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Effects of Variable Density Thinning on Spatial Patterns of Overstory Trees in Mt. Hood National Forest

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Abstract

Variable density thinning (VDT) is a method of restoration thinning that attempts to increase ecosystem resilience and spatial heterogeneity in forest stands to more closely resemble mosaic-like patterns characteristic of late-successional forests, which consist of clusters of multiple trees, individual trees, and gaps. This study examines the spatial patterning of overstory trees resulting from VDT of conifer forests in Mt. Hood National Forest in the western Cascade Mountains and compares these patterns with reference conditions. Stem maps were created from field surveys of study plots within one mature stand and six thinned stands designated as Late-Successional Reserve (LSR) with varying minimum inter-tree spacing distances and implementation methods (designation by description and designation by prescription). A cluster analysis and global point pattern analysis were conducted for each of the seven stands. Spacing-based prescriptions below 15 feet resulted in approximately twice as many trees belonging to large clusters compared to reference conditions. Additionally, the results suggest that the designation by prescription method produces forest spatial patterns that are more similar to reference conditions than the designation by description method. This suggests that more flexible prescriptions that incorporate site-specific information should be utilized for restoration thinning in LSR stands.

1. INTRODUCTION

1.1 Background

1.1.1 Even-Aged Harvesting Methods

Traditional silviculture employs even-aged systems that create homogeneous plantation-style forest stands that are repeatedly clearcut. Rotation length varies between 40 to 100 years, which is not a sufficient length of time to allow structural complexity to develop in stands, especially in the case of clearcutting when very few biological legacies are left post-harvest (McRae et al. 2001). Managing stands solely for the purpose of commodity extraction drastically reduces forest complexity, which has many negative ecological implications. Harvested stands that arise post-clearcut are comprised of dense, uniform monocultures that lack the compositional diversity and spatial heterogeneity present in natural late-successional stands (Carey 2003; Carey and Harrington 2001). This simple structure of post-harvest stands can lower the probability of occurrence of species that are naturally common and increase some species' risk of local extirpation (Carey and Harrington 2001). Further impacts of intensive timber management include compromised food web functioning and alterations to the structure of biotic communities (Carey 2003; Aubry 2000; Carey et al. 1999).

Emulation silviculture attempts to mimic natural disturbances; however, there are many differences in post-disturbance stand structure between intensive timber harvest such as clearcutting and wildfires including the following: reduced conifer dominance, sharper edges around disturbed areas, more even distribution of age classes, and lower retention of live trees, snags, and coarse woody debris in post-harvest stands compared to post-fire stands (Bergeron et al. 1999; McRae et al. 2001; Carleton and Maclellan 1993; Fleming and Freedman 1997). These factors impact the post-harvest successional pathways, which indicates that harvesting activities have substantial impacts on the future biological communities of forest stands.

Clearcutting, though a controversial harvesting method, is a widely applied method of timber extraction because of the higher economic gain as a result of the larger volume of timber that can be extracted, ease of artificial regeneration, and lower cutting expenses compared to retention harvesting methods (Keenan and Kimmins 1993). However, diversification of forest valuation beyond economic gain from timber products, which occurred in the late 1980s and early 1990s, has led to a greater emphasis on ecosystem complexity and biodiversity in forest management (Swanson and Franklin 1992; Gustafsson et al. 2012). Specifically, in the Pacific Northwest, approximately 30% of Federal forest land not including Wilderness Areas had been converted to plantations by 1990 (Swanson and Franklin 1992). Forest managers have since been challenged with meeting a broad range of objectives for these even-aged, regenerated stands.

1.1.2 The Importance of Structural Complexity

In response to social pressures for more sustainable natural resources management, concern for threatened species such as the northern spotted owl (*Strix occidentalis caurina*), and growing understanding of ecological systems, the USDA Forest Service developed its "New Perspectives" and the concept of "New Forestry" emerged, which offered a way to balance environmental and economic objectives of the land (Kessler et al. 1990; Franklin 1989). Integral to these ideas were the concepts of the structural complexity of natural forest stands throughout succession as well as biological legacies and the importance of coarse woody debris for maintaining biodiversity (Swanson and Franklin 1992). These ideas were then integrated into forest management with the goal of increasing the complexity of managed stands to more closely resemble natural forest habitat particularly through the retention of live trees and dead woody material such as snags and downed logs (Swanson and Franklin 1992; Franklin 1989). Such concepts of ecological understanding and prioritization were also important in the development and implementation of the Northwest Forest Plan in 1994, which provides legal protection of old-growth forest habitat essential for the northern spotted owl and requires a minimum of 15% retention of cutting units on federal land designated for harvest (USDA and USDI 1994).

In order to use late-successional forest structure to guide management decisions, however, it is necessary to understand the structural development of these forest systems. The classification scheme developed by Franklin et al. (2002) use the following stages to describe the structural development of Douglas-fir forests over time: disturbance and legacy creation, cohort establishment, canopy closure, biomass accumulation/competitive exclusion, maturation, vertical diversification, horizontal diversification, and pioneer cohort loss. Gap development is a primary process of the horizontal diversification stage of Douglas-fir forests, which begins when the stand is about 300 years old (Franklin et al. 2002). Gaps are created naturally by small-scale disturbances that cause tree mortality or damage such as wind, disease, and insects and result in spatial variability in resources such as moisture, nutrients, and light and other environmental conditions (Franklin et al. 2002; Van Pelt and Franklin 1999). In this system after a coarse-scale disturbance (from 0.1 to more than 100,000 ha), Douglas-fir, which is a relatively shade-intolerant pioneer species, initially dominates post-disturbance creating a closed, dense canopy (Spies and Franklin 1989). However, after fine-scale gaps (less than 0.1 ha) develop in the canopy due to density-independent mortality during the maturation stage, shade tolerant species such as western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) that are present in the understory can grow and establish dominance in the canopy (Spies and Franklin 1989; Franklin et al. 2002). Spies et al. (1990) found that the gap formation rates of Douglas-fir-dominated forests in the western Cascade Range were 0.2 and 0.3% for old-growth and mature stands, respectively, during a period of 25 years. This process gives rise to the mosaic pattern of uneven-aged single trees and clusters of multiple trees as well as canopy openings that defines late-successional Douglas-fir forest structure (Larson and Churchill 2012).

1.1.2.1 Restoring structural complexity in harvested stands

Despite many areas of continued clearcutting and even-aged management of harvested forests, especially on privately owned land, the importance of structural complexity has been widely integrated into sustainable forest management practices in the Pacific Northwest. Transforming even-aged stands to more variable uneven-aged stands that include an appropriate number, type, and pattern of retained structures is a complex and difficult process (O'Hara 2001; Franklin et al. 2002). Silviculture prescription plays a large role in the resulting forest community after partial cutting and thinning treatments. For example, within uneven-aged stands, the pattern and intensity of partial cutting affects the subsequent succession and competitive abilities of the vegetation such that light partial cutting favors tolerant species, particularly those that are already present in the understory, and partial cuts that are moderately heavy and group selection harvest favor midtolerant species (Barnes et al. 1998 p. 434-5). Such considerations are especially important given that silviculturists often attempt to encourage the development of a new cohort in the understory of these stands (O'Hara 2001). Increasing the degree to which harvesting methods can maintain or develop attributes of old-growth forests improves the spatial complexity of the stands, which is key to conserving biodiversity and ecosystem functions and services (Bauhus et al. 2009; Carey et al. 2001).

1.1.3 Variable Density Thinning

Based on their comparison of the plant diversity in natural and managed Douglas-fir forests in the Pacific Northwest, Halpern and Spies (1995) suggest that moving away from intense plantation forestry and instead utilizing silvicultural practices that maximize both temporal and spatial diversity of resources and horizontal and vertical heterogeneity that more closely resemble natural forests is key to maintaining plant diversity. Variable density thinning is one method of inducing such spatial heterogeneity in harvested stands. Implementation of variable density thinning (VDT) treatments began around 1995 in Canada and the western United States with the goal of balancing biodiversity and wildlife habitat requirements with economic priorities, though the long-term stand response is still being studied (Harrington et al. 2005). VDT implementation in forested stands involves creating "gaps," which are openings in the stand, and "skips," areas that are left unthinned.

Restoration VDT treatments release not only individual trees but also clusters consisting of multiple trees, which increases the small-scale spatial heterogeneity and the degree to which the within-stand spatial patterns of trees in treated stands are similar to late-successional conifer forests (Larson and Churchill 2008). As a result, variable density thinning treatments have impacts at a variety of scales, including on individual tree responses. For example, Roberts and Harrington (2008) found that the basal area growth for canopy trees within a thinned matrix was significantly greater than that of canopy trees in unthinned areas in just five years after the variable density thinning treatment. Additionally, the presence of internal edge effects as a result of the VDT treatments produces variability in individual tree response such that trees near gaps experienced about 15 percent less local competition than trees located farther from gaps (Roberts and Harrington 2008).

VDT can artificially alter canopy dynamics through the selective removal of trees for timber harvest to rapidly accelerate the gap formation process, resulting in a variable tree spatial structure consisting of clumps of trees as well as gaps, which are essential components of late-successional forests. This structural complexity has important implications for biodiversity. For example, Thysell and Carey (2001) observed a 173% increase in understory species richness three years after VDT treatments in homogenous, second-growth Douglas-fir stands in western Washington, which was likely due to the presence of both high-and low-light patches in thinned stands.

The spatial variability created by VDT can improve habitat quality and provide essential habitat features by increasing the understory and structural variability needed for a high diversity of wildlife (Wilson and Puettman 2007). For example, Carey and Wilson (2001) found that increased biocomplexity of forest communities as a result of variable density thinning allowed for a greater amount of niche diversification and subsequently a greater abundance and diversity of small mammals. Additionally, increased structural diversity in forested stands can enhance foraging opportunities including for some bird species, especially as a result of increased aerial insect presence in gaps, as well as increase suitable habitat for a greater variety of species such as those that require open habitat that is not present in dense, unthinned canopies (Hagar et al. 2004).

1.1.3.1. Implementation methods

There are two primary methods of VDT implementation used by the U.S. Forest Service: designation by description (DxD) and designation by prescription (DxP). However, individual tree marking (ITM) is a third method used in which each tree is marked to be either left or cut. In DxD treatments, trees are designated for removal based on pre-defined, verifiable characteristics such as tree diameter, species, and spacing, whereas in DxP treatments a desired end result for forest cover including basal area or spacing targets is used to guide contractors (USFS 2018; Franklin et al. 2013). DxP is the most subjective of the tree designation methods because implementation is based on the individual contractor's decisions on how to best meet the desired conditions. Due to this subjectivity and individual variation, the DxP method produces the least certainty in results and a greater potential for mistakes and disputes than other methods (USFS 2018). However, DxP approaches can create stand complexity from relatively simple prescriptions due to the creativity and flexibility that contractors are able to incorporate during implementation (Franklin et al. 2013; Dubay et al. 2013). DxP is overall more complex in its designation guidelines, making it time consuming for contractors, who must have a relatively high level of experience in order to appropriately meet the specified desired end results, as well as for sales administration (USFS 2018; Franklin et al. 2013). Because all DxP sales must be scaled (Sale by Amount), which has different cruise and check cruises requirements than tree measurement sales, the cruise-associated costs are reduced compared to DxD sales (USFS 2018; Dubay et al. 2013). Though DxD is simpler and has greater certainty in results compared to DxP, this method is oftentimes perceived by loggers as too rigid (Dubay et al. 2013). Both methods, however, are able to create spatial heterogeneity in forest stands through the selective designation of trees for removal.

1.1.4 Late-Successional Reserves

Within the range of the northern spotted owl, 30% of federal land (7,430,800 acres) was designated as Late-Successional Reserves (LSRs) by the Northwest Forest Plan (USDA and USDI 1994). The purpose of LSR networks is to protect and enhance late-successional and old-growth forest systems that are important habitat for species such as the northern spotted owl that are dependent on these old-growth forest conditions (USDA 1997). Silviculture treatments including thinning are allowed in LSRs in stands up to 80 years old if they increase the late-successional characteristics of even-aged stands (USDA and USDI 1994). Variable density thinning is one such treatment method that has been implemented in LSRs on both the westside and the eastside of the Cascade Mountains.

1.1.4.1 Future forest management

As forest managers in the Pacific Northwest continue to implement VDT in the youngest Late-successional Reserve stands, they are challenged with the task of inducing old-growth structure in young, dense, and even-aged stands. The resulting stand structure left post-thinning will become the initial cohort in LSR stands, so collecting data on overstory tree stand structure is a crucial step in helping forest managers ensure that the treatments being implemented are successfully meeting their objectives (Larson and Churchill 2008). Monitoring of overstory tree spatial structure in LSR stands treated with restoration thinning will contribute to the growing understanding of the ability of variable density thinning to create spatial patterns that are similar to late-successional stands.

1.2 Study Questions

VDT has been used as a method of restoration thinning in the western Cascade Mountains, specifically in the conifer forests of Mt. Hood National Forest. This study will attempt to answer the following questions for this study area: (1) What clumping patterns are produced by different methods of variable density thinning treatments? (2) Does variable density thinning produce overstory tree spatial patterns that are similar to reference conditions? It is expected, based on the results of Wilson and Puettmann (2007), that VDT and gap creation treatments will increase the spatial variability within stands. Additionally, based on the results of

Churchill et al. (2013), it is predicted that treatments that are less rigid (like DxP) and incorporate a greater amount of complexity in prescription implementation will have a higher number of trees in clumps of different sizes and more closely resemble reference conditions. The exact clumping patterns that result from VDT treatments in moist Douglas-fir forests in the western Cascades will be explored. The results will be used to develop management recommendations and inform forest managers about the current effectiveness of these treatments in approximating late-successional conditions.

2. METHODS

2.1 Study Area and Sampling Units

Field data was collected in Clackamas River Ranger District of Mt. Hood National Forest in the western Cascade Mountain Range of Oregon (45.29486, -122.34411). The western region of the Forest has lower elevation and higher precipitation than the eastern side and is dominated by *Pseudotsuga menziesii* (Douglas-fir) forests, which are productive and fast-growing (USDA 2006). Westside forest communities also include western hemlock (*Tsuga heterophylla*), mountain hemlock (*Tsuga mertensiana*), noble fir (*Abies procera*), and Pacific silver fir (*Abies amabilis*) in various age classes, though mid-seral is currently the most prevalent (Hrubes 2006). The average precipitation for the Clackamas River Basin within the Mt. Hood National Forest Boundary is approximately 75 inches per year (USGS StreamStats).

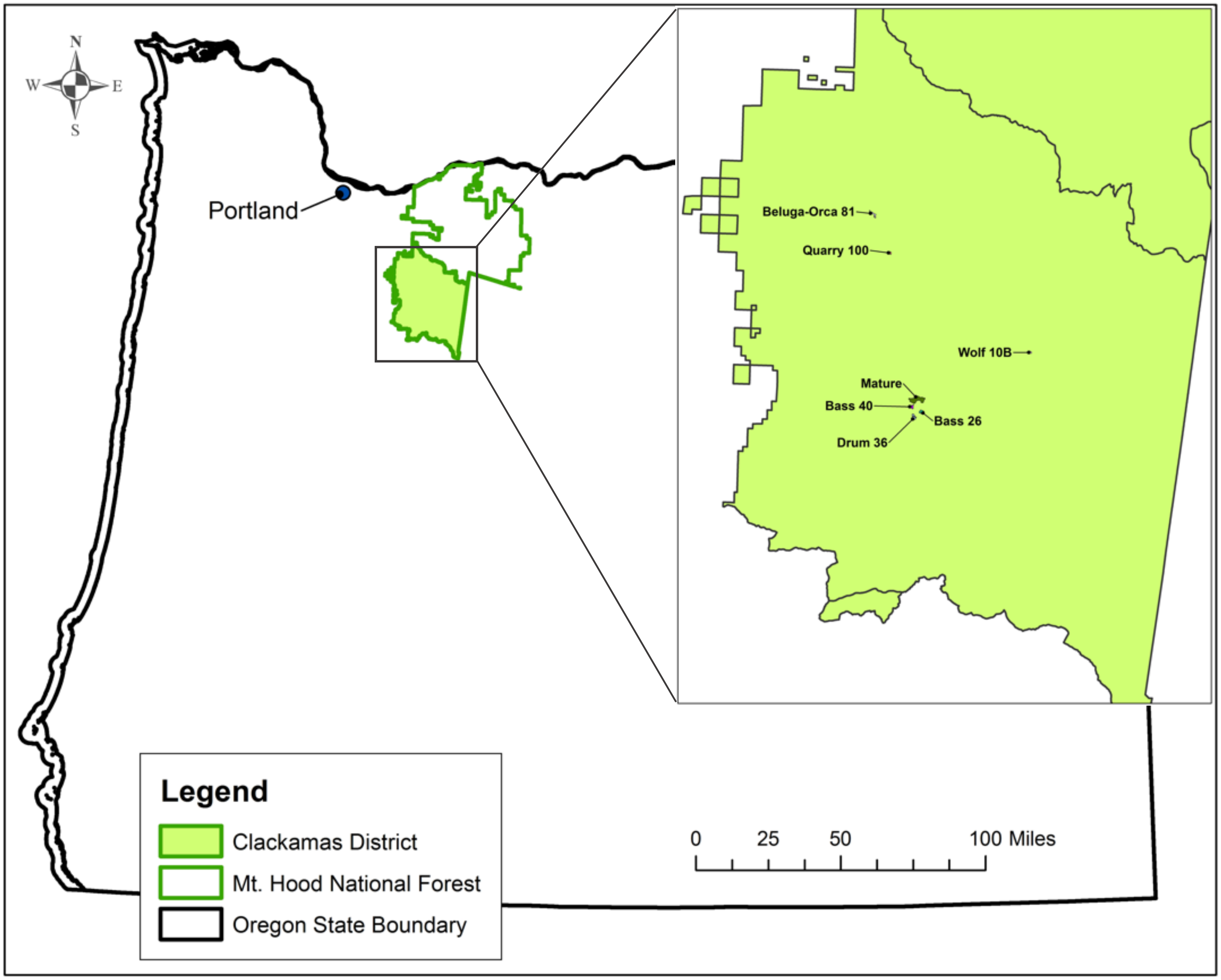

Figure 1: Mt. Hood National Forest and Clackamas River Ranger District map. Study locations are shown in the close-up district map.

These productive conditions make the westside forests ideal for timber harvest. About 188,000 acres were designated as Timber Emphasis (C1) lands in Mt. Hood National Forest by the Mt. Hood National Forest Land and Resource Management Plan. The primary method of harvest has shifted to commercial thinning since the early 1990s with an increasing emphasis on enhancing diversity, both structural and species, through the use of variable density thinning.

Desired future conditions of these forests include a greater proportion of late-successional structural classes in the Forest (Hrubes 2006).

Study units were selected from recently (2012 to 2015) thinned stands within the Clackamas River Ranger District of Mt. Hood National Forest that had been designated as Late-Successional Reserves (LSR) (Figure 1). Thinning prescriptions varied amongst the stands to incorporate several different methodologies including designation by description (DxD) and designation by prescription (DxP). The specific prescriptions for each of the selected stands are listed in Table 1. Stands were subjectively selected based on several criteria including thinning prescriptions that would be most appropriate for stand mapping (i.e. more heavily thinned) as well physical characteristics such as topography that could create dangerous conditions during the data collection process. Additionally, a mature stand was also selected to serve as a reference stand based on the proximity to the thinned stands. This stand was categorized as mature because it had never been clearcut and had clear signs of late-successional structural development such as relatively large diameter trees and canopy gaps that had naturally developed as a result of Douglas-fir mortality.

Table 1: Prescription and year of thinning for each of the seven selected stands according to respective contracts.

Stand	Prescription	Year	Details
Bass 26	DxP 80	2014	• LSR leave trees: All trees ≥20 DBH • Species designated for cutting: Douglas-fir, noble fir, western hemlock, Pacific silver fir, grand fir • Target basal area per acre=80 (USDA 2012a)
Bass 40	DxP 80	2014	• LSR leave trees: All trees ≥ 20 DBH • Species designated for cutting: Douglas-fir, noble fir, western hemlock, Pacific silver fir, grand fir • Target basal area per acre=80 (USDA 2012a)

Drum 36	DxP 80	2014	• LSR leave trees: All trees ≥ 20 DBH • Species designated for cutting: Douglas-fir, noble fir, western hemlock, Pacific silver fir, grand fir • Target basal area per acre=80 (USDA 2012b)
Quarry 100	DxD 14 ft	2013	• Cut trees: "Trees that meet the following criteria are designated for cutting: The tree is within 25 feet of a tree that has yellow paint above and below stump height or the tree is within 14 feet of a tree that has a larger stump diameter than it, and the larger tree is not designated for cutting." • Leave trees: "The following are designated as leave trees and will be used to determine the spacing of the cut trees described above: trees with a diameter that is 25 inches or greater outside of the bark at 4 inches above the ground. In addition to the leave trees designated above, the following trees will be left standing and will not be used to determine spacing of the trees described in the above paragraph: trees within 25 feet of a tree marked with orange paint above and below stump height; Western Red Cedar trees; dead standing trees; and non-coniferous trees except Red Alder." (USDA 2006b)
Beluga-Orca 81	DxD 15 ft	2015	• Leave trees: "All trees greater than 25 inches diameter measured outside bark at 4 inches above ground shall be left." • DxD: "Outside of the above described areas, all trees except dead standing and non-coniferous trees are designated for cutting if they are within 15 feet of a tree that has a larger stump diameter than it. Trees within Skips described above may be used to determine cut trees outside of the Skip." • Skips: "All trees, within 25 feet of a tree that has Orange paint above and below the stump height are to be left standing. Orange painted trees are to be left standing." • Gaps: "All trees, except dead standing and non-coniferous trees, within 25 feet of a tree that has yellow paint above and below stump height are designated for cutting. Yellow painted trees left standing." (USDA 2006a)
Wolf 10B	DxD 16 ft	2012	• LSR leave trees: all trees >25 inches DBH

			• Species designated for cutting are Douglas-fir and western hemlock • DxD: All live trees except those excluded from cutting are designated for cutting if they are within 16 feet of a live, standing with a larger stump diameter • Skips: All trees within 25 feet of designated leave tree are to be left standing • Gaps: All trees except those excluded from cutting within 25 feet of a specifically marked tree (which will be left standing) shall be cut (USDA 2004)

2.2 Data Collection

Within the selected thinned stands, a point was randomly selected and the canopy opening nearest to the random point was selected as the first reference point. At the reference point, a tripod setup including a Zephyr antenna, Trimble GeoXH, and Laser RangeFinder 360 was positioned. A minimum of 70 reference points was logged using the program TerraSync with the antenna fully extended to the tripod maximum height plus the bracket height of 9.4 meters. The total number of positions logged varied somewhat according to cloud coverage, location, time of day, and canopy density. After the reference position location was established, the RangeFinder with a Canopy Lens attached was used to collect offset data (bearing, distance, and height) for all trees within the line of sight. Tree species and diameter at breast height (DBH) were also recorded. Subsequent reference points were selected based on canopy openness and proximity to the previous endpoint of offset collection until approximately 5 acres were surveyed.

2.3 Stand Mapping and Clump Size Analysis

Reference point data was transferred to ESRI ArcMap 10.4 using the program GPS PathFinder following differential correction to improve accuracy. Tree offset XY locations were calculated using the collected distance and bearing data. Tree height was estimated from DBH measurements using height-diameter equations and regression coefficients used by Hanus et al. (1999) for Pacific Northwest tree species. Any trees having an estimated height of less than 25 meters, the minimum height used to define overstory trees in the western Cascades by Larson and Churchill (2006), were excluded from the analysis of overstory tree spatial patterns. Bubble plots were then used to create stem maps that display the diameter, species, and spatial patterns of trees within each of the stands.

The normalized mean cluster size was determined for each of the surveyed stands using the procedure developed by Plotkin et al. (2002) in ArcMap 10.4. Trees are in the same cluster if they are within a specified radius *d* of one another such that each tree is in a distinct cluster when *d*=0 and when *d* is very large, all trees are in the same cluster due to overlap of pairwise distances. The mean cluster size (Plotkin et al. 2002) was calculated using the following algorithm:

$$\bar{c} = \frac{1}{n}\sum_{i=1}^{m} c_i^2$$

In this equation, *n* is the total number of points in the pattern:

$$n = \sum c_i$$

Additionally, *m* is the number of distinct clusters and c_1, c_2, c_3 … c_m is the size of individual clusters. In order to normalize the mean cluster size to allow comparison of results of different values of *n*, $\hat{c}$, the normalized mean cluster size, was calculated:

$$\hat{c} = \frac{\bar{c}}{n}$$

The estimated critical distance for the Mature stand was used to define clumps for each of the stands. Proportions of structural groups were calculated based on the following classifications: single tree, small cluster (2-4 trees), medium cluster (5-9 trees), and large cluster (more than 10 trees), as recommended by Churchill et al. (2013).

2.4 Global Point Pattern Analysis

A global point pattern analyses was conducted to provide another measure of the spatial structure of the forest stands. The test was conducted using version 1.55-1 of the Spatstat package (Baddeley et al. 2018) in R Studio 1.1.383 (R Core Team, 2017). The L-function and isotropic edge correction was used to compare the observed clumping patterns of each stand to a complete spatial randomness (CSR) envelope created using 99 simulations. The L-function is the variance-stabilized square root transformation of the commonly used Ripley's K point pattern analysis, which is used to summarize the point pattern of two-dimensional spatial data across distance scales (Dixon 2001).

3. RESULTS

3.1 Stem maps

Based on the approximations of each of the polygonal sample plots, the area surveyed in each of the stands varied from 3.3 to 9.7 acres and therefore did not precisely match the intended 5 acres (Table 2). Calculation of tree density showed that Beluga-Orca 81 and Quarry 100 had the highest density with 70 and 67 overstory trees per acre, respectively, and Bass 40 had the lowest with 37 overstory trees per acre (Table 2).

Stem mapping revealed that overstory tree spatial patterns varied across each stand, though multiple tree clusters and gaps were present in all stands (Figures 2-8). The overstory canopy of several stand plots contained solely *P. menziesii* (Bass 26, Bass 40, and Drum 36).

The number of overstory tree species was highest in the Mature stand; however, the other thinned stands contained more than one species. The largest tree DBHs occurred in the Mature stand as well as well as the largest range in tree sizes.

Table 2: Sample area and stem density in each stand.

Stand	Treatment	Area Sampled (Acres)	Overstory Tree Density (trees/acre)
Bass 26	DxP 80 BA	6.46	39.1
Bass 40	DxP 80 BA	6.55	36.7
Drum 36	DxP 80 BA	5.39	51.6
Quarry 100	DxD 14 ft	4.45	67.0
Beluga-Orca 81	DxD 15 ft	3.32	70.4
Wolf 10B	DxD 16 ft	5.99	42.1
Mature	None	9.68	39.4

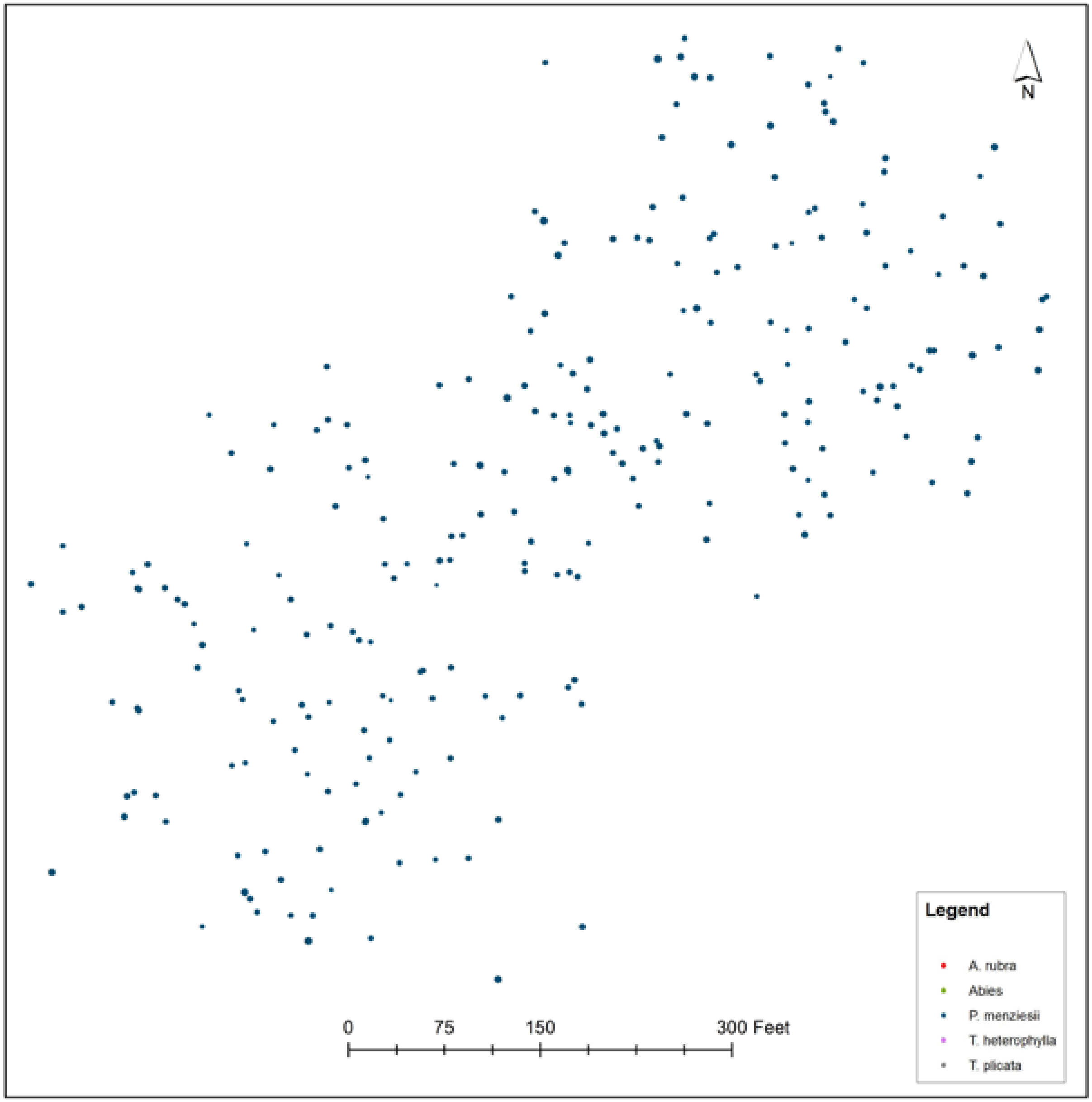

Figure 2: Bass 26 (DxP 80 BA) stem map. The size of each circle is representative of the tree DBH with a minimum height of 25 meters used to define overstory trees.

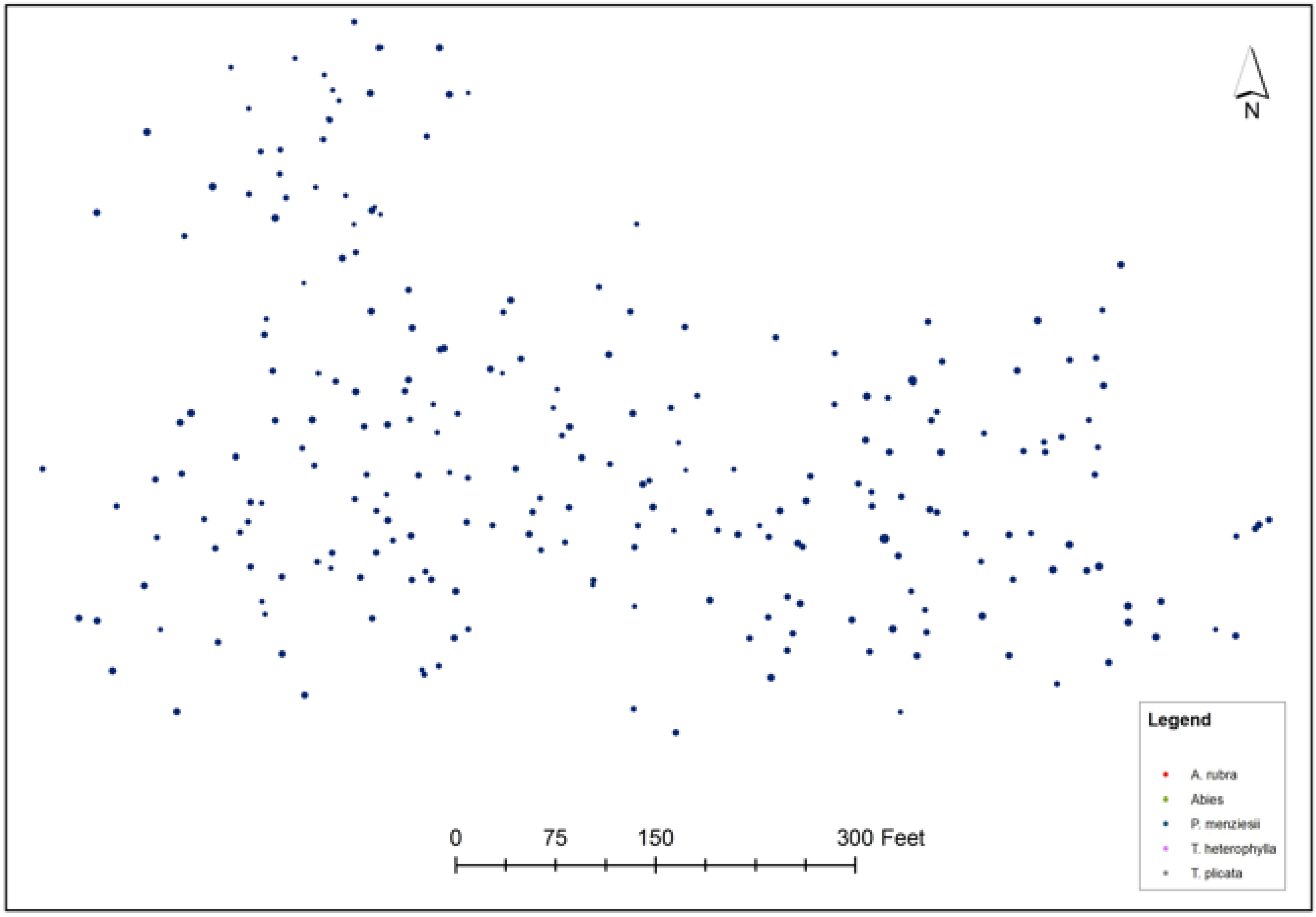

Figure 3: Bass 40 (DxP 80 BA) stem map. The size of each circle is representative of the tree DBH with a minimum height of 25 meters used to define overstory trees.

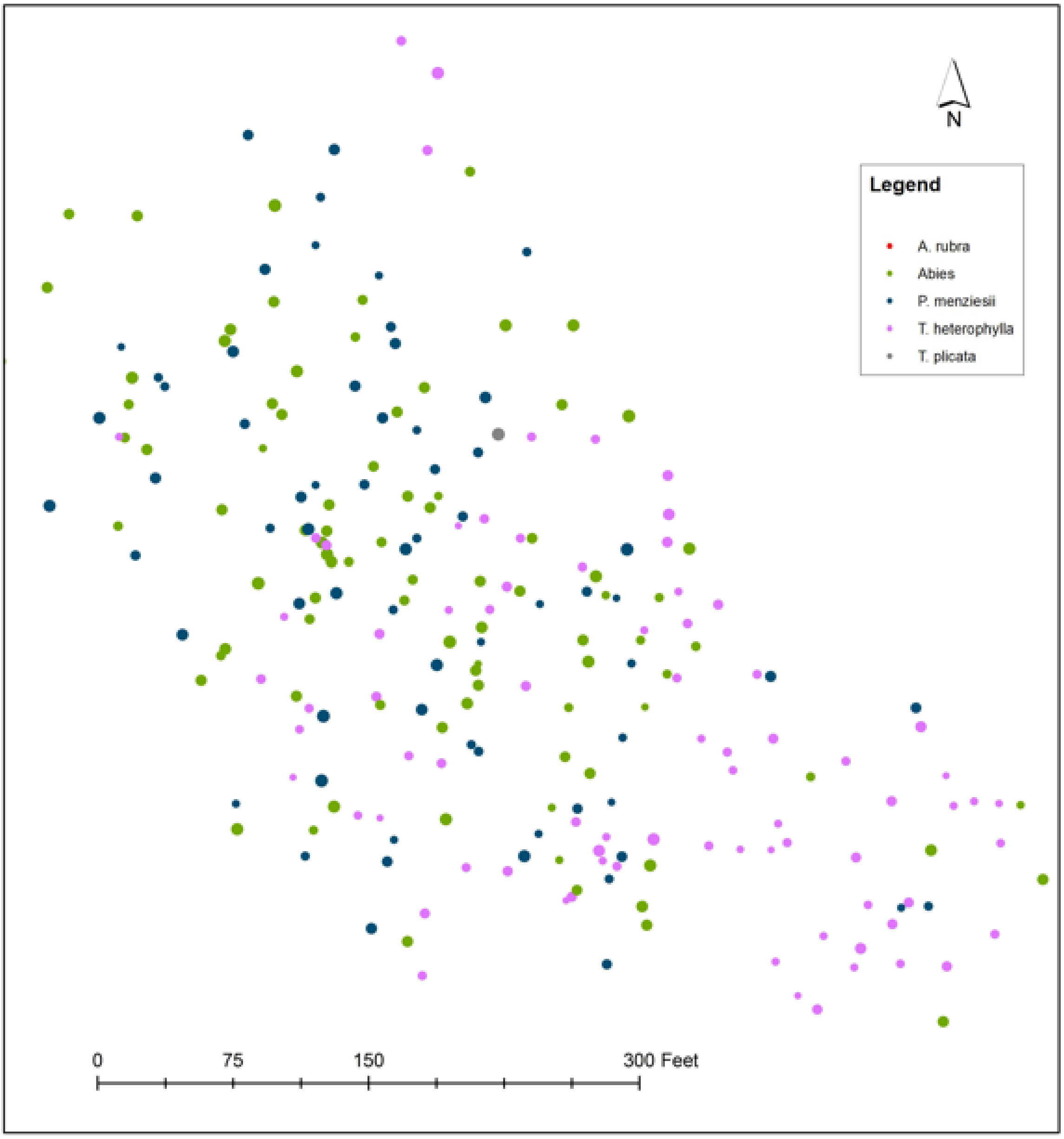

Figure 4: Beluga-Orca 81 (DxD 15 ft) stem map. The size of each circle is representative of the tree DBH with a minimum height of 25 meters used to define overstory trees.

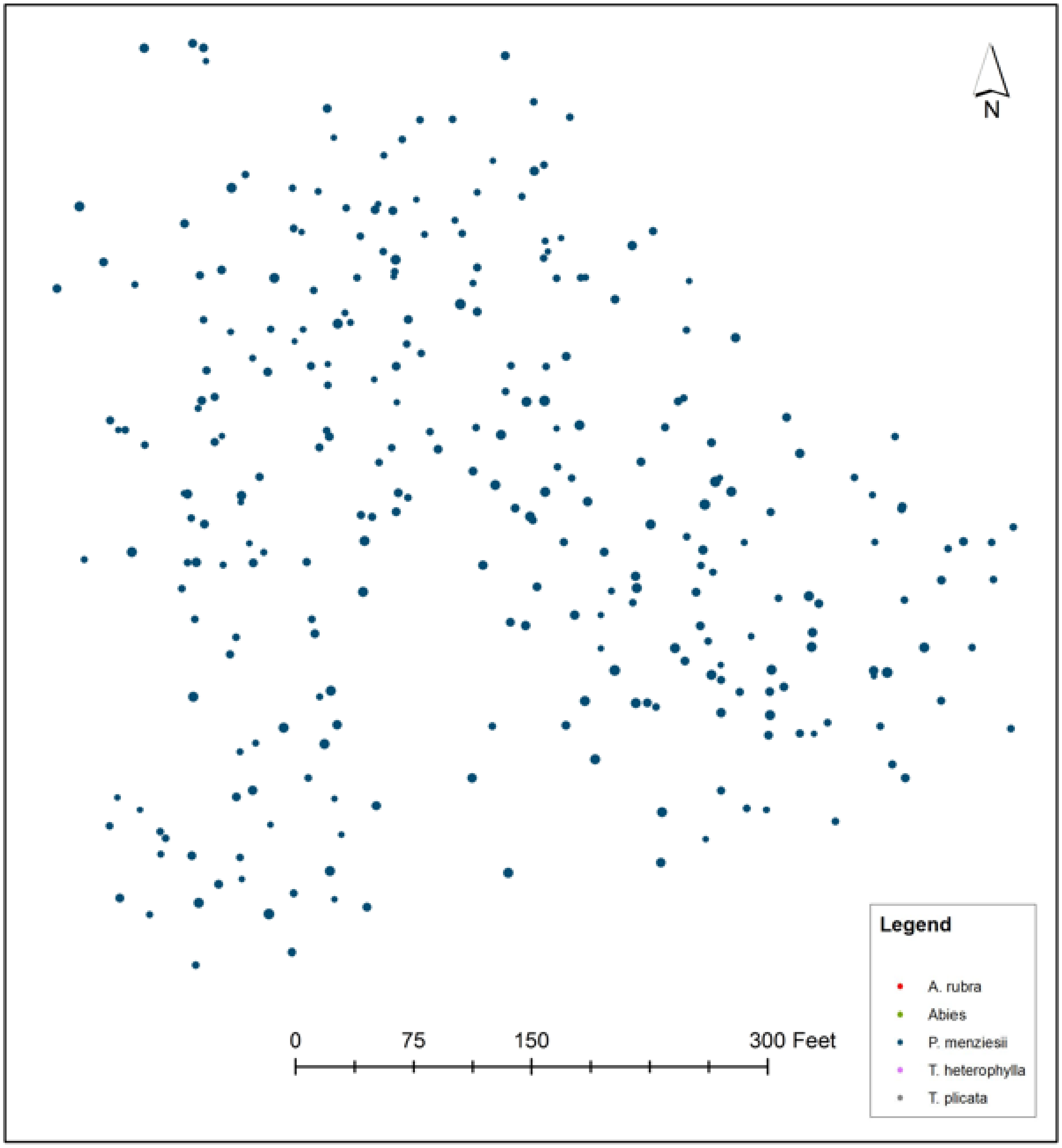

Figure 5: Drum 36 (DxP 80 BA) stem map. The size of each circle is representative of the tree DBH with a minimum height of 25 meters used to define overstory trees.

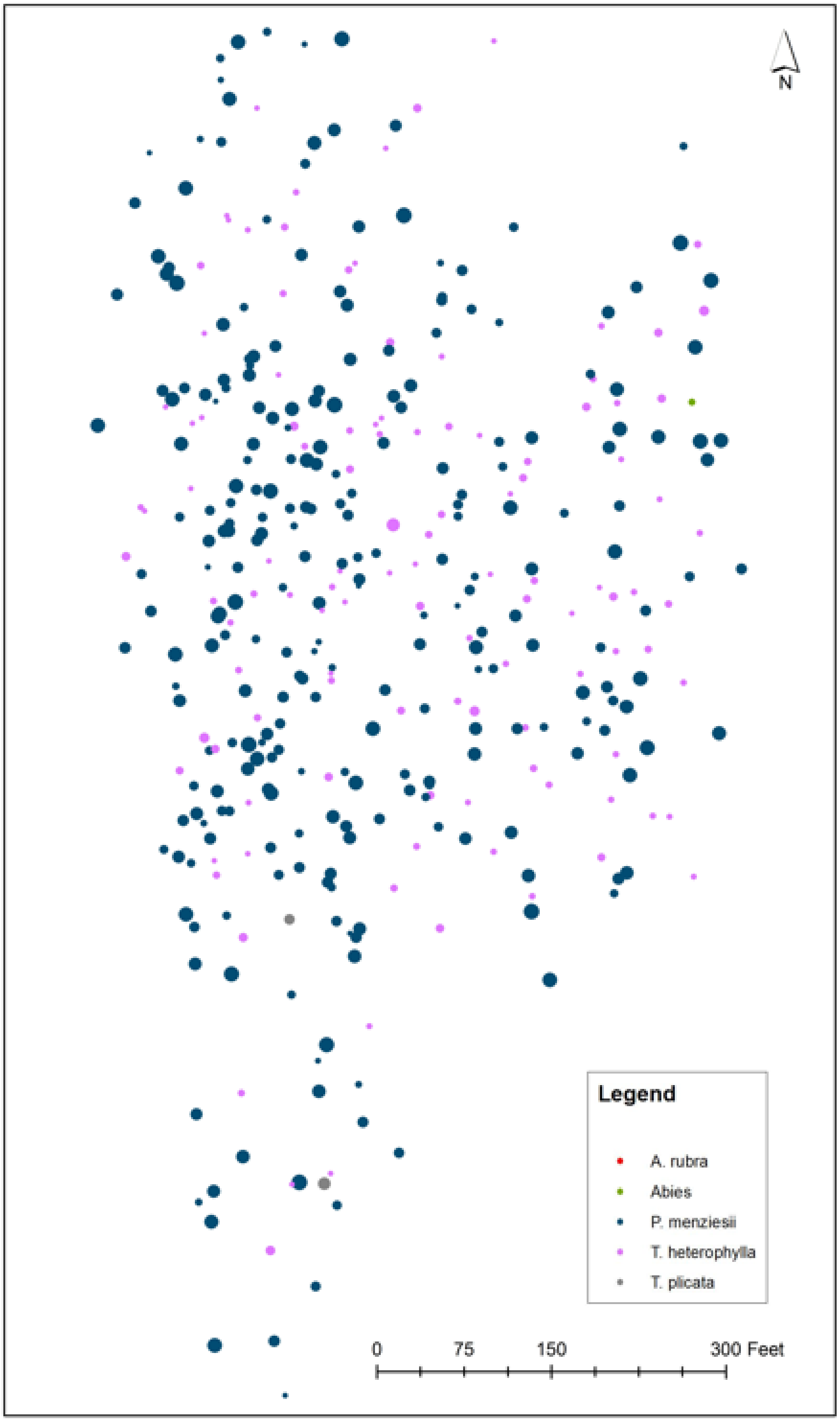

Figure 6: Mature stem map. The size of each circle is representative of the tree DBH with a minimum height of 25 meters used to define overstory trees.

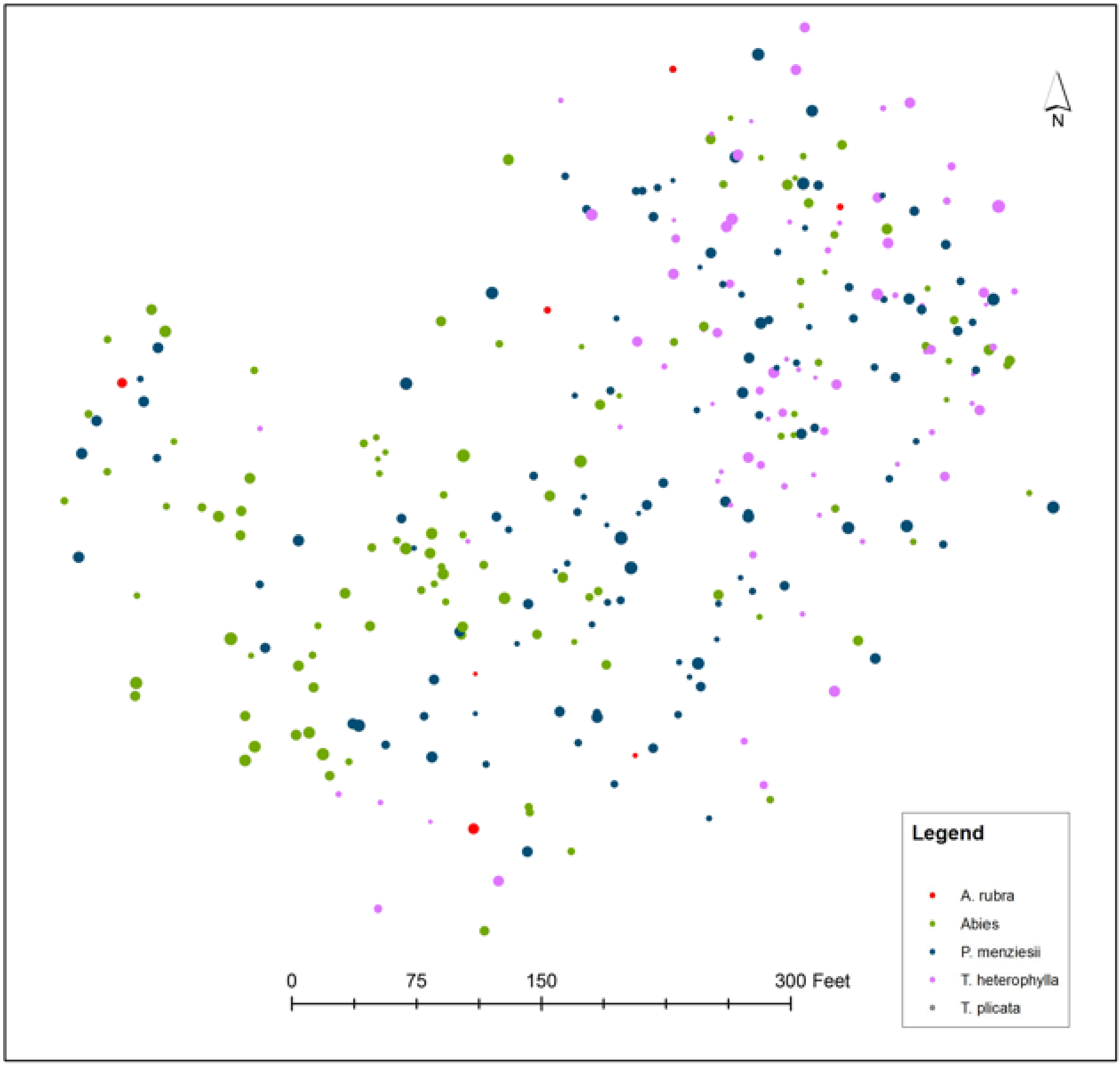

Figure 7: Quarry 100 (DxD 14 ft) stem map. The size of each circle is representative of the tree DBH with a minimum height of 25 meters used to define overstory trees.

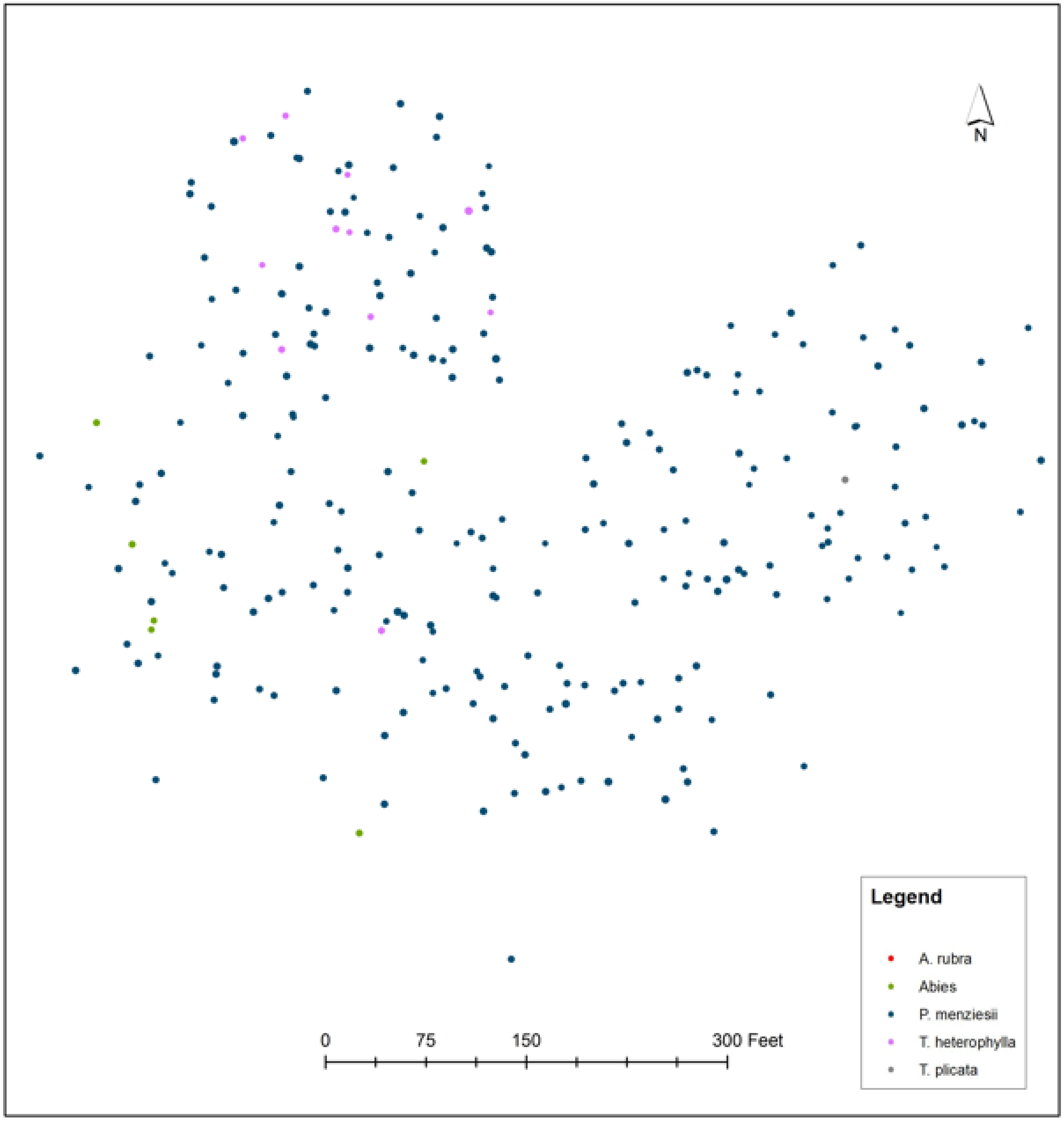

Figure 8: Wolf 10B (DxD 16 ft) stem map. The size of each circle is representative of the tree DBH with a minimum height of 25 meters used to define overstory trees.

3.2 Clump size

Calculation of the normalized mean cluster size revealed that the critical distance of the sampled stands varied between 8 and 15 feet (Figure 9). The critical distance is the distance at which a transition from many small clusters to one large cluster occurs and is reflected in the inflection point at which a majority of the trees are within clusters (Plotkin et al. 2002). Bass 26, Bass 40, and Wolf 10B had approximately the same critical distance of 15 feet, the highest among the seven the stands. Quarry 100 had the smallest critical distance of about 8 feet. Unsurprisingly, a larger inter-tree spacing distance in DxD prescriptions resulted in a larger critical distance. The Mature stand had a critical distance of 12 feet, which was approximately equal to Drum 36 (DxP 80).

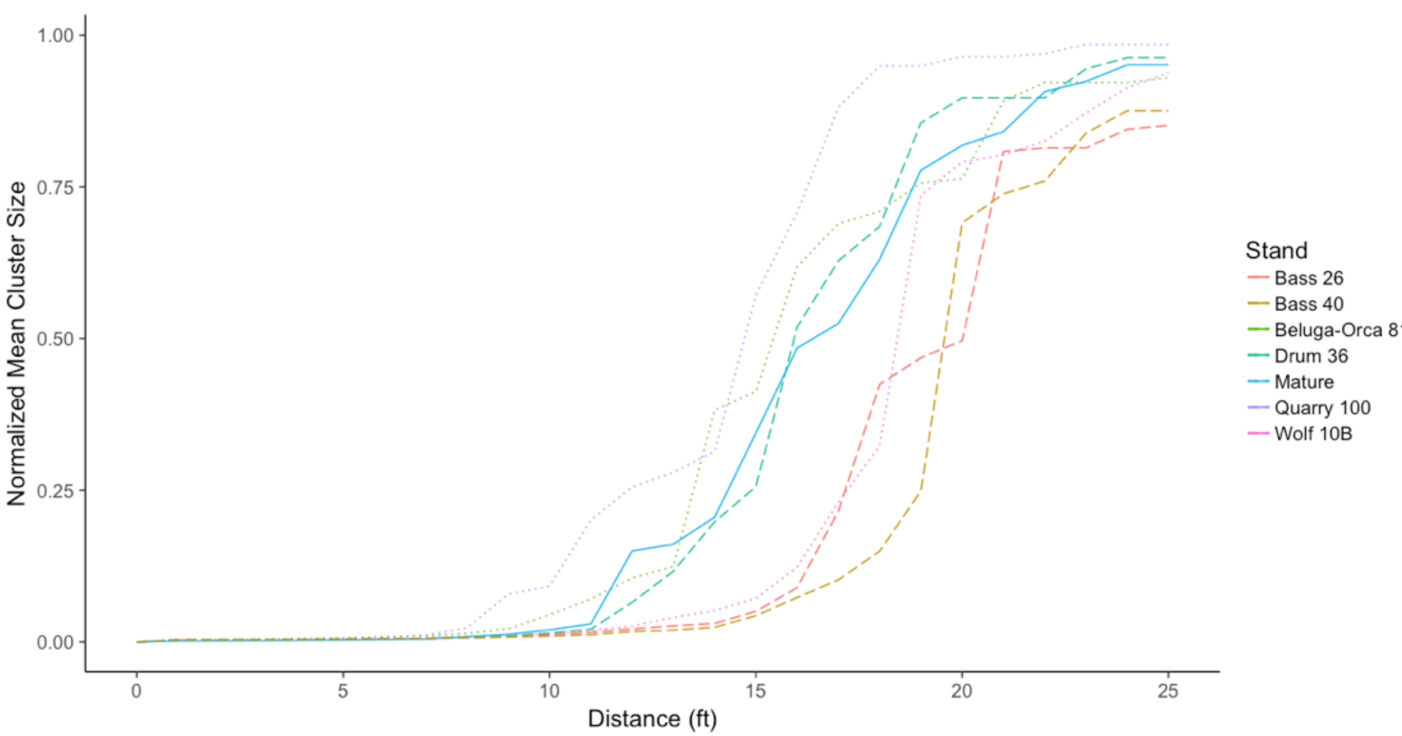

Figure 9: Normalized mean cluster size for all overstory trees plotted as a function of distance for each of the seven surveyed plots. DxD treatment is indicated by dotted lines. DxP treatment is indicated using dashed lines. Normalized mean cluster size ranges from 0 to 1 such that at 0 all trees are single trees and at 1 all trees belong to the same cluster. The critical distance is reflected by the inflection point at which a majority of the trees are within clusters (Plotkin et al. 2002).

The proportion of the structural groupings of overstory trees (single tree, small cluster, medium cluster, and large cluster) of the Mature stand was most similar to the Drum 36 and Bass 40, which were both treated with DxP (Figure 10). The similarity with Drum 36 is consistent with the similar normalized cluster size analysis in the previous analysis of the critical distance. Despite having the same prescription, the stands thinned using DxP methods exhibited variability in the proportions of structural groupings.

Beluga-Orca 81 and Quarry 100, the DxD treatments with the smallest spacing distance (15 feet and 14 feet, respectively), contained the highest percentage of large clusters, with more than half of overstory trees occurring in groups of 10 or more trees. The DxD stand with a spacing distance of 16 feet (Wolf 10B), however, had a structural grouping that had a substantially lower proportion of overstory trees in large clusters (12%) compared to the Mature stand (28%) and the two other DxD stands (53 and 57%).

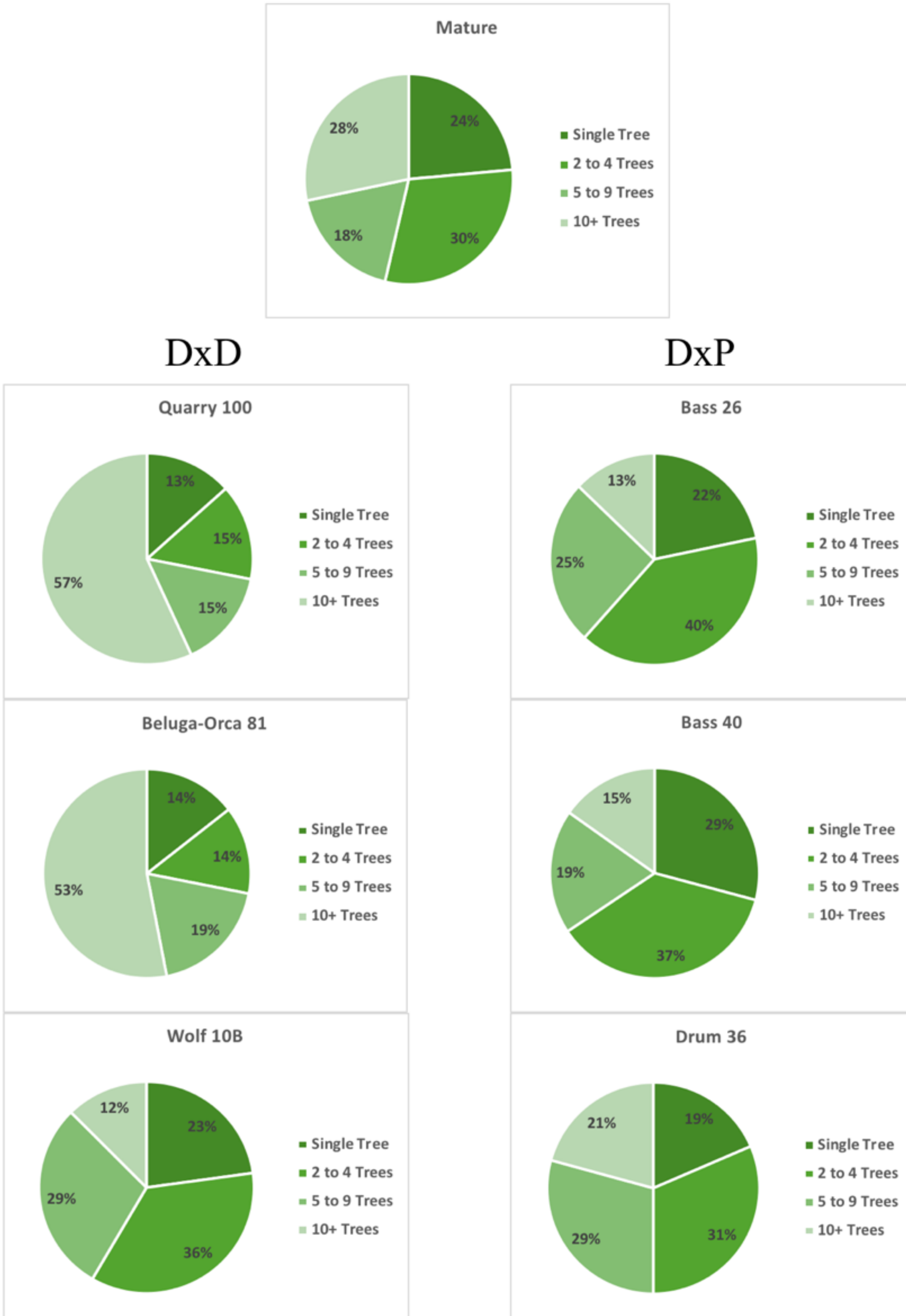

Figure 10: Proportion of overstory trees in each structural grouping: single tree, small cluster (2-4 trees), medium cluster (5-9 trees), and large cluster (10 or more trees) using the critical distance of the Mature stand (12 feet) to define clusters.

3.3 Global Point Pattern Analysis

Global point pattern analysis found that none of the stands had a statistically uniform stand structure (Figure 11). Overstory trees in the Mature stand had a clustered spatial pattern at inter-tree distances greater than 7 meters. Quarry 100 overstory had a very similar clustered pattern (also becoming clumped around 7 meters) and Beluga-Orca 81 displayed a clustered pattern only at distances greater than about 22 meters. The L statistic value for Drum 36 only intermittently rose above the CSR envelope (about 18 to 30 meters and 35 to 40 meters). The three remaining stands (Bass 26, Bass 40, and Wolf 10B) did not exceed the CSR envelope and therefore were neither statistically clustered nor uniform. The pattern of L statistic values of Quarry 100 was the most similar to the Mature stand.

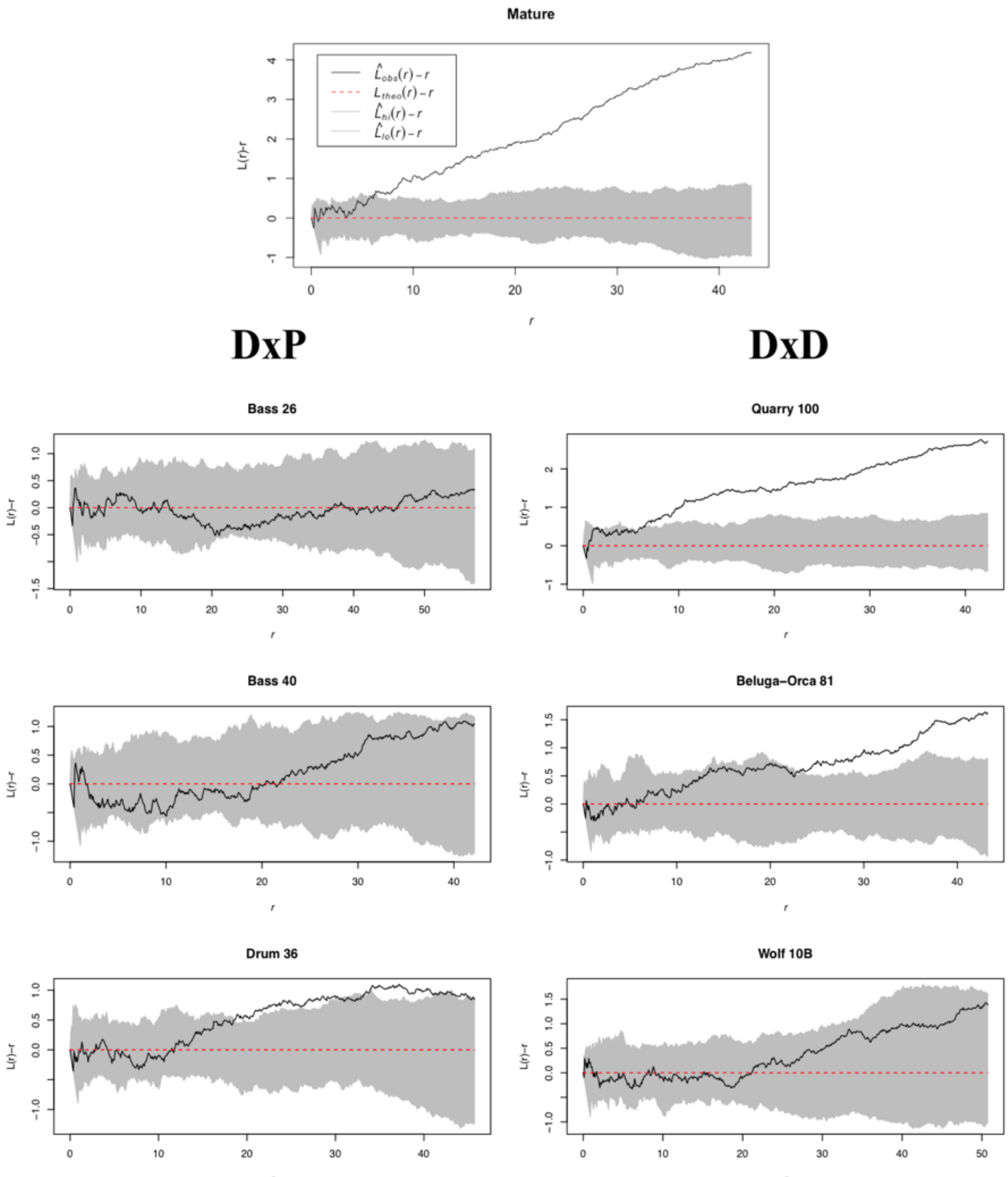

Figure 11: Global point patterns (L function) for sampled stand at inter-tree distances r (in meters). The gray zone indicates complete spatial randomness (CSR) such that values above the envelope are indicative of a clumped pattern and values below are indicative of regular, or uniform, patterns. 99 Monte Carlo simulations were used to create the CSR envelope.

4. DISCUSSION

Silvicultural thinning, specifically variable density thinning, is designed to mimic naturally occurring density-dependent mortality and increase the rate of development of desired forest structure and conditions (Tappeiner et al. 1997; Franklin 2007). Because it increases the late-successional characteristics of young, dense, and even-aged stands that have regenerated post-clearcut, restoration thinning has been utilized on Federal land in the Pacific Northwest designated as Late-Successional Reserve. A variety of methods have been used to implement variable density thinning in these areas, but the goal of all treatments is to approximate late-successional structure to the greatest possible degree, as these conditions are essential for species such as the northern spotted owl (USDA and USDI 1994).

4.1 Forest Spatial Patterns

Based on the results of this study, variable density thinning treatments were successful in creating spatially heterogeneous stand conditions. No stand had a statistically uniform structure, which indicates that the restoration thinning created a forest spatial structure markedly different from evenly spaced, plantation-style monocultures that have previously been utilized in the cultivation of timber trees in the Pacific Northwest (Swanson and Franklin 1992). Four of the seven stands had statistically clumped spatial structures across a range of inter-tree distances; however, multiple tree clusters were present in all stands. Beluga-Orca 81 and Quarry 100, the thinned stands that had a statistically clumped pattern over a large range of inter-tree distances, had the smallest DxD spacing requirements (15 and 14 feet, respectively) and subsequently the smallest critical distances as well as the highest proportions of large clusters. The small spacing used in these stands likely contributed to the trends observed in the global point pattern analysis.

This is further supported by the smaller inter-tree distance at which Quarry 100 begins to have a statistically clumped pattern (8 meters) compared to Beluga-Orca 81, which has a statistically clumped pattern beginning at approximately 22 meters. This is consistent with the fact that the tree spacing that was implemented in Beluga-Orca 81 was larger than Quarry 100.

The Mature stand also had a statistically clumped pattern starting at approximately 7 meters. The uneven-age class of this stand likely contributes to this clumped pattern, especially considering the relatively large number of western hemlocks that are growing in the lower and mid-canopy beneath the large, shade-intolerant Douglas-firs that currently comprise the upper canopy. As the stand ages, western hemlock will continue to grow and begin to co-dominate the canopy as overstory Douglas-firs are naturally thinned by mortality thereby increasing the amount of light reaching the lower canopies and understory (Franklin et al. 2002). As stands transition from mature to old-growth age-classes, the shade-intolerant species density will decrease and the shade-tolerant species density will increase (Spies and Franklin 1991). The mature stand sampled in this study is clearly undergoing this transition. This increasing density of shade-intolerant species and the numerous clusters of multiple Douglas-fir trees that are characteristic of late-successional forests contribute to the clumping pattern that is observed in the global point pattern analysis.

A similar result was observed by North et al. (2004) in their global point pattern analysis of an old-growth (estimated 375 to 500 years old) Douglas-fir and western hemlock-dominated forest in southern Washington, which found that large trees had a statistically clumped pattern beginning at 15 meters. However, the tree spatial pattern was regularly spaced at distances below about 10 meters (North et al. 2004). As previously discussed, the mature stand used in this study is undergoing structural development, so this trend of regular spacing at small inter-tree distances could develop over time as the stand ages.

A previous study by North et al. (2007) in mixed conifer forests in the Teakettle Experimental Forest in Sierra Nevada found that tree spatial patterns post-thinning were more clumped than reconstructed reference conditions and concluded that a more aggressive removal of small-diameter stems would increase the degree to which treated stands resembled reference stands. Because removal of small-diameter trees was part of the thinning treatment and the statistical analysis of the sampled stands in this study, this likely decreased the observed degree of clumping and led to most of the young, thinned stands having a point pattern within the CSR envelope. Over time, as regeneration continues and more trees grow to become overstory trees, clumping will likely become more apparent in the more heavily thinned stands.

4.2 Forest Structure

Each of the six sampled thinned stands contained each type of structural grouping (single tree, small cluster, medium cluster, and large cluster) as well as canopy openings when cluster size was defined using the critical distance of the Mature stand (12 feet). This result provides further evidence that all of the restoration thinning treatments created spatial variability in the clustering of overstory trees. The variable patches resulting from canopy gaps and skips create an uneven distribution of resources such as light that can increase growth and diversity of understory vegetation (Harrington et al. 2005; Ares et al. 2009). Spatial heterogeneity in overstory trees also releases shade-tolerant trees such as western hemlock and western redcedar, which are important species in old-growth forest systems of the western Cascades, such that they are able to rapidly grow post-thinning due to reduced competition (Comfort et al. 2010).

The treated stands that most closely resembled the structural pattern of the Mature stand (Bass 40 and Drum 36) were thinned using the DxP method. Conversely, the stands that differed the most from the proportions of structural groupings of the Mature stands were Beluga-Orca 81 and Quarry 100, which had a notably higher proportion of trees in large clusters and a much lower proportion of single trees and small clusters. In a study of mixed conifer forests in Sierra Nevada, Lyderson et al. (2013) found that 33.5% of trees greater than or equal to 25 cm DBH belonged to large clumps (10 or more trees) in an old-growth forest in 1929 compared to 89.1% of trees belonging to large clumps in the same plots 78 years after the clearcut logging. This discrepancy between post-harvest regenerated stands and old-growth stands is similar to the difference observed between the lightly thinned DxD stands and the Mature stand in this study. This indicates that DxD thinning prescriptions that use 15 feet or smaller spacing requirement may not be heavily thinned enough to produce overstory tree spatial patterns that closely resemble late-successional stands. The DxD stands with 14 and 15 feet spacing requirements also had substantially higher overstory tree densities than the other thinned stands and the mature stand, which further supports the idea that these treatments are not thinned heavily enough to approximate late-successional forest structure (Table 2).

Overall, it appears that DxP creates a forest structure more similar to late-successional forest stands. This indicates that more flexible thinning prescriptions like DxP that allow for site-specific modifications are more successful in approximating late-successional forest structure and should be preferred over methods that utilize rigid spacing requirements as DxD does. Overall, in silviculture prescriptions, specification of minimum basal area and other desired structural attributes in stands improves the degree to which the structure of post-harvest stands resemble old-growth forest complexity (Moore et al. 1999; Larson et al. 2012).

This is consistent with the recommendations put forth by Churchill et al. (2014) in implementing their Individual, Clumps, and Openings (ICO) method of restoring mosaic spatial patterns in forest stands in pine and mixed conifer forests such that an ICO prescription could only be incorporated into a DxP prescription and not a DxD prescription. The ICO method uses approximate clump targets for entire units (for example, 25% individual trees, 30% small clumps (2-4 trees), 25% medium clumps (5-9 trees), 10% large clumps (10-15 trees), and 10% super clumps (16-20 trees)) to allow for flexibility in clumping and density variation according to site conditions (Churchill et al. 2014). Another option for ICO DxP prescriptions is to utilize BA targets for average density as well as targets for large openings and medium to large clumps (Churchill et al. 2014). The ICO approach can successfully create tree spatial patterns within the range of reference conditions (Churchill et al. 2013) and the combination of ICO and DxP may provide a useful method for restoration thinning, especially in LSR stands.

Despite being thinned using the same prescription (DxP with a target of 80 basal area/acre), there was variability in the proportions of structural groupings (Figure 10). This is consistent with the findings of Willis et al. (2018) such that forest structure including tree density and size and species composition differed among plots treated with VDT and, 14 years post-treatment, these differences resulted in variation in forest conditions and tree growth in each plot. However, variability in the number of overstory trees per cluster is characteristic of natural late-successional systems and is important for contributing to larger-scale heterogeneity (Larson and Churchill 2008).

4.3 Study Limitations

A primary limitation of this study was the small sample size. This was largely due to the time and labor-intensive nature of the surveying methodology of forest stands, especially those with a more closed canopy and high density of trees. Specifically, the lack of reference site spatial structure made comparison to late-successional conditions challenging and less informative. Inclusion of additional stands, both thinned and late-successional for reference, should be emphasized in future study.

4.4 Future Research

Most studies of this type that specifically analyze tree spatial patterns have focused on fire dependent, dry forests in the eastern Cascade Mountains and Sierra Nevada (North et al. 2007; Lyderson et al. 2013; Churchill et al. 2013; Larson and Churchill 2008). This highlights a need for more research in moist forests on the westside of the Cascade Mountains to establish late-successional reference conditions to guide management and prescription development as well as determine the success of applied variable density thinning treatments in approximating these late-successional forest conditions. Long-term monitoring will be needed to capture the ecosystem impacts of variable density thinning treatments because of the relatively long timescale over which forest succession and development occur.

Within the context of this study, further research is necessary to increase the number of stands sampled and subsequently the strength of the conclusions that have implications for forest management. Increasing the sample size to include a greater number of each prescription type is critical for increasing the applicability of the study results. Including a gap analysis would also be useful information for forest managers to ensure the canopy gaps created using restoration thinning are an appropriate size for this type of forest system.

4.5 Management Recommendations

Increasing the amount of structural diversity is key to successful long-term forest management, which can be achieved using natural-disturbance-based management that recognizes the importance of biodiversity and structural heterogeneity (Larson et al. 2012; Bergeron et al. 1999). Specifically, adaptive and flexible site-specific prescriptions like DxP can help forest managers meet ecological and economic goals for the forests they are managing. When developing thinning prescriptions, information such as current conditions and previous management activities should be utilized (Comfort et al. 2010). Rough guidelines can be based off of local late-successional forest structure; however, site-specific considerations and modifications are essential for the appropriate application of variable density thinning treatments (Larson and Churchill 2008).

Given the high degree of uncertainty of future climatic conditions, it is necessary to manage forests as complex systems and focus on the system's resilience and ability to adapt rather than its efficiency and potential for generating profit as traditional silviculture does (Elmqvist et al. 2003). Increasing stand-level variation can increase a forest system's resistance and ability to adapt to disturbances that may occur in the future (Puettmann et al. 2009). Accelerating forest succession in even-aged regenerated stands using variable density thinning should continue to be a tool utilized to increase spatial heterogeneity and resilience in regenerated LSR-designated stands.

Continued monitoring of sites treated with different methods of restoration thinning is critical, especially on the westside of the Cascade Mountains where data are lacking due to the research focus drier, more fire-prone forests of the eastern Cascades. This increase in data and understanding of westside forest conditions will help inform future management decisions in these areas. As previously discussed, long-term monitoring is critical due to the length of time necessary for forest structural development to occur. For example, Willis et al. (2018) found that a period of 14 years was not sufficient to capture significant changes in forest structure and size classes. Therefore, monitoring of LSR stands treated with variable density thinning should continue into the future.

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