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Original article

Structural response of black locust (*Robinia pseudoacacia* L.) and small-leaved lime (*Tilia cordata* Mill.) to varying urban environments analyzed by terrestrial laser scanning: Implications for ecological functions and services

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ABSTRACT

Quantitative measurements of structure and morphology of urban trees are hardly exhausted so far, especially in regard to variations caused by altering urban environments. However, structure and functions of trees are heavily interwoven. In fact, knowledge about structural attributes is essential for a better understanding of urban ecosystem functions and services. In order to scrutinize spatially explicit and detailed structural attributes under varying urban environments, we acquired terrestrial laser scans and applied the according methodological approaches to the common urban tree species black locust (*Robinia pseudoacacia* L.) and small-leaved lime (*Tilia cordata* Mill.). We analyzed 52 small-leaved limes and 41 black locust trees within the city of Munich (Germany). Species as well as growing location had a significant effect on the height-diameter relation. We also found greater crown volumes for small-leaved lime. Black locust however, displayed more crown projection area and likely more shade efficient crown shapes at similar volumes. Stem inclination of black locust was found to be higher in parks than in street canyons with town squares lying in between. Furthermore, black locust displayed strong crown asymmetry in park areas, likely caused by competition with neighbors. The angles of main branches did not differ significantly between both species nor between the growing location. Branch angles, branch bending, the length of the branches as well as species and growing location had a significant effect on vertical crown center position, i.e. general crown shape. Surface complexity of lime is lower than of black locust, with its lowest manifestation in parks. Fractal-like crown surface structures, increasing surface roughness and complexity, were found to be more pronounced for black locust than for small-leaved lime. Thereby, black locust featured the highest crown surface complexity in parks, the lowest in street canyons. The results suggest that studies on spatially explicit tree structures may contribute to more target oriented tree plantings and thus, more effective exploitation of ecosystem services and benefits.

1. Introduction

Within urban landscapes, many environmental challenges are important for human health and well-being but costly to mitigate (Livesley et al., 2016). Given enough understanding, urban planers might exploit ecosystem services and functions in order to address these challenges. Consequently, trees are a key aspect in urban green space planning. Besides aesthetic considerations, structural traits, for example size, shape and density, surface complexity and transparency of tree crowns are among the most important drivers of their ecological features and benefits (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013). Urban trees are not only important for pedestrian comfort by providing aesthetic benefits, rain-cover, shade and wind-flow mitigation (Mochida and Lun, 2008; Mochida et al., 2008) but can also help to save energy on larger scales due to air cleaning, cooling (Rahman et al., 2017), wind buffering and shading (McPherson et al., 1997; Rosenfeld et al., 1998). Potential noise reduction (Aylor, 1972; Kragh, 1981; Fang and Ling, 2003), temperature management (Akbari et al., 2001; Akbari, 2005; Bolund and Hunhammar, 1999; Hardin and Jensen, 2007), waterflow regulation and water runoff mitigation (Higgens et al., 1997; Villarreal and Bengtsson, 2005; Pataki et al., 2011), wind-flow (Mochida and Lun, 2008; Mochida et al., 2008), air purification (Nowak, 1994, 1996; Escobedo and Nowak, 2009) and habitat functionality (Hinsley et al., 2009; Goetz et al., 2010; Tews et al., 2004; Müller et al., 2012) are directly related to tree structure as well.

As awareness of the potential benefits of urban trees grows, a better understanding how and under what circumstances services can be

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expected, designed, planned and optimally exploited becomes increasingly relevant. In order to select the right tree species for planting in an urban location, to ensure tree health and provided benefits, knowledge about the growth of the respective tree species and its structural development from planting to maturity is essential (Peper et al., 2014). However, even for the most common urban tree species, research about tree structure, morphology and growth is scarce. Even more so, if the variation of these traits at different tree ages (Kjelgren and Clark, 1992; Rust, 2014) and under varying urban environments such as streets, public squares, parking sites, etc. is considered. Because urban site conditions are totally different from forest site conditions (Nowak et al., 1990), knowledge from forest research cannot be applied. Moreover, even existing data of urban trees cannot simply be transferred to other cities and different climates because of distinct maintenance practices and differing durations of growing seasons (Peper et al., 2001a,b).

Taking tree age and varying urban environment into account, Moser et al. (2015) for example, studied the growth patterns and services of the two common but physiologically contrasting tree species *Tilia cordata* and *Robinia pseudoacacia* to uncover growth relationships and the development of provided benefits over age in three typical urban site categories (street canyons, public squares and parks). Nonetheless, tree growth and structure are usually described and modeled using classical dendrometrical measurements such as diameter at breast height (*dbh*) and tree height and thus, are rather limited in detail and resolution. However, advanced, spatially explicit measurement techniques have emerged during the last decades.

Terrestrial laser scanning (TLS) provides high resolution three dimensional data. In archaeology, architecture, geology and several other fields, TLS is already extensively used and may be considered common practice (Vosselmann and Maas, 2010). In forest research, recent TLS-based methodologies have begun to outgrow pure methodological development (e.g. Côté et al., 2011; Hackenberg et al., 2015; Olivier et al., 2016; Olivier and Robert, 2017; Kelbe et al., 2017). More and more, results based on TLS data contributes to the understanding of forest (e.g. Bayer et al., 2013; Seidel et al., 2016; Liang et al., 2016) and in some cases urban ecosystems (e.g. Jones et al., 2016). Among others, Bayer et al. (2013) used terrestrial laser scanning beyond the scope of pure methodology to gain more detailed knowledge about the structure of trees and the resulting implications for a forest stand's functioning.

In order to quantify structural attributes of small-leaved lime and black locust in urban environments, we scanned 52 small-leaved lime and 41 black locust trees within the city of Munich growing at streets canyons, public places and parks. Based on this, we investigate if there are structural differences within tree species, depending on the surroundings (street, place, park) and discuss implications of found structural attributes for functions and urban ecosystem services.

2. Material and methods

2.1. Study area and sample trees

The sample trees (Table 1) are located within the city of Munich (48° 09′ N, 11° 35′ E, 519 m above sea level) in southern Germany. On long-term (1961–1990), the annual precipitation amounts to 959 mm, while the mean temperature averages at 9.1 °C (DWD, 2015).

Table 1
Overview of the scanned sample trees by species and growing location.

	N	*dbh* (cm)	*se*	*h* (m)	*se*
T. cordata					
Park	8	26.7	3.2	12.5	1.2
Town square	14	37.9	5.1	12.9	1.1
Street	30	26.5	2.3	11.2	0.7
R. pseudoacacia					
Park	7	43.2	10.8	19.3	2.0
Town square	11	37.8	4.5	14.3	1.0
Street	23	35.1	4.3	12.4	0.7

Within the municipal area of Munich, 750,000 trees have been planted according to tree inventories. For our study, 52 *T. cordata* and 41 *R. pseudoacacia* trees have been measured by a Riegl LMS-Z420i, a class 1 near infrared terrestrial laser scanner (Table 1). Besides the TLS scans, stem diameter data at the height of 1.3 m (*dbh*) has been collected using standard diameter measurement tapes. We chose the tree species *T. cordata* and *R. pseudoacacia* for our study because they are among the most common urban trees in Munich (Pauleit et al., 2002) and represent considerably different ecological features (Moser et al., 2015, 2016). The overall tree selection was random, yet the visual impression was also taken into account, so that damaged, low-forked and pruned trees have not been included. Depending on their respective surroundings, each measured tree was classified as park tree (Pa), street tree (St) or tree growing at town squares (Ts). For each the classes of growing location, several locations within the city have been sampled. Park trees were defined as growing in a green space without surrounding buildings. Street trees were defined when planted within a street canyon and trees at town squares were classified when growing free-standing in smaller, mostly paved places.

2.2. TLS scan acquisition

A Riegl LMS-Z420i TLS-System was used for the tree scanning. The device works based on the time-of-flight principle. A short near-infrared laser impulse is emitted towards a specified direction. Once a target is hit, a part of the light is reflected back towards the device's sensor. The time between the emission and the return of the impulse in combination with the speed of light in air yield the distance to the target. The specified azimuth and inclination are recorded with a precision of 0.002°. Combining each measured distance and direction of a large number of consecutive measurements yields the spherical coordinates representing a precise three dimensional image of the scanned region. The maximum field of view of the device is 80° vertically and 360° horizontally. By tilting the device and the combination of several scans from the same position, gapless measurements of the area can be achieved.

A typical problem with laser scanning of tree crowns is, that objects behind other targets cannot be measured (Hilker et al., 2010). While the sight on tree crowns in urban areas is usually much less prone to being blocked by neighboring trees and other objects than it is in forests, self-occlusion can still be detrimental to the overall data quality of individual trees (Bayer et al., 2013; Olivier et al., 2016). To overcome this, we combined the point-clouds of scans from at least two opposing sides of each sample tree and used a distance measurement mode called last-pulse. Hereby, not the first but the last echo of the laser pulse is recorded, favoring deeper penetration of the crown while still yielding an accurate representation of the crown's periphery. Furthermore, we acquired scans of our sample trees under leaved and leafless conditions in order to provide the best-suited data basis for specific target parameters. We used leafless scans for the measurement of skeletal structure and leaved scans for crown shapes and inner density distribution, for example.

The TLS-device's manufacturer's software RiSCAN Pro has been used for the preprocessing of the point clouds. By exclusion of everything not being part of the respective tree's point-cloud - such as buildings, vehicles, and ground for example - each individual tree's TLS data was isolated. Our sample tree data was then exported and converted into various formats like .csv matrices for single tree point clouds and .xml in case of tree skeletons.

2.3. Skeletonization

In order to quantify the inner crown structure of the sample trees, we used a specific software developed by Bayer et al. (2013). Hereby,