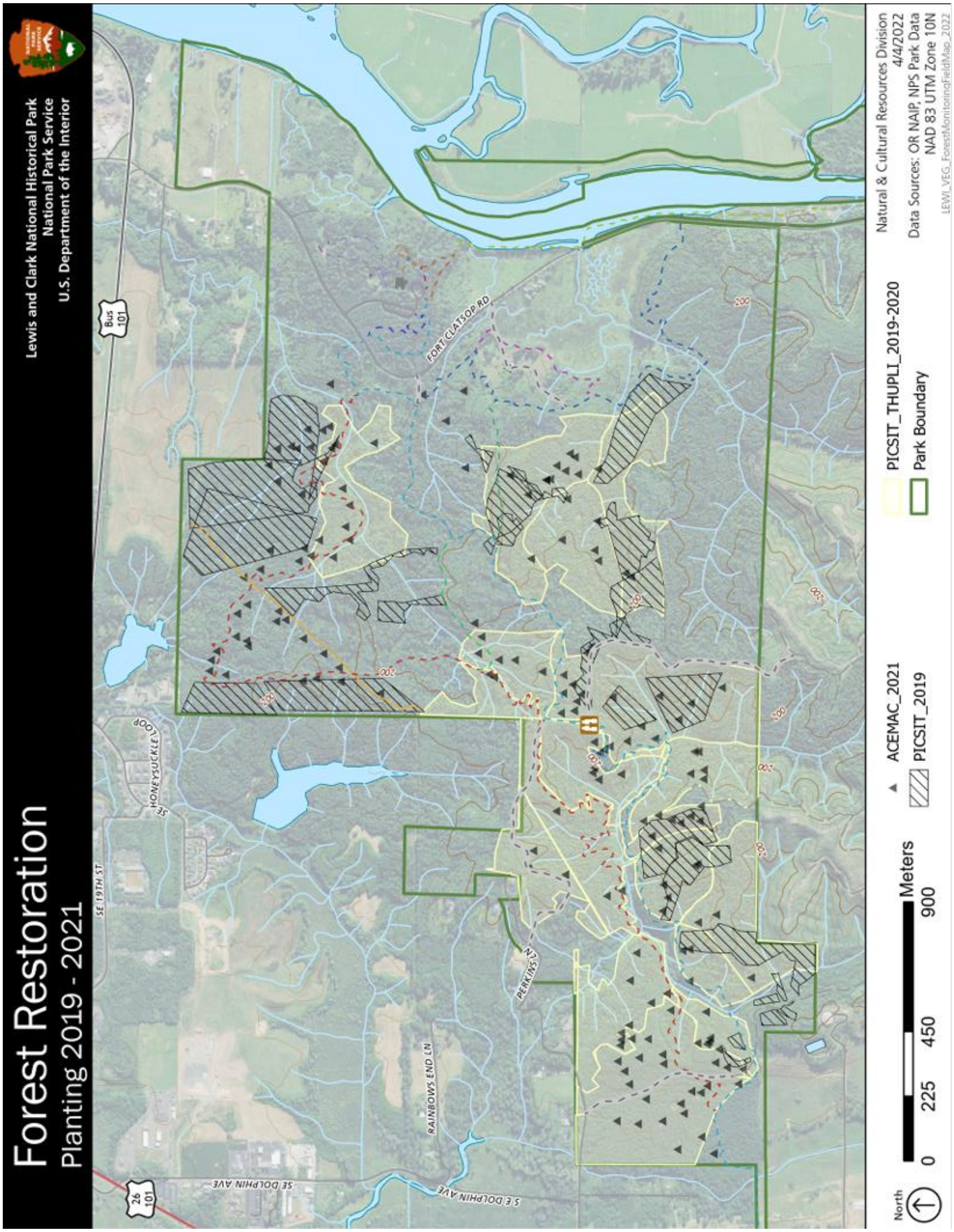

Figure A3. Forest Restoration native species planting locations within the Fort Clatsop Unit (2019-2021). (THUPLI = Western Red Cedar, PICSIT= Sitka Spruce, ACEMAC= Bigleaf Maple).

Stand Level Prescription and Implementation Guidelines
Cut between 25 and 40% of the basal area in thinning, and between 10 and 25% of the basal area in small irregularly spaced patch cuts, for a total removal of no more than 50% of the basal area. Consider windthrow risk and regeneration potential in determining the thinning level and consider setting residual basal area targets that would result in a favorable Relative Density value for the stand (Hayes et al 1997). The first thinning can be followed again in approx. 10 years by another thinning if needed.
Favor spruce, alder, and hemlock (in that order) for retention, and cut heavily the Douglas-fir, especially where it is affected by Swiss needle cast.
Generally thin from below by cutting smaller diameter trees in the main canopy. Do not cut trees in the understory as they provide an additional level of vertical diversity in plantations.
Underplant spruce, cedar, maple or shrubs as desired to promote species diversity. Protect favored ungulate browse species such as cedar with fencing or, alternatively, experiment with cedar wildings such as those used on the Ecola Creek Forest Reserve in Cannon Beach. Tree plantings should not amount to more than 100 per acre and should be planted in clumps to avoid replicating the look and feel of a plantation. Planting hemlock is not necessary.
Lop and scatter the branch wood from felled trees to minimize short-term fuel loading and fire risk.
In general, do not initiate thinning within 200 feet of a major opening, such as a property boundary, road, or previous heavy canopy opening from windthrow.
In stands with relatively few snags, conduct some snag creation. A combination of girdling and topping can be used; girdled snags do not last as long but are much cheaper to create.

Table A2. Stand level prescription and implementation guidelines for LEWI's thinning treatments. These guidelines were observed when thinning treated forest stands.