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Operational assessment of aboveground tree volume and biomass by terrestrial laser scanning

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ABSTRACT

The assessment of aboveground tree biomass (AGB) is essential to the evaluation of tree populations in forests, open landscapes, and urban areas. The predominant method used to determine AGB relies on error-prone functions derived from the statistical relationships of tree attributes and biomass. Terrestrial laser scanning (TLS) offers a new approach that replaces statistical AGB estimates with consistent measurements.

Aboveground tree biomass (AGB) comprises stems and branches. While the biomass assessment of stems is straightforward, TLS measurements of tree crowns are far more complex because of branch overlapping. Because placing reflecting targets in the crowns of tall standing trees is impractical, yet necessary for merging the point clouds from different laser scan positions, TLS measurements often fail in operational applications.

This study introduces a straightforward algorithm that simplifies biomass measurements of complex branch geometries using TLS and derives AGB by averaging measurements from individual scanning positions. We verified our approach through an experimental setup of branching systems with different complexities and known true biomass volumes. The results show that biomass extraction from branches by TLS systems is not affected by scanning distance. The combination of biomass measurements from individual scanning positions by averaging provides reliable biomass figures. Compared to the known true biomass figures, the overall accuracies achieved by our approach are 95% or higher, which brings the operational application of TLS for AGB measurements within tangible reach.

1. Introduction

Forests resource assessments collect a multitude of attributes that provide information on ecosystem functions, including timber production, biodiversity, health and vitality, or protective functions. Only a few attributes can be directly assessed by measurements (e.g. stem diameters, tree height) or visual observations (e.g. tree species, stem damage). These attributes provide input parameters for models or functions used to determine additional information. A widely known example is the estimation of stem volume based on allometric models using stem diameters and tree height as input parameters (Schreuder et al., 1992; Hush et al., 2003; Köhl et al., 2006). Because volume functions provide only an approximation to the true volume, they are prone to prediction errors (Gertner, 1984; McRoberts and Westfall, 2013). The problem of model prediction errors is further compounded when estimating the AGB of individual trees. While volume is a cubic measure (e.g. m^3), AGB is generally presented as a weight measurement (e.g. kg). AGB is obtained by either multiplying tree volume by wood density or by allometric biomass equations, which use tree attributes such as stem diameters or tree height as input variables (IPCC, 2003, 2006). Chave et al. (2004) state sources of errors associated with the estimation of AGB by means of allometric biomass equations, among which are errors due to tree measurement and errors due to the choice of an allometric model relating AGB to other tree dimensions. They found the choice of the allometric model to be the major source for errors.

According to Newnham et al. (2015) Terrestrial Laser Scanning (TLS) "presents an opportunity to go beyond simple empirical isometric and allometric equations to the point where three-dimensional measurements . . . are used as a basis for assessing volume, . . .". This statement is of particular significance considering the increasing importance of ABG assessments in forest carbon stock inventories (IPCC, 2003, 2006). TLS provides point clouds that can be used for geometrical modeling.

In our study we focus on the assessment of ABG with a special reference to measuring tree crown volumes, which has an even

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greater margin of error than measuring tree stem volumes. We utilize an experimental setup of different branching patterns. The true volume of branches was assessed by water displacement. We develop a straightforward algorithm for the extraction of branch volumes in individual scans. Theoretically, TLS could potentially be an ideal tool for assessing the complex geometrical structures of tree crowns. In practice, however, the occlusion of branches presents a major obstacle for the geometrical modeling of tree crowns. The problem of occlusion can be minimized when scans from multiple scan locations are merged into a single point cloud. This approach uses highly reflective targets that can be observed from the multiple scan locations. In practical applications the positioning of targets in tall tree crowns can be cumbersome, as they in turn may be subject to occlusion. Therefore, Henning and Radtke (2006) consider the use of reflective targets in forest applications to be impractical. Instead of merging scans into one point cloud we use the mean of volumes extracted from individual scans to provide an estimate of the total volume.

1.1. TLS measurements for tree volume and biomass assessments

Terrestrial laser scanners measure the relative position of laser beam reflecting objects. In addition to the reflection intensity, scanners record the reflection's position using polar coordinates based on horizontal angle, vertical angle, and the object distance. Distances can be measured either by the concept of (1) time of flight or the (2) range distances approach. While a time of flight scanner derives the distance from the time period between signal emission and the detection of the reflected signal, range distance scanners use the phase shift of a permanent emitted laser beam. Systems working with the range distance approach can detect various reflections from the first to the last palls. These are mainly used for airborne laser scanning. Most terrestrial laser scanners use the time of flight concept, whereby each point has one return and one distinct measured coordinate (Danson et al., 2014).

Different approaches are described for the analysis of point clouds from TLS systems. The general idea behind TLS analyses is the transfer of point clouds into geometric objects, which is realized through geometric modeling. Another approach is voxelation (Hosoi et al., 2013; Fernández-Sarría et al., 2013), which combines clusters of points into cubes, i.e. 3D-pixels, of defined size. A third approach is point cloud meshing (Kazhdan et al., 2006), which approximates a given volume by an entity of small and simple objects. Nölke et al. (2015) used this approach to measure the volume of plank buttressed tropical trees. A major obstacle in analyzing TLS clouds is occlusion. From a scanner position occlusion is caused by objects that cast shadows and thus hide background objects from detection. Combining points clouds from multiple scan positions into one common cloud can partly solve the problem of occlusion (Hilker and Coops, 2012).

Xu et al. (2013) compared different methods for tree crown projections and crown volume estimations for a virtual set of 22 common tree species in China derived by TLS. He showed how the different methods influenced the estimation accuracy, whereby the potential of estimation of branch and twigs structures was excluded.

In forestry applications the analysis of TLS mainly focuses on the extraction of attributes from point clouds that are traditionally used in terrestrial forest surveys, such as stem diameters, height, or number of trees (Dassot et al., 2012). The estimation of standing timber volume based on TLS data has been described by Hopkinson et al. (2004), who extracted stem diameter and tree height from laser point clouds and used those as input variables for allometric timber volume functions. Aschoff and Spiecker (2004) used TLS-derived stem diameters at 1.3 m and 7 m, which are frequently used input variables for volume functions in Europe (Kaufmann, 2002; Tomppo et al., 2010). Taper functions, which are a recognized alternative for the assessment of stem volumes (Kublin and Breidenbach, 2013; Kublin et al., 2013), were extracted from TLS by Maas et al. (2008). Further applications of TLS for assessing tree height, diameter at breast height (DBH), stem density, canopy cover, and AGB are presented by (Hopkinson et al., 2004; Bienert et al., 2006; Kankare et al., 2013). In addition, TLS has been used to estimate leaf area(Huang and Pretzsch, 2010) sweep and lean (Thies et al., 2004), tree value (Murphy et al., 2010), fibre quality (van Leeuwen et al., 2011), forest canopy structures (Parker et al., 2004) or fuelwood quantity (Loudermilk et al., 2007).

Nölke et al. (2015) are among the few who do not limit the analysis of TLS point clouds to the extraction of individual tree attributes, but use the entire point cloud for measuring volumes of tree buttresses. As tree buttresses are solid objects the problem of occlusion can be solved by merging the point clouds assessed from multiple scan positions. This precondition does not hold true for tree crowns, where overlapping of branch structures frequently occurs. This is a crucial issue for the estimation of AGB, as a considerable proportion of aboveground biomass is located in tree crowns and not in the stem (Otto, 1994; Burschel and Huss, 2003). Because the assessment of stem volume is generally more accurate than the assessment of tree crowns, the total error of AGB assessments is substantially driven by the uncertainties related to tree crown assessments. Therefore, methods for improving the reliability of the assessment of tree crown volume are of uttermost importance.

2. Material and methods

Branches originating from the crowns of Sessile oak trees (*Quercus petraea*) are the objects of our study. Three to four meter long branches were collected from logging residuals after harvesting operations in a sustainably managed oak stand near Reinbek, Germany (53°31′N, 10°16′E). Due to microclimate of the forest, some of the branches were lichened. We systematically arranged branch segments for a terrestrial laser scanning under standardized laboratory conditions which allowed for an exact assessment of biomass and volume of the scanned objects. To ensure standard conditions, we used a reference cube with a fixed side length (of 540 mm) the outlines of which determine the biomass which has to be assessed in different ways. Any twigs protruding from the surface of the cube were cut back to the cube's boundary.

2.1. Experimental setup

While Hildebrandt and Iost (2012) studied the applicability of laser scanning for tree volume estimation by utilizing regular, artificial bodies, we choose an approach that provides for the variability of tree crowns caused by different patterns of branch structure and branch size. Branches of Sessile oak (*Quercus petraea*) were collected before foliation and arranged in a $50 * 50 * 50$ cm reference cube (Fig. 1). In 19 different experimental setups the reference

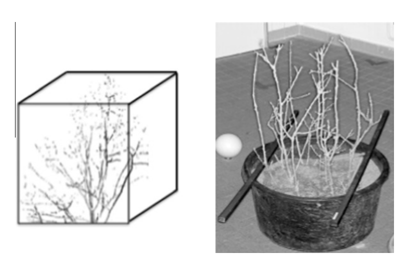

Fig. 1. Schematic sketch (left) and sample image (right) of the reference cube filled with branches.