



Assessing different components of three-dimensional forest structure with single-scan terrestrial laser scanning: A case study



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ABSTRACT

Efficient quantification of the three-dimensional forest structure is of increasing importance for our understanding of forest functions and services, but it remains challenging with conventional methods. We used a single-scan ground-based laser approach in stands with a known difference in management history and associated differences in structures. The data were used to test whether the measurement approach could distinguish various structural measures among the stands, including overall density, vertical structure, competitive conditions for regeneration, horizontal visibility, and three-dimensional structural variability. In general, our data reflected known differences in stand structure. However, in some cases the different measures showed contradicting results, highlighting the limited information represented in each measure when considered in isolation. At the same time, our results suggested that all components of stand structure do not develop in sync. The variability of horizontal and vertical structural heterogeneity appears to be a good indicator of structural elements typically found in old-growth forests, i.e., spatially homogenous (scale independent) horizontal structural variability in combination with a scale-dependent vertical structural variability. In addition, our results provided information with direct management implications. For example, gap creation, a prominent practice in restoration treatments in the region, increased spatial variability, but the hard edges and removal of all trees inside the gap, are not reflecting structural conditions found in our old-growth stand. In summary, our results suggest that this new technology can efficiently provide objective and holistic inventories of stand structures. However, more work is needed to fully understand the implications of the novel structural measures for ecosystem processes and services.

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1. Introduction

Land owners who are focused on a broader set of ecosystem services, rather than emphasizing wood production only, utilize a broad set of alternative silvicultural management practices (Puettmann et al., 2015). These practices typically emphasize the development of heterogeneous forest structures. This is because the variability of the spatial arrangement of structural components within forests ecosystem is positively correlated with many desirable ecosystem functions and services, e.g. biodiversity or habitat suitability (Lindenmayer et al., 2000), productivity (Ishii et al., 2004), and forests scenic beauty (Ribe, 2009). Critical processes leading to formation of diverse stand structures include differential resource use and growth rates of species and the mortality of large trees resulting in canopy gaps (e.g. Franklin et al., 2002; Franklin and van Pelt, 2004; Lutz and Halpern, 2006).

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Starting in the 1960s, typical regeneration practices after clear-cut harvesting of old-growth stands in the Pacific Northwest resulted in relatively homogenous stand structures, dominated by high density, regular spaced, even-aged and even-sized Douglas-fir trees (Lavender and Hermann, 2014). Especially on public lands, concerns about biodiversity in the 1990s led to implementation of numerous silvicultural management practices in these homogenous plantations to encourage development of more spatially complex and heterogeneous, old-growth-like forest structures. Such restoration treatments include variable density thinning, underplanting, untreated leave islands or the creation of artificial gaps (Lutz and Halpern, 2006; Davis et al., 2007; Wilson et al., 2009; Schliemann and Bockheim, 2011). Much is known about the effect of these treatments, e.g. about canopy gaps, on individual structural elements, such as tree growth (Dodson et al., 2012), natural regeneration (Dodson and Root, 2013), canopy (Davis et al., 2007; Chan et al., 2006) and crown characteristics (Seidel et al., 2016). However, the changes in the spatial scales and arrangement of structural features within stands (and the

landscape) as a consequence of restoration treatments have received less attention (but see Bradshaw and Spies, 1992). This is at least partially due to the challenge of measuring spatial variability (e.g. Seidel et al., 2011), which has direct implications for management prescription and assessment, as we “only manage what we can measure”. For example, if foresters could simply quantify the degree of “old-growthness” (sensu Bauhus et al., 2009) they might be able to evaluate the influence of specific treatment components, e.g. whether artificial gaps successfully resemble old-growth structures, and modify restoration treatments accordingly.

To disentangle the complex spatial arrangement of plant material in forests, earlier studies recommended a multiscale-approach, and the assessment of stand-scale structural variability was identified as the most important task (e.g. Spies, 2004; O'Hara, 1998). From a practical standpoint, emphasizing stand-scale structural variability holds the best potential to actually lead to improved management practices, which are typically implemented at the stand scale.

One attempt to describe stand-scale structural variability comprehensively is the ‘old-growth index’ (Acker et al., 1998), which does not include spatial information. Even approaches that utilized spatial information (e.g. Zenner, 2000; McElhinny, 2002) do not comprehensively represent the three-dimensional structure of forests. Often structural measures are focused or limited to individual elements and are presented as statistical distributions, such as height or diameter distribution curves. Alternatively, approaches focused on variations in spatial relationships, such as distance between trees (e.g. Moeur, 1997) or were based on species composition, richness, or relative abundance (cf. review by McElhinny (2002)). So far, indices of structural variability are mostly lacking precise descriptions of the three-dimensional structure. Novel approaches that integrate spatial patterns in two dimensions have been used, i.e. by calculating mean information gain from photographs taken in different vertical angles to represent the canopy, stem, and ground vegetation (Witté et al., 2013). Early results were promising, but three-dimensional spatial distributions of vegetation cannot be obtained from this approach. Also, Zenner (2005) showed that reliable descriptions of structural pattern in Pacific Northwest's forests need to consider areas larger than 2500 m². Regardless of which indices or measures are used, conventional field measurements to acquire data that include detailed spatial information for large areas are very laborious.

Terrestrial laser scanning (TLS) has been used to describe the structure of forests (e.g. Van Leeuwen and Nieuwenhuis, 2010; Palace et al., 2016). Three-dimensional (3D) point clouds created from TLS measurements provide data that can characterize the 3D forest structure efficiently and in more detail than any other available method (Newnham et al., 2015). Earlier studies focusing on forest structure assessment via TLS were often based on multiple terrestrial scans that were combined to achieve the best possible 3D representation of the forest scene of interest (e.g. Raunonen et al., 2013; Seidel et al., 2013; Hackenberg et al., 2014). Hardiman et al. (2011) quantified three dimensional structural variability based on a measure named ‘rugosity’. Rugosity is defined as the standard deviation (in horizontal direction) of the standard deviation of the vegetation density along the vertical axis (cf. Hardiman et al., 2011, 2013). This required a method other than single or multiple terrestrial scans. To obtain data an operator walked along transects with the system constantly scanning in upward directions (hand-held mobile scanning).

The sampling approach of taking multiple measurements in single-scan mode is receiving greater and greater interest due to the reduced field effort and faster post-processing. In contrast to multiple-scan data, point clouds derived from single-scans are used as an independent data source (each scan is a sample,

assuming sufficient distance between sampling points) and they do not require time consuming co-registration during the field work and post-processing. Such co-registration efforts include the distribution of targets in the scene prior to scanning and semi-automatic registration of the coordinate systems into a single coordinate system defined by a “master”-scan during post-processing of multiple-scan approaches, which is necessary to enable real three-dimensional representations of scanned scenes. In contrast, single-scans can only provide information on what is visible from the scanners perspective. Hence, they can show high levels of “occlusion” that result in systematic biases (Van der Zande et al., 2008; Seidel et al., 2015; Ehbrecht et al., 2016). This can lead to problems for quantification of selected structural elements, such as crown volumes, but may be suitable for others, such as stand density. For example, single-scans were successfully used for the estimation of wood volume (Astrup et al., 2014), basal area measurement (Seidel and Ammer, 2014), stem mapping (Liang et al., 2012), and for assessment of vertical plant profiles (Calders et al., 2014).

In this study, we use single-scan data to calculate variables that reflect different structural elements and have a direct ecological interpretation. We evaluated whether multiple TLS measurements in single-scan mode have the potential to differentiate these structural elements in five stands with different stand conditions that resulted from contrasting management regimes. Furthermore, we investigated whether the single-scan approach can quantify differences in stand structures among plantations with different management histories and structural differences between these plantations and a nearby old-growth forest.

2. Methods

2.1. Study sites

Our study was conducted in the Willamette National Forest of Lane County, east of Eugene, Oregon, USA. We used two sites located on the western slopes of the Cascade mountain range. The first site was on Christy Flats, about 20 miles north of Highway 58 near Oakridge, (43.902781 N, -122.363822 W). It was part of the Young Stand Thinning and Diversity Study (YSTDS; see Davis et al. (2007) and Manning and Friesen (2013) for details), and dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the overstory with a small component of western hemlock (*Tsuga heterophylla* Raf.) and hardwood species. The forest was planted in the 1950s and ten to fifteen years later was pre-commercially thinned to 4 m spacing. Because of the homogenous structural properties in the early 1990s, the forest was included in the YSTDS to test whether different silvicultural management regimes can accelerate the development of late-successional structures in these plantations. At the time the forest was 35–45 years old, averaged 855–871 trees per ha and a basal area of 39.5 m² ha⁻¹. The forest was divided into four stands and each stand received one of four restoration treatments in 1996/7. These treatments included a heavy thinning, a light thinning, a light thinning with gaps and a control with no thinning (Manning and Friesen, 2013). Earlier analysis showed that the thinning operations successfully altered a variety of stand conditions, including canopy structures. For example, canopy cover varied strongly with treatment intensity (heavy thinning > light thinning with gaps > light thinning > control; cf. Puettmann et al., 2013a,b). Also, gap creation increased the variability in overstory cover distribution (Davis et al., 2007). In contrast, the vertical distribution of crown material (foliage height diversity, FHD) was unaffected by the thinning treatments five years after thinning (Davis et al., 2007). Since stand differences and similarities after treatment were already verified in earlier

studies that used conventional field based measures (e.g. Puettmann et al., 2013a,b), we used these four stands to evaluate the potential of the TLS-based approach for a description of stand structure.

The second site was located in the H.J. Andrews Experimental Forest, near Lookout Creek (44.229985 N, -122.217439 W). Here an old-growth stand on flat terrain, a critical factor for single-scan TLS, was identified. Based on data from five nearby permanent reference sites, the stand was dominated by Douglas-fir, with this species contributing 70% of the total basal area of $84 \text{ m}^2 \text{ ha}^{-1}$. The density of large, dominant Douglas-fir was 53 trees per ha, out of a total of 443 trees per ha. The age of the dominant Douglas-fir trees was estimated to be around 400 years. Fig. 1 provides a graphical illustration of the stand structures created by the treatments at the Christy Flats site as well as the old-growth stand at the H.J. Andrews site.

2.2. Data acquisition

In each stand we conducted 12 single-scan measurements with a Faro Focus 3D 120 terrestrial laser scanner (Faro Technologies Inc., Lake Mary, FL, USA). In each stand at Christy Flats we performed six scans on two transect lines, one of which always crossed the stand from the northwest to the southeast corner and the other was aligned northeast to southwest (see Fig. 2). The first scan on every transect line was positioned at least 60 m from the stand edge and the following scans were positioned every 100 m along the transects. After six scans we changed to the second transect line and repeated the procedure. This design lead to unbiased samples and ensured good coverage of the stands. For example, a rectangular sampling grid could provide biased results in the 'light thinning with gaps'- stand, as the gaps were also spaced in a rectangular grid pattern. Whenever a tree stem blocked

the exact position in the field we chose the closest available spot with sufficient space for scanning.

The old-growth stand had a different spatial layout. To ensure unbiased samples that are comparable with the samples from Christy Flats, we used a random number generator for distances (30–100 m) and azimuthal directions (180 steps of 1° from left to right of the current position to determine sampling positions. In one instance (after scan s9) where we reached the vicinity (closer than 50 m) of the stand boundary we reversed the transect direction by 180 degrees. The final sampling scheme is visualized in Fig. 3.

At each sampling point, we took GPS coordinates, positioned the scanner on a tripod at 1.5 m above ground and conducted a TLS scan with a field of view of 310 degrees in vertical direction and 360 in horizontal direction. The instrument was set to an angular step of 0.035 degrees at which laser beams with a wavelength of 905 nm were emitted. The distance to any object that reflected a laser beam was determined based on the phase-difference technology. All scans were performed during calm, dry weather conditions on April 14th (Christy Flats) and 15th (H.J. Andrews). At the time of the scans none of the five stands had any remaining snow pack on the ground or in the tree canopies. In contrast to earlier studies, which aimed to cover fixed "sample plot" areas (e.g. Seidel and Ammer, 2014) or single tree attributes within so called "TLS field plots" (Liang et al., 2016), we used all spatial information on the surrounding forest scene provided in the field of view of each single-scan, focusing on the distribution of plant material rather than on distinct plant characteristics like diameter or height.

2.3. Data processing- filtering

Each scan-file created by the instrument was imported to Faro Scene (Vers. 5, Faro Technologies Inc., Lake Mary, FL, USA) for

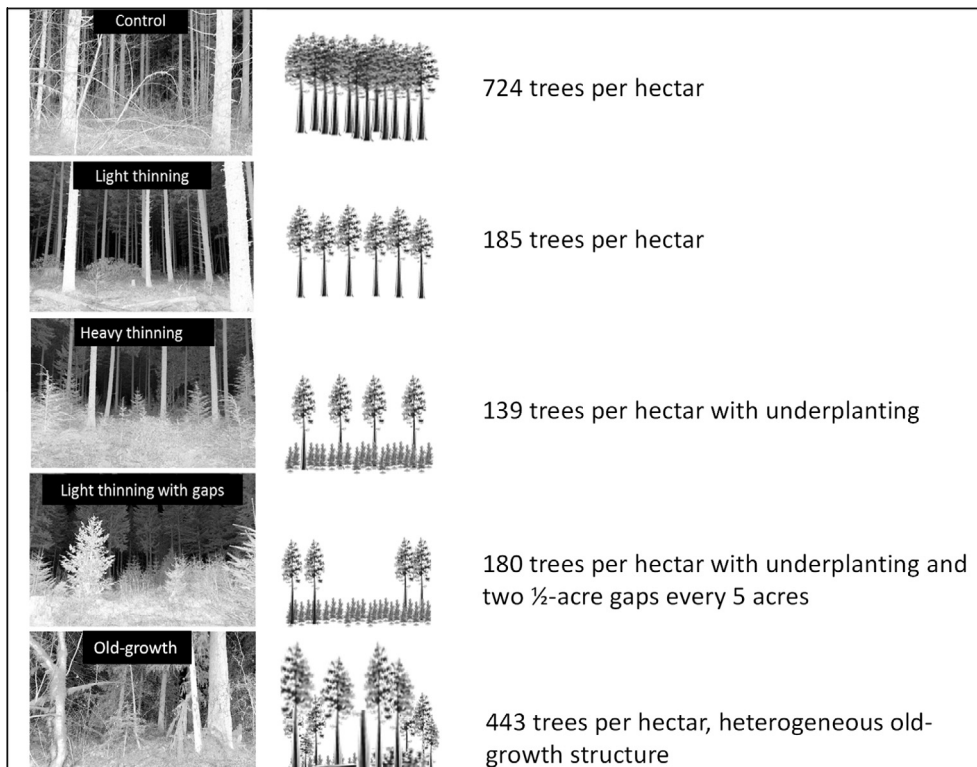


Fig. 1. 2-D representation of exemplary single-scans for each stand (left), corresponding schematic draft of the stand structure (middle; changed after Manning and Friesen, 2013) and description of the characteristic tree density for the differently treated stands (year 2006, after Puettmann et al., 2013a,b), including the old-growth stand with data from the H.J. Andrews reference site network (year 1995); (right).

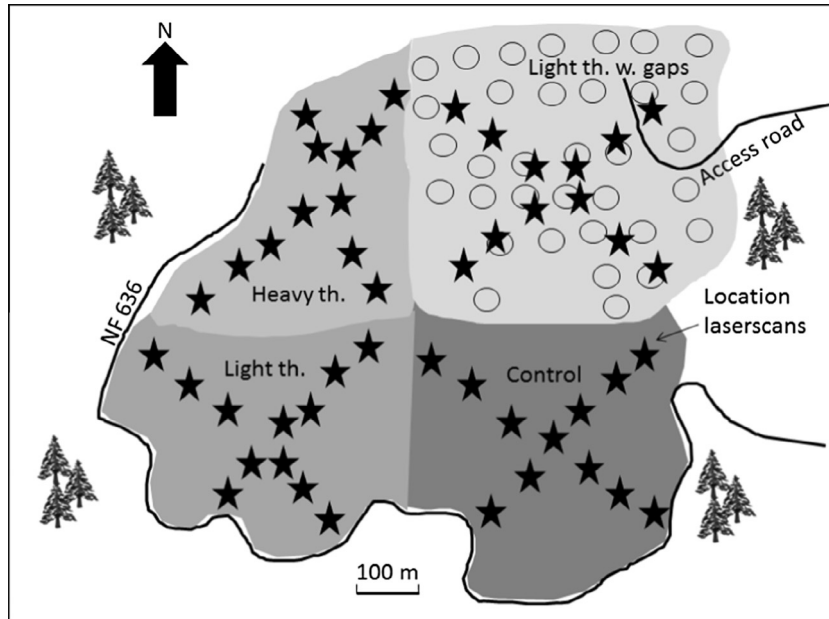


Fig. 2. Final sampling scheme at the Christy Flat site. The artificial gaps in the ‘light thinning with gaps’-stand are indicated by circles. The scan positions are marked as stars.

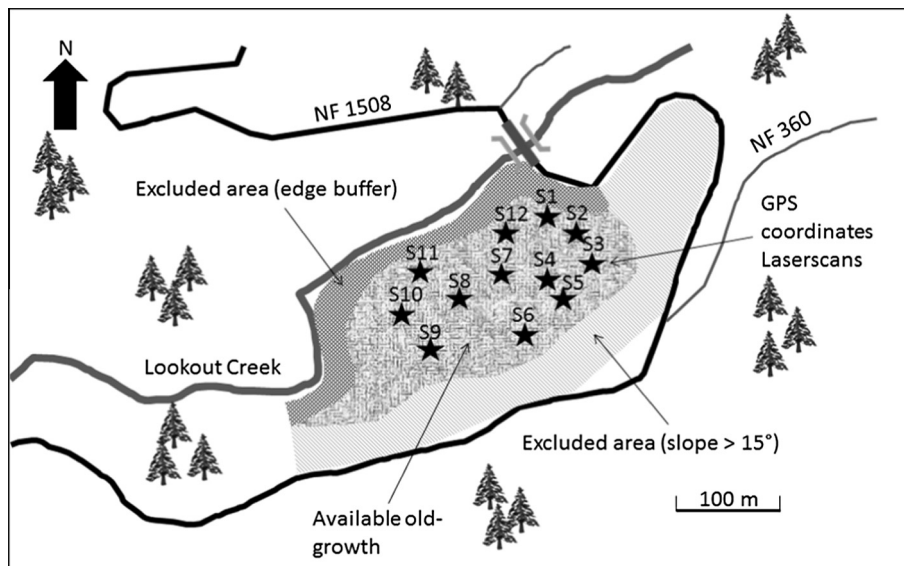


Fig. 3. Final sampling scheme in the old-growth stand located in the H.J. Andrews Experimental forest. The scan positions are marked as stars.

filtering. To eliminate erroneous measurements, we applied the standard filters as provided by the software (see Faro, 2004). This deleted all laser points that did not have a neighboring point within 2 cm and points with less than a predefined brightness value (here: 300). After filtering the point clouds were exported as xyz-files.

2.4. Data processing- single-scan based structural measures and their quantification

An algorithm written in Mathematica (Vers. 9, Wolfram Research, Champaign, USA) was used to calculate a list of variables (see Fig. 4) that describe vertical and horizontal stand structures and that we tested in regards to their usefulness for differentiating the five sampled stands.

First, to describe the overall density of the surrounding forest vegetation, we counted the total number of beams in the upper

hemisphere that were reflected by the surrounding forest (no. of hits in upper hemisphere). The upper hemisphere was used to ensure the measure describes the forest canopy and to avoid inclusion of ground returns or annual vegetation (herbs). This simple approach was possible without correction for slope effects as all study sites had only very minor inclinations (<5°).

Second, as a measure of variability in the vertical structure we calculated foliage height diversity (FHD). This measure has been related to habitat suitability, biodiversity and biomass growth (e.g. MacArthur and MacArthur, 1961; Hays et al., 1981; Stark et al., 2012). Based on vertical layers (1 m thickness) FHD and was calculated based on the formula:

$$FHD = -\sum_i h(i) * \ln(h(i)), \tag{1}$$

with $h(i)$ being the ratio of number of hits in layer i to the total number of hits in all layers. It is worth noting, that FHD is influenced

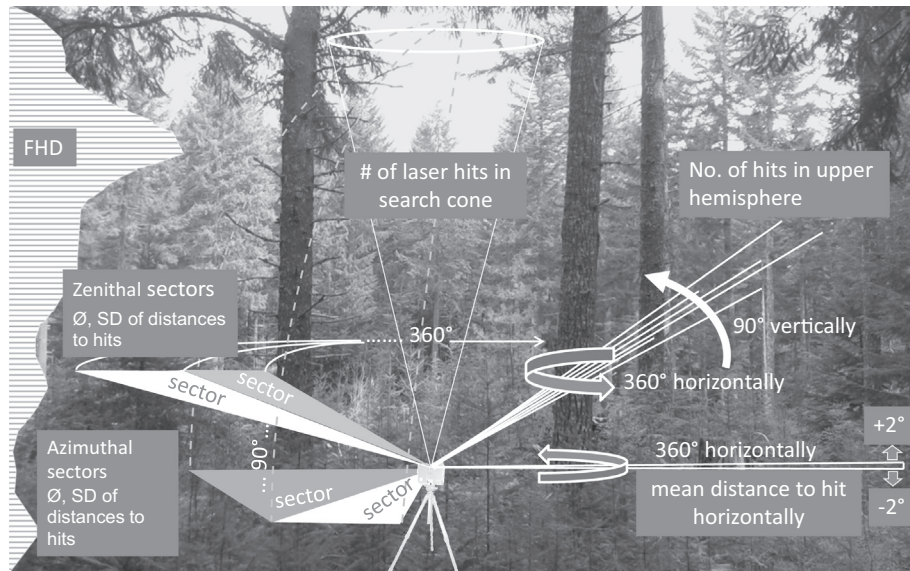


Fig. 4. Graphical visualization of the tested structural variables based on single-scan TLS.

by the relative amount of vegetation in each strata. This can lead to results where stands with every vertical layer filled may have higher *FHD* values than stands with distinct canopy layers that are separated by vertical gaps. This is not intuitive as a high diversity in filling of the vertical layers will not result in high but low *FHD* values. This is a carryover from the original work by MacArthur and MacArthur (1961), which was designed to quantify habitat diversity for birds. Based on their usage, it may be more intuitive to interpret stands with high *FHD* as providing more habitats throughout the vertical canopy profile than stands with low *FHD*.

Third, to characterize competitive conditions for regeneration, such as light regimes, microclimate, as well as potential growth and survival of tree regeneration (Howard and Newton, 1984; Jennings et al., 1999), we calculated the number of returns in a search cone with 60° opening angle facing the canopy (no. of hits in search cone; see Seidel et al., 2015). This variable has been shown to be a good predictor for the amount of available resources due to overtopping competition for plants in a specific location, in our case the scanner positions (Pretzsch, 2010; Seidel et al., 2015).

Fourth, we investigated the visibility in the stand, which is related to forest aesthetics (e.g. Ribe, 2009), flight paths and habitat suitability, e.g. for large raptors and large mammals such as deer, respectively, (e.g. Desrochers and Hannon, 1997; Tufto et al., 1996) as well as overstory density (e.g. Davis and Puettmann, 2009). It was calculated as the mean distance to the recorded hits in near-horizontal directions ($\pm 2^\circ$ above/below horizon).

Finally, we quantified the three-dimensional structure of the stand. Structural variability across spatial scales is considered an important variable for the assessment, conservation, or rehabilitation of ecosystems (e.g. Parrott, 2010). It is also considered a key attribute of old-growth forests (e.g. Van Pelt, 2007). We developed two algorithms that addressed the structural variability more holistically than previous measures. Specifically, we were interested whether the variation of our 3D characterization varied across spatial scales, as this relationship has been suggested to be an indicator of old-growth conditions (Seidl et al., 2012) and the complexity of forest stands (Puettmann et al., 2012). Finally, we tested whether our sampling was sufficient to use this information to differentiate structures of the different stands.

For this analysis, we treated the horizontal and vertical structural variability separately. The first algorithm, from here on referred to as *azimuthal sectors*, determined the mean (formula 2) of the distances to recorded hits (above scan horizon only, coordinates with $z > 0$) for predefined azimuthal sectors (similar to a piece of cake).

$$\frac{\sqrt{\sum_{j=1}^n (\{0, 0, 0\} - \{x_j, y_j, z_j\})^2}}{n} \quad (2)$$

with $\{0, 0, 0\}$ being the scanners position, $\{x_j, y_j, z_j\}$ being the Cartesian coordinates of a point j in a given sector and j ranging from 1 to the total number of points (n). We also calculated the standard deviation of these mean values.

This process was repeated for varying sector sizes. The size (span or angle) of individual azimuthal sectors ranged from 180°, 90°, 45°, 22.5°, 11.25°, 5.63°, 2.81° to 1.41°, resulting in 2, 4, 8, 16, 32, 64, 128 and 256 sectors, respectively. Thus, the range of spatial scales investigated was defined by sector size (angle) and not a fixed maximum distances to objects. The mean distances (per sector) were used to calculate the overall mean distance (per scan). To quantify how the variation changes across spatial scales, we calculated the coefficient of variation (CV) of the standard deviations of all sectors.

The second algorithm, referred to as *zenithal sectors*, used an identical approach, but sectors were bounded by two zenith angles (lower and upper angle = bands) with 360° horizontal extent. We used 2, 4, 8, 16, 32, and 64 sectors for the 90° vertical field of view (90–0° zenith angle), resulting in angle ranges of 45°, 22.5°, 11.25°, 5.625°, 2.8125° and 1.40625° per sector, respectively. A graphical visualization of the tested variables is given in Fig. 4. Again we calculated the coefficient of variation (CV) of the standard deviations of the distances to hits for each sector. We calculated the mean distances again for the vertical sectors but the results were only marginally different from what we found for the horizontal sectors (data not shown). Hence, we will only present the data for the horizontal sectors. Both, the azimuthal sectors and zenithal sectors are considered useful to quantify structural characteristics associated with old-growthness (Van Pelt, 2007; Seidl et al., 2012).

2.5. Statistical analysis

Our inference scope is limited to determining which structural measures are able to distinguish the five investigated stands. We do not claim that our data and these stands are representative for the respective stand types, as our sample size for stand type is only $n = 1$. Thus, we did not test whether general differences among stand types exist. To a large part, this work has already been done in earlier studies that showed significant differences in various measures between the stands that received different restoration treatments (e.g. Davis et al., 2007; Davis and Puettmann, 2009). We will refer to those results whenever necessary for interpretation of our results. Our intention was to evaluate the potential of various measures based on terrestrial laser scanning data in single-scan mode to differentiate among stands that we know actually differ in structure. In addition, we also test the potential of the single-scan technology to provide information about the degree to which the treated stands mimic the structure of an old-growth stand in the region.

We used the software 'R' (R Development Core Team, 2008) to perform analyses of variance (ANOVA) with Tukey post hoc tests to identify whether the means of the variables from the twelve scans per stand differed among the studied stands. Pairwise t-tests were used to reveal significant differences in means based on a significance level of $p < 0.05$. Shapiro-Wilk tests were performed to test for normal distributions of the variable values (significance level of $p < 0.05$). For normal distributions, we then used two-sample F-tests to identify whether the variances from the twelve scans per stand varied between the different stands ($p < 0.05$), which we interpreted to indicate differences in structural variability. In case of heterogeneity of the variances ANOVAs were conducted with the Kruskal-Nemenyi post hoc test (only in case of azimuthal sectors).

3. Results

The overall vegetation density was higher in the two unmanaged stands (old-growth (OG) and control (C)) than in the thinned stands (heavy thinning (HT), light thinning (LT) and light thinning with gaps (LTwg)); see Fig. 5). The variability in vegetation density of the C, LTwg and OG stand were not significantly different. However, these three stands showed significantly higher variability than the two conventionally thinned stands (HT and LT).

The foliage height diversity (FHD), was significantly lower in the old-growth stand than in the control (C) and in the LT stand, indicating a higher structural variability (lower diversity value = structural variability value, cf. 'Methods' chapter) in the old-growth stand. The planted forests (C = LTwg = LT = HT) did not differ in terms of average FHD. Furthermore, only the variability of the OG stand was significantly different from all other stands (see Fig. 6).

The competitive conditions for regeneration, quantified as number of hits in the search cone, were similar in all stands. Only the mean competitive conditions in the old-growth stand were significantly higher than in the LTwg stand (Fig. 7). The LTwg and OG stands had similar variability, which were significantly higher than in the C, HT and LT stands. Also, the heavily thinned stand (HT) had a higher variability than the LT stand.

The visibility in the stand, as reflected in the average distance to a hit in horizontal directions was significantly shorter in the old-growth stand than in the LT, LTwg and C stands. The highest average visibility was found in the LT stand, where it was significantly higher than all other stands, except in the LTwg. The HT, C, and LTwg stand had similar average visibility, with the values being intermediate between the OG and LT stand. The variability in distances to hits in all four tested planted stands were similar, but significantly larger than in the old-growth stand (see Fig. 8).

The horizontal variability in stand structure, as reflected in the coefficient of variation calculated for the different azimuthal sectors (based on the standard deviations of distances to hits) was similar in terms of patterns and magnitudes in the four planted stands. A slight trend towards higher CV values, and therefore higher structural variability, can be seen in the thinned stand with gaps only for intermediate sectors sizes. The horizontal variability in stand structure in the old-growth stand appeared generally and consistently higher across all spatial scales (sector sizes, see Fig. 9).

The second measure of horizontal variability, i.e., the average distance to a hit in the azimuthal sectors showed a different trend. This measure ranked the stands in the following order (short distances to large distances): $OG < C < HT < LTwg < LT$ (see description of Fig. 10 for significant differences). This pattern was consistent across sector sizes.

The vertical variability in stand structure, as reflected in the standard deviation of distance to hits across zenithal sectors, was lowest in the control stand (Fig. 11). The variabilities in vertical structure for all the thinned stands were higher than the control. The CV of the standard deviations appeared to be little influenced by sector sizes for all these stands. However, the old-growth stand

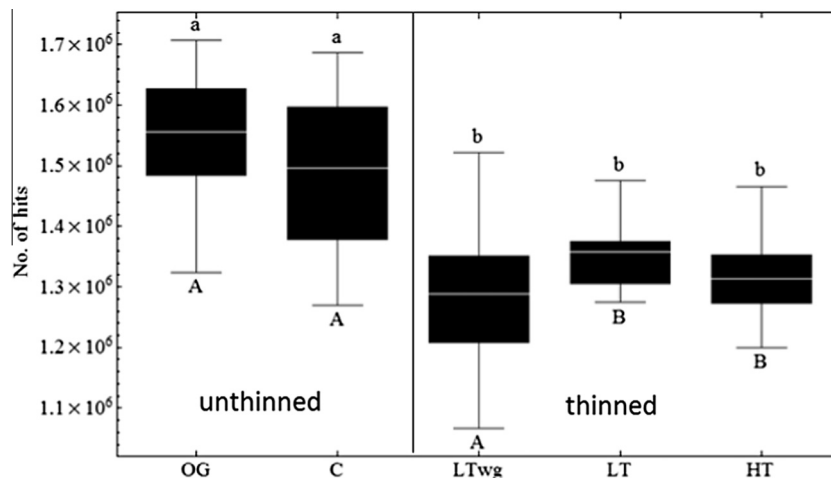


Fig. 5. Box-and-Whisker plots showing the number of hits recorded in the five different stands. Different lowercase letters indicate significant differences between the means of the stands at $P < 0.05$. Sample size was $n = 12$ for each stand. Means are indicated by horizontal markers. Different uppercase letters indicate significant differences in the variability.

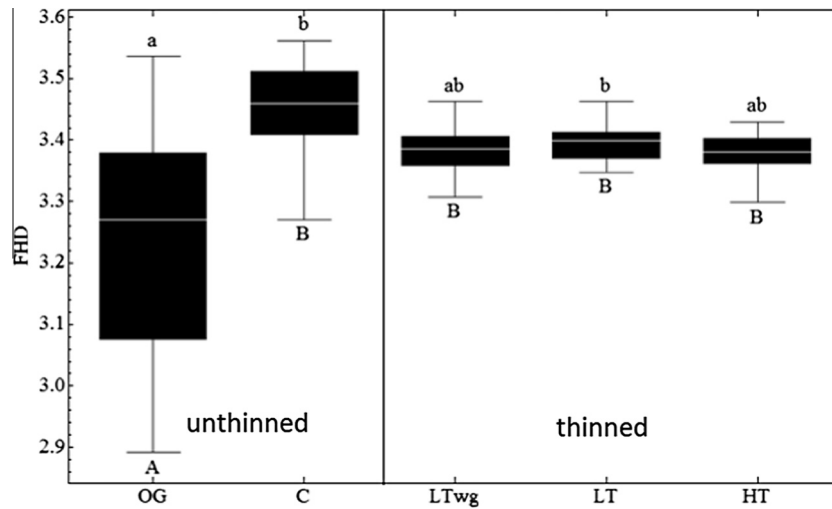


Fig. 6. Box-and-Whisker plots of foliage height diversity. Different lowercase letters indicate significant differences between the means of the stands at $P < 0.05$. Sample size was $n = 12$ for each stand. Means are indicated by horizontal markers. Different uppercase letters indicate significant differences in the variability.

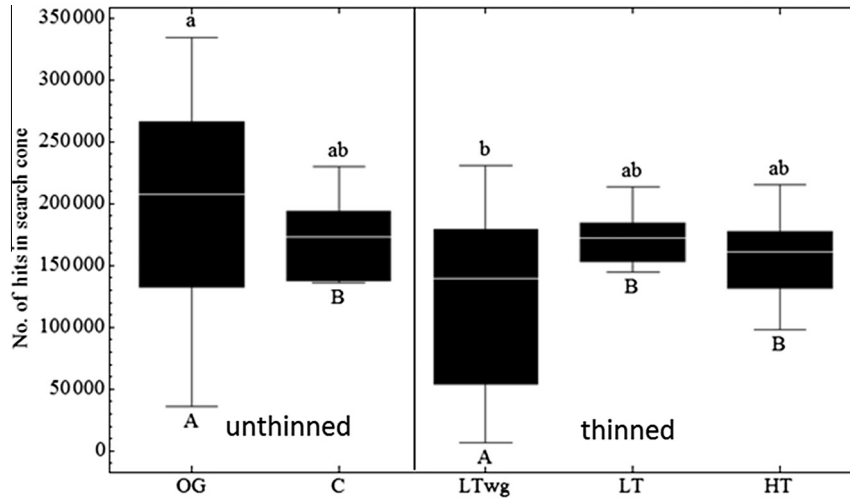


Fig. 7. Box-and-Whisker plots of the number of hits detected in a search-cone (over the scanners position with an opening angle of 60°) for the five investigated stands. Different lowercase letters indicate significant differences between the means at $P < 0.05$. Sample size was $n = 12$ for each stand. Means are indicated by horizontal markers. Different uppercase letters indicate significant differences in the variability.

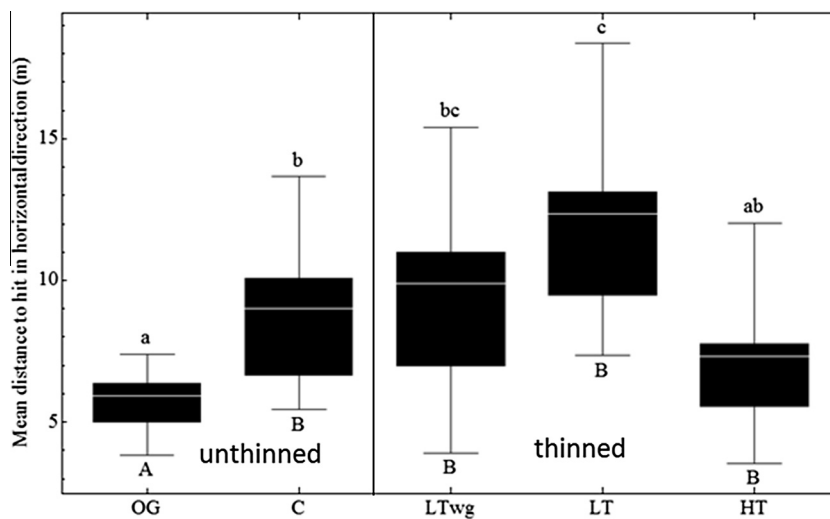


Fig. 8. Box-and-Whisker plots of the mean distance to a hit detected in horizontal directions of $\pm 2^\circ$ (scanner's height above ground; 1.3 m). Different lowercase letters indicate significant differences between the means at $P < 0.05$. Sample size was $n = 12$ for each stand. Means are indicated by horizontal markers. Different uppercase letters indicate significant differences in the variability.

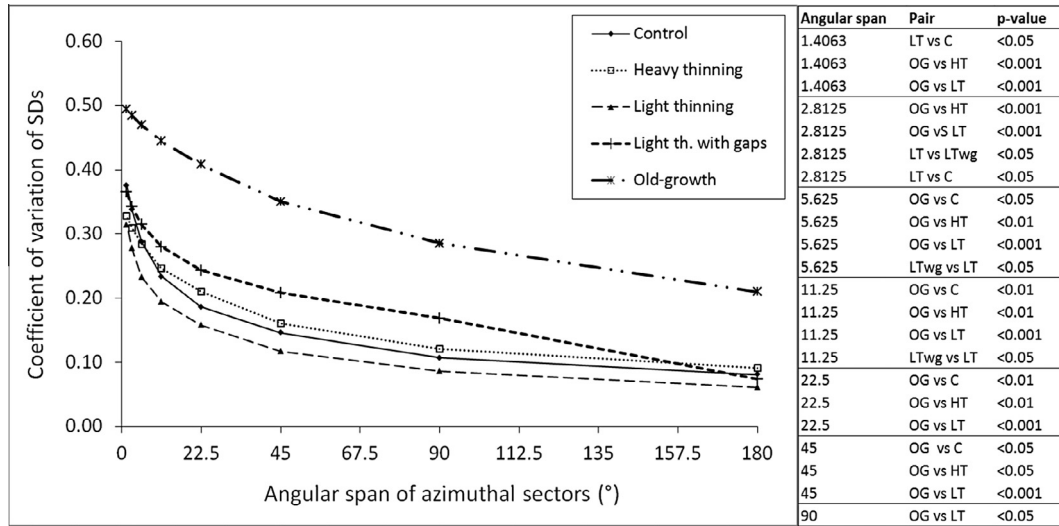


Fig. 9. Left: Coefficient of variation (CV) of the standard deviations of distances to a hit within azimuthal sectors of varying sizes. Shown are the mean CVs for all 12 scans per stand. Right: Significant differences for each angular span and corresponding p-values.

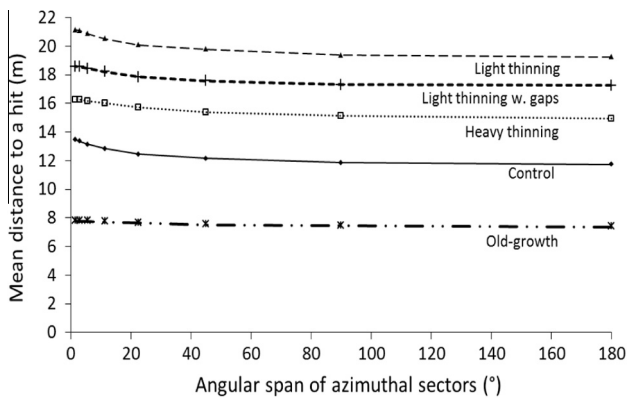


Fig. 10. Mean distance between the scanner and a hit averaged for all 12 scans per stand and shown for the eight different (azimuthal) sectors sizes tested. Means in all stands were significantly different from the mean in the OG stand (for all angular resolutions). Furthermore, for all resolutions means of LT and LTwg were significantly different from C and OG, and LT was significantly different from HT.

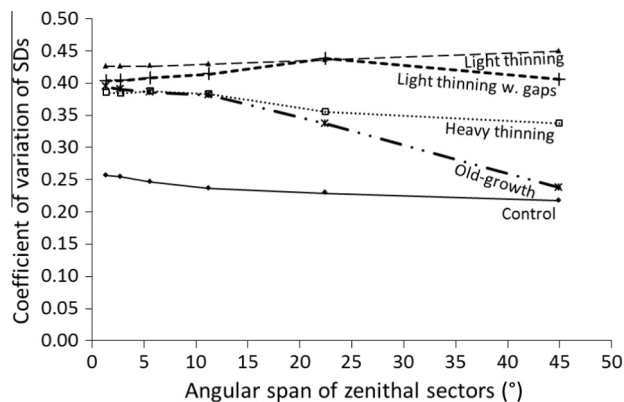


Fig. 11. Coefficient of variation (CV) of the standard deviations of distances to a hit within zenithal sectors of varying sizes. Shown are the mean CVs for all 12 scans per stand. While the mean in C was significantly lower than in all other stands for angular resolution up to 11.25°, it was not lower than the mean in the OG and HT for 22.5° and 45°. Additionally, OG and LT as well as LTwg differed significantly for the largest angular span.

showed a different trend. Here similar levels of variation as in the thinned stands were found when small vertical sectors (up to 10° angular span) were used. As vertical sector size increased, the variability among these sectors in the old-growth stand dropped, basically reaching control levels at the largest sector size.

4. Discussion

Our case study suggests that multiple single-scan TLS measurements can be used to differentiate different structural elements in a variety of forest conditions. While we did not cover the full suite of structural development (e.g. as described by Franklin et al. (2002)), our sampling stands included even-aged forests with different management histories and an old-growth stand, i.e., covered conditions relevant to silvicultural treatments, such as variable density thinnings, that are of global interest (Gustafsson et al., 2012; Puettmann et al., 2015). Quick and efficient quantification of structural variability (also labeled structural heterogeneity (e.g. Zenner, 2000), or “old-growthness”, sensu Bauhus et al., 2009) is key for inclusion of structural variability into forest inventories, which then can provide the basis for forest planning and assessment of treatment impacts. Similarly, being able to efficiently measure structural variability is important in research settings, e.g. for large scale assessments whether stand structure and its variability could be used as an indicator for various aspects of biodiversity (Van Den Meersschaut and Vandekerckhove, 1998; Neumann and Starlinger, 2001; Zenner, 2005) and associated evaluations of protection priorities or certification decisions (e.g. Löhmus and Kraut, 2010). Our results suggest that transects of single-scan TLS plots with around 44 million laser beams for each scan captures sufficient area and detail to facilitate quantitative descriptions stand structures. The following discussion provides more detail about the strength and weaknesses of our measurement approach to distinguish the sample stands in terms of various elements of stand structures and the ecological and management implications of our findings.

4.1. Overall stand density

The single-scan approach used in this study appeared to be able to reflect differences in stand density, as impacted by past thinning operations. Furthermore, earlier measurements showing that tree

densities were inversely related to understory cover (Puettmann et al., 2013a,b) in our stands, allowed us to separate different stand structural components. For example, the total number of hits in our stands appeared to be driven by the presence of tree stems, rather than understory vegetation. Despite large differences in tree heights between the old growth and the younger stands, our results did not follow this pattern. We hypothesize that other aspects of stand structure may have outweighed the height effect. In our case, the density of dominant trees was much lower in the old-growth stand compared to the younger stands and the prevalence of mid-and understory vegetation in this stand may have prevented beams from reaching many of the tall crowns (cf. Fig. 10).

Our results also suggested that including gaps in thinning treatments appears to have created old-growth-like structural variability, at least as reflected in terms of variability of stand density. However, the lower average density in the LTWg stand may be indicative of the “artificial” nature of the treatment. Specifically the prescription that not a single tree was left inside the gaps resulted in many emitted beams not being intercepted when sampling points were in the gap or near the gap edge. Natural gaps of younger (Lutz and Halpern, 2006) and older stands (Spies and Franklin, 1989) do not display such a sharp, distinctive circular boundary, and this may be reflected in the old-growth stand. The impacts of gaps on a variety of ecosystem processes and functions have been documented globally, e.g. Muscolo et al. (2014) and Zhu et al. (2014). In the Pacific Northwest, gaps have received special attention by managers due to their impact on wildlife, specifically on spotted owl (Forsman et al., 1982) and songbird populations density (Hagar and Friesen, 2009; Yegorova et al., 2013). Our results suggest the assumption by managers that the drastic and complete density reduction inside gaps accelerates development of old-growth conditions (e.g. Cissel et al., 2006) may not be true. This complete removal may explain negative effects of such gaps as found, e.g. for selected songbirds or flying squirrels (Desrochers and Hannon, 1997; Steventon et al., 1998; Manning et al., 2012; Yegorova et al., 2013).

The findings that both the average and variability in number of returned hits were similar for e.g. old-growth and the control young stands, showed the limitations of our sampling method. The approach is unable to distinguish few giant tree stems from large numbers of small stems, since the approach is not object based. This is not necessarily a flaw but whenever conventional definitions of old-growthness are considered, features such as giant trees are important (Van Pelt and Sillett, 2008). We further hypothesize that our results are due to the inability of the used approach to distinguish between stems and foliage. The variability in the presence of leaning and downed dead wood close to scan positions, as indicated by Puettmann et al. (2013a,b), may have resulted in remarkable differences in beam interception among the different scanner positions.

4.2. Vertical stand structure

Our data confirmed the findings from earlier studies (Davis et al., 2007) that used conventional tree crown and height data to show that *FHD* was not influenced by the thinning treatments. Even though our data included understory vegetation and were sampled 18 years after thinnings were applied, it appears that *FHD* is not very sensitive to restoration treatments. More detailed measurements of crowns of trees growing adjacent to gaps showed that crown dynamics are not quickly responding to changes in growing conditions (Seidel et al., 2016, see also Wilson and Oliver, 2000). At the same time, our data suggests that none of the applied treatments was yet able to mimic the vertical structure of an old-growth forest after 18 years.

Our high resolution analysis also points out idiosyncrasies when using *FHD* as e.g. a predictor of species diversity. High *FHD* values are typically interpreted as being indicative of forest with a high variability in vertical canopy structure (e.g. Berger and Puettmann, 2000). In contrast, our results show that the choice of layer height (scale) may influence the results to the point where the above listed interpretation is questionable. Higher vertical homogeneity (by itself intuitively an indicator of lower diversity) of canopy structures may impact the *FHD* to the point where stands with single canopy layers (this study) have higher *FHD* values than vertically homogeneously filled tropical stands (Hunter, 1990). These findings suggest that comparisons of *FHD* in stands with very different structures, e.g. different tree heights or should be viewed with caution. Further research is needed to overcome this limitation, e.g. how different layer thicknesses (Erdelen, 1984) and other differences among stands influence *FHD* values. More detailed analysis in our study (data not shown) confirmed that the lower *FHD* values of old-growth stands are indeed mostly due to the fact that on average vertical structures are more homogeneously filled than in the younger stands. Furthermore, the variances in *FHD* across the twelve samples per stand highlight the higher structural variability in old-growth stands. The thinning treatments, as applied in our study stands, were apparently not suited to fully represent the horizontal and vertical structural variability in the short term. Distinguishing different aspects inherent in *FHD* and understanding the variability in stand structure can be useful to fine-tune management for specific ecosystem functions and services, such as habitat suitability for insects (e.g. Tanabe et al., 2001), vertebrates (e.g. MacNally et al., 2001), or flight paths, that may be critical for wildlife species (Smart et al., 2012). The fact that gap creation in thinning operations does not have the same structural impact as natural gaps, which was shown in terms of overall stand density (see above), was also evident in the *FHD* data.

4.3. Competitive conditions for regeneration

Using TLS data to quantify vegetation in a search-cone (sensu Pretzsch, 2010) as an indicator of overtopping and thus competitive condition for low growing vegetation, including tree regeneration, revealed that on average the stands differed fairly little. Apparently, any impacts of past treatments or even differences between young and old-growth stands averaged out across the stands, at least in terms of growing conditions for understory vegetation, seedlings, and saplings. This contrasts with lots of evidence that showed that in the short term (e.g. within a decade) the overstory cover after thinning is lower than pre-thinning or in control stands (e.g. Chan et al., 2006; Brandeis et al., 2001; Davis et al., 2007). Accordingly, this was reflected in increased number and growth of tree seedlings and saplings. Other understory vegetation, specifically tall shrubs, suffered physical damage during the harvesting and their recovery was not necessarily reflecting the increased resource levels available to them after thinning (Puettmann et al., 2013a,b; Olson et al., 2013). It appears that 18 years after the thinning entry, such initial differences in over- and thus understory conditions are not detectable anymore, even though single-scan TLS provides a large amount of data for this measure, in contrast to e.g. moosehorn measurement (Davis et al., 2007) or ocular “bubble cover” data (Brandeis et al., 2001). An earlier study of the thinning treatments in the Christy Flats showed that the differences among canopy cover (a variable that is closely related to gap fraction) already were shrinking five years after treatments implications (Davis et al., 2007). In contrast to structural differences, impacts of thinning on vegetation composition may linger longer (Lindh, 2004). Again, just like the previous two variables (density, canopy naturalness), the search-cone data confirmed that light thinning with gaps created conditions that

were on average less similar to the old-growth stand than those found in the conventionally thinned stands or in the control.

On the other hand, the variabilities across scans in the conventionally thinned stands (HT, LT) suggested that the thinning homogenized stand structures. The larger range of conditions in the old-growth and LTwg stands are likely reflected in higher variability in understory vegetation (e.g. Spies and Franklin, 1989; Gray and Spies, 1997) and tree regeneration (Kobe and Coates, 1997; Dodson et al., 2014). While the average light availability might be low in an old-growth stand (high mean in Fig. 7), this distinct variability or patchiness ensured the presence of areas with open conditions that enable establishment and growth of early seral vegetation, including tree regeneration (e.g. Kneeshaw and Bergeron, 1998; Abe et al., 2002). Such variability in understory conditions can be important for a variety of ecosystem processes and services, including habitat for selected animal species, such as macropods (Lunney and Ashby, 1987) or reptiles (Lunney et al., 1991), snow accumulation and melting patterns (Hedstrom and Pomeroy, 1998).

4.4. Visibility in the stand

The horizontal visibility in the stands clearly reflected understory more than overstory vegetation. A dense understory that was less developed in the control, but developed after the light and heavy thinning treatments as suggested by the trends in Davis and Puettmann (2009) and Puettmann et al. (2013a,b), was likely responsible for the visibility (in horizontal direction) trends in these stands. The findings in the LTwg stand further supported the hypothesis that understory vegetation was mainly responsible for the horizontal visibility. The two extremes in these stands included extremely low visibility in the dense vegetation areas within the gaps, and high visibility in the rather open understory conditions in the remaining thinned stand. Again, the inability of our approach to distinguish between stem and foliage may be reflected in the low visibility in the old-growth stand, where the low distance to hits was likely influenced by the large number and dimension of tree stems in combination with fallen trees and dense patches of understory vegetation. This pattern was fairly consistent in the old-growth stand as the variation of distance values among the sample points was significantly lower than the variation in any of the planted forests. Thus, in these conditions, the single-scan TLS approach may be quite useful as a replacement for traditional field measurements of vegetation density (e.g. Griffith and Youtie, 1988; Saunders and Puettmann, 1999). Our methods thus allows for efficient quantification of habitat conditions, such as flight paths (Smart et al., 2012), hiding cover for large (Smith, 1987) and small mammals (Maser et al., 1979). Further research may be necessary to relate such measurements of visibility in a stand to other ecosystem services, such as the perceived forest scenic beauty (Hull et al., 1987; Ribe, 1990, 2009).

4.5. Three-dimensional structural variability

The analysis of the *azimuthal sectors* that span a vertical field of view of 90 degrees ranked the stands according to the expected result that old-growth stands have the highest horizontal structural variability (Franklin and Van Pelt, 2004). High structural variability across spatial scales, as found in these stands (see also Franklin and Van Pelt, 2004), is fundamental for the maintenance of biodiversity (e.g. Noss, 1999; Wilson and Puettmann, 2007). For example, tree level structural complexity is related to the richness of invertebrate species (Majer et al., 1997) while structural variability on a larger spatial scale, e.g. differences between gaps and stand interiors, can support distinct vegetation (Fahey, 2006), bird (Yegorova et al., 2013) and insect communities (e.g.

Doherty et al., 2000). Earlier studies also argued that the exposure to disturbance agents on different spatial scales may impose demographic contrasts between plant populations (Parker et al., 2001) which may also support stand level biodiversity.

The trend of constant mean values of the distances to a hit (~8 m) regardless of sector (sample) sizes reflected a pattern considered typical for Douglas-fir dominated old-growth forests (Franklin and Van Pelt, 2004): large structural variations (CV of standard deviations; 0.5–0.21 depending on sector size) and a distinct homogeneity in horizontal heterogeneity, which could be interpreted as scale-independency of horizontal heterogeneity. These patterns are considered a result of what has been labeled 'horizontal diversification' during stand development (Franklin et al., 2002; Van Pelt, 2007). This late stand development phase is characterized by pattern of gap formation and consecutive filling of gaps with understory trees that persist (e.g. Oliver and Larson, 1990; Franklin et al., 2002; Van Pelt, 2007).

In contrast to some of the other structural measures tested above, the horizontal heterogeneity of the LTwg stand was most similar to the old-growth stand for the majority of sectors sizes (also see Fig. 10). Such contrasting findings highlight that none of these variables should be interpreted in isolation. Also, any management practice, such as creating gaps, will likely accelerate the development of selected structural elements or measures, while at the same time not impacting or reversing development of other structural elements.

The interpretation of the results from the analysis of *zenithal sectors* is not straightforward as plants from all heights are represented in the results in varying proportions, which is in contrast to the *azimuthal sectors*, where vegetation elements are always included over their full visible vertical extent. Canopy foliage, stem, and understory vegetation of different individuals are included in the *zenithal sectors*. Most conventional measures and other TLS studies assessed vertical structures not based on *zenithal sectors*. Instead, they sort the vegetation into parallel horizontal layers, for example to determine the canopy shannon index (Stark et al., 2012), to derive relative vegetation profiles (Palace et al., 2016) or foliage height diversity (MacArthur and MacArthur, 1961; Hays et al., 1981). We chose zenithal sectors because they represent plot-focused results (around the laser location) and because "layered" approaches suffer from a lack of comparability (cf. chapter 4.2; see also Parker and Brown, 2000).

The *zenithal sectors* analysis showed that planted forests exhibited fairly constant variability as sector sizes increased. In contrast, the variability in old-growth stand decreased with increased sector sizes. Such trends can result from different patterns in vertical heterogeneity. In the thinned stands, the findings reflect the more concentrated distribution of plant material, i.e. similar height of all trees, as opposed to several canopy heights in the old-growth stand. The unique three dimensional pattern in old-growth stands, i.e., high vertical heterogeneity at small spatial scales vs. vertical homogeneity at larger spatial scales, can be described as 'scale-dependent zenithal variability'. We hypothesize that these patterns are developing in the 'vertical diversification' phase during natural stand development (Franklin et al., 2002; Van Pelt, 2007). Such patterns require fairly homogenous vertical plant material distribution with varying tree heights, and the presence of understory vegetation, conditions that are considered typical for Douglas-fir dominated old-growth forests (cf. Spies and Franklin, 1991; Van Pelt, 2007). Hence, the combination of vertical and horizontal structure analysis based on single-scan LiDAR measurements appears to be able to identify patterns unique to the old-growth stand. The findings for the unmanaged control stand further supports this hypothesis. The homogeneous tree height in the control stand would result in homogenous values across different *zenithal sectors*. In these stands, a single canopy height is detected in all but

the lowest sectors (if sector sizes are very small) and hence variations are small along different zenithal zones, a finding supported by the foliage height diversity (FHD) data. Methodologically, our sector-based analysis is a single-scan adapted derivative of the rugosity index (Hardiman et al., 2011). Rugosity is based on the same idea, namely measuring the variation of the standard deviation of a structural measure. However, our less laborious single-scan sampling approach does not allow calculation of rugosity (sensu Hardiman et al., 2011) due to the shadowing effect (e.g. Seidel and Ammer, 2014), but appears to provide a meaningful alternative.

5. Conclusions

Our study showed that single-scan based sample schemes can provide useful information about different elements and measures of stand structures. The method was able to distinguish stands in terms of various structural elements that are relevant for a variety of ecosystem goods and services. Also, our study showed that not all structural elements develop in sync and thus using only a single variable/measure may not be sufficient to understand stand dynamic trends. Clearly, each variable has strengths and weaknesses in terms of what structural aspects (and associated ecological principles) are best reflected and this needs to be considered in the interpretation of study results. Our results suggest utilizing multiple variables from single-scan data for a more holistic understanding, especially since these multiple calculations are efficiently done on the computer, without the need for more expensive field sampling. This can be especially helpful when variables reflect structural elements that are of high conservation or management interest, e.g., visibility or fly ways for spotted owl habitat in the Pacific Northwest.

Even without a direct comparison with conventional measures and an occlusion bias, our results show that the single-scan based sampling approach can represent the three-dimensional stand structure sufficiently to distinguish a variety of different stand conditions. This is important for restoration efforts, as the question how to restore older forest habitat in areas dominated by plantations is discussed globally (e.g., Gustafsson et al., 2012; Puettmann et al., 2015). Also, our results show that TLS can provide data that simultaneously enables for objective measurements of various stand characteristics and suggest that TLS can replace lengthy field sampling methods. However, further research is needed to fully understand the linkage between variables calculated from single-scan TLS measurements and ecosystem processes and services (Hunter, 1998).

A more holistic approach to quantification of horizontal and vertical forest structures (Figs. 9 and 11), namely the sector-based analyses, showed that dimensions of individual objects were not as important as their spatial configuration, even though dimension and spatial configuration are related to one another. Putting the emphasis in terms of variable calculation on the structural configuration instead on individual dimensions allowed us to evaluate whether old-growth structures (their spatial configurations) can be resembled in younger stands, despite differences in stand age and tree height and diameters. Thus, the single-scan TLS may be able to provide efficient measures that can guide silvicultural decisions when managing for selected stand structures. For example, despite the small sample of stands, our results suggest that “soft gaps”, i.e., gaps with fuzzy edges and/or trees of different sizes left inside the gap, may appear to better reflect old-growth conditions than gaps as currently implemented (i.e., hard, often circular edges with no trees remaining in the gap). Thus, we propose that single-scan TLS provide efficient opportunities to integrate structural information in decisions about conservation, preservation, certification (e.g. FSC) and rehabilitation projects.

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