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How neighborhood affects tree diameter increment – New insights from terrestrial laser scanning and some methodical considerations

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ABSTRACT

In an even-aged mono-specific stand we evaluated the use of unclassified point clouds from single- and multiple-scan terrestrial laser scanning as a tool to determine various attributes of growing space and neighborhood structure of fifteen *Metasequoia glyptostroboides* (Hu.) trees. It was found that almost all tested attributes were related to diameter increment at breast height (D_i) of the target tree, but also to diameter at breast height itself (DBH). A comparison of various additive models that accounted for the additional explanatory power of attributes other than DBH revealed that measures of space filling were most suitable estimators of D_i. Upside-down search cones fixed at low heights in the stand performed best to explain D_i, which is in contrast to previous studies that recommended the use of search cones fixed at greater heights in the tree. Surprisingly, we found search-cones fixed at 60% of the tree height to be more closely related with diameter increment at that height (D_i60%) than with D_i.

Furthermore, our study revealed that multiple-scan based measurements of space filling in the neighborhood of a tree should always be favored over single-scan measurements due to their generally higher quality and greater comprehensiveness in the representation of a forest scene.

1. Introduction

Modern silviculture is undergoing a change in management paradigm by focusing on the provision of a wide range of ecosystems services while improving ecosystem resilience and stability at the same time (e.g. Ammer and Puettmann, 2009; Puettmann et al., 2013). As a consequence, one main goal of today's forest management in Central Europe is the conversion of mono-specific forest stands into mixed stands (Schraml and Volz, 2004; Knoke et al., 2008). In mixed forests competition for resources, e.g. light, water or nutrients, and the related processes that affect tree growth are different from those occurring in monocultures (e.g. Forrester, 2013). In pure stands trees respond much more similar to competition and disturbances than in mixed stands where the tree species differ in demand and efficiency of resource use. In diverse neighborhoods growth patterns of the trees are altered by the more complex dynamics taking place when several species are involved in the forest community (Metz et al., 2013; Pretzsch, 2014). This was found for the root system of trees (e.g. Beyer et al., 2013) and also holds notably for the tree crown. In mixture with other species trees were found to change typical architectural attributes of the crown, e.g. branching pattern (Bayer et al., 2013), the general shape of the crown (e.g. Seidel et al., 2011) and even the overall biomass allocation and growth efficiency (e.g. Pretzsch and Schütze, 2005). These changes can be related to the amount of light available which is the most important resource trees compete for in a forest canopy (e.g. Valladares and Niinemets, 2008).

Direct measurements of light at specific points in the canopy are difficult to conduct as they require canopy access. However, the availability of light is related to the amount of growing space a tree can occupy in its direct vicinity (e.g. Biging and Dobbertin, 1992). This is why growing space was often used as a proxy for light (e.g. Canham et al., 2004, Sinoquet et al., 2001). Canham and colleagues differentiated between 'shading', describing the sole effect of the neighbor in terms of light, and 'crowding' which is the remaining effect of "(...) belowground competition and physical, aboveground inhibition of crown development" (Canham et al., 2004, p. 779). Above-ground, the combined effect of shading and crowding can be quantified from measurements of the actual presence or absence of plant material based on a simple rule: if biomass is present at a certain position there is no growing space available for a competing tree and vice-versa. This dichotomy (space occupied/unoccupied) has a distinct three-dimensional character which has also been difficult, if not impossible, to access directly in the

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past. Therefore indirect measurement approaches have often been used. Today direct measurements of space occupation in forest canopies are possible through terrestrial laser scanning (e.g. Seidel et al., 2013). However, we are not aware of studies that have used terrestrial laser scanning (TLS) for measuring the three-dimensional configuration of a forest patch or tree group in direct relation with tree growth or architecture. Sinoquet and Rivet (1997) used 3D digitizing devices to address tree architecture in detail but without relating it to the tree neighborhood.

Previous studies usually relied on point clouds of tree individuals that have been selected manually from the point cloud of the forest. Such single-tree point clouds have been used as input for voxel models (Metz et al., 2013) or were converted into a geometrical tree model with the intention to provide data on branch diameters, solid wood volume or other selected attributes (e.g. Côté et al., 2009; Dassot et al., 2012). Côté and colleagues (2009) successfully used detailed 3D-tree architectural models obtained from TLS to model light and radiation regimes in forests but did not relate the findings to tree growth measurements, competition or neighborhood situations. Most studies that used unclassified point clouds focused on the light regime, canopy gap fraction (and openness) or measurements of leaf area in forest stands (e.g. Danson et al., 2007; Huang and Pretzsch, 2010; Béland et al., 2011, 2014; Cifuentes et al., 2014) but not on tree growth.

As one of the first studies Bayer et al. (2013) used TLS to investigate how tree morphology in mixed stands differs from pure stands and how tree growth is related to the surrounding stand. To perform this task the authors manually extracted single tree individuals from the stand. This identification and selection of single tree individuals from the point cloud of a forest scene requires significant post-processing efforts. If the focus is only on a target tree the effort might be justified but in case of several neighbor trees being looked at it becomes a laborious task. Using unclassified point clouds of the neighborhood is less laborious. Even though measured attributes, such as surrogates for competitive forces lasting on a target tree, cannot be assigned to a specific neighbor tree anymore, there is still information available for the entire neighborhood. For explaining tree growth, the sum of all neighbors may be sufficient and there is no need to account for each neighbor's contribution individually. Previous studies based on TLS often summed up characteristics derived from single tree level and used the combined values to relate a tree's neighborhood to its growth (e.g. Metz et al., 2013) or shape (Seidel et al., 2011). A direct evaluation of the relationship between a tree's growth performance and the presence of plant material in its neighborhood (all neighbor trees considered together) would be more straightforward than addressing each neighbor tree on its own but remained untested so far. We know of no study that used unclassified point clouds of a tree's vicinity to explain its growth.

Apart from the utilization of unclassified point clouds the efficiency of the TLS applications in forest stands could also be increased by using only a single scan to derive the desired information (Dassot et al., 2011). The efficiency of single-scan approaches is much higher than that of multiple scans made at various positions and combined afterwards based on artificial targets distributed in the scene. Therefore an increasing number of studies recently focused on the measurement of stand characteristics from single scan data (e.g. Astrup et al., 2014; Ducey and Astrup, 2013). However, none of them related the spatial configuration of the neighboring stand to growth performance of a target tree. TLS clearly has the potential to provide deeper insights to the tree-stand interaction by bringing in all three dimensions of the complex forest system instead of using mathematical tree models that have been the backbone of our existing knowledge (Pretzsch, 2010).

The present study focused on improving our understanding of how neighborhood structure affects tree growth, measured as diameter increment, by evaluating unclassified point clouds from single- and multiple-scan TLS. It was assumed that competition-related processes will be easier to study in a mono-specific stand when compared to mixed stands as the investigated canopy will be less complex if formed by trees of the same species and age (Thorpe et al., 2010). Hence the study was conducted in an even-aged, mono-specific stand. As a second focus options and limitations of the application of single- and multiple-scan TLS as a tool to measure surrogates of tree competition in the stand will be accessed and discussed. In contrast to previous studies we focused on the extraction of stand characteristics from unclassified point clouds that describe a trees neighborhood in a comprehensive manner, instead of using pre-selected, object-based point clouds that represent each single neighbor tree. We hypothesized that parameters characterizing the amount of growing space available for a target tree can be obtained from TLS (single and multiple) and will be clearly related to diameter increments at different heights. We will use TLS data to relate diameter increment at a height different from breast height, here at 60% of the total tree height (D_i60%), to the explicit spatial structure of the surrounding canopy at that height (search cone at 60% of total tree height according to Bachmann, 1998).

2. Methods

2.1. Study site

The study was conducted in the Arboretum Burgholz, located near the City of Wuppertal (North Rhine-Westphalia, Germany) at 51°13′4.67″N and 7°6′21.31″E. Here a number of non-native tree species is cultivated in subplots of varying area, topography and size. In the eastern part of the arboretum about 500 individuals of *Metasequoia glyptostroboides* (Hu.) were planted between 1980 and 1983. The trees form a mono-specific stand of 1.4 ha in size that is located close to the river Wupper (20–50 m). It is situated at about 145 m above sea level and has an inclination of about 10–30° to East, with the steeper slopes being located in the southern part of the stand.

2.2. Conventional inventory

All conventional inventory data was obtained between October and November 2013. Fifteen vital and undamaged trees that were no direct neighbors of each other were selected from the stand with the aim to cover the full range of social positions according to Kraft (1884) and hence facing a gradient in competition. We identified four trees of class 1 (predominant), five trees of class 2 (dominant), four trees of class 3 (co-dominant, intermediate) and two trees of class 4–5 (dominated or suppressed). All trees were measured for total height (TTH) and crown base height (CBH; defined as height of the lowermost knag with three or more needle-bearing branches) using a Vertex (Haglöfs, Sweden). Diameter at breast height (DBH; measured at 1.3 m above ground) was not available for early 2013. Hence, we considered DBH in early 2013 as the mean of two perpendicular measurements of stem diameter made with a standard caliper in October 2013 minus twice the width of the last growth ring including the bark (see Section 2.3). Crown width was measured for each individual as the largest possible distance between the ends of two branches of a tree crown.

2.3. Determination of tree growth

All study trees were felled in late November 2013 and wood discs were cut out of the stems at 1.3 m and at 60% of total tree height. Based on the wood discs diameter increment data was