Agricultural and Forest Meteorology 151 (2011) 1305–1311

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

3D-laser scanning: A non-destructive method for studying above- ground biomass and growth of juvenile trees

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ARTICLE INFO

Article history:
Received 4 October 2010
Received in revised form 1 April 2011
Accepted 19 May 2011

Keywords:
Allometric regressions
Growth monitoring
Leaf biomass
Point cloud grid
Leaf area
Biomass harvest

ABSTRACT

Many experiments with juvenile trees require the non-destructive monitoring of plant biomass and growth which is most often conducted with allometric relationships between easy to measure morphological traits and plant biomass. In a growth experiment with potted juvenile *Fagus sylvatica* L. trees, we tested the practicability and accuracy of the portable 3D-laser scanner ZF Imager 5006 using the phase difference method for measuring total above-ground biomass (stems, twigs, leaves), the biomass of axes (stems and twigs), of leaves biomass and the leaf area of 63 experimental trees. The trees were scanned from 20 (or 21) different positions with an angular step width of 0.036° in horizontal and vertical direction and the 3D-point cloud of every tree was translated into a point cloud grid with defined distances between the data points to standardise the spatial resolution of the data. The validation of the laser scan data against traditional biomass harvest data gave good correlations for total above-ground biomass (green and woody plant material combined), leaf biomass and leaf area (obtained by measurements before and after leaf harvest), and the mass of stems and twigs (only woody compartments of the plants) with R^2-values between 0.61 and 0.88, all significant with $p < 0.001$. Biomass estimates using allometric regressions between total plant height or total leaf number and above-ground biomass as alternative non-destructive methods were found to be weaker than laser scanning (R^2 0.54–0.67) and required a similar calibration effort. Repeated scanning of the same plant can be used to monitor biomass increase over time. We conclude that 3D-laser scanning is a promising technique for the non-destructive monitoring of biomass and growth in experiments with juvenile trees.

1. Introduction

Accurate monitoring of plant biomass and growth is a prerequisite of most experiments with potted juvenile trees that investigate responses to altered environmental factors (e.g. Spinnler et al., 2002). A conventional approach are consecutive harvests of a subsample of the test plants (e.g. Pregitzer et al., 1990) which requires a large number of replicate trees, is labour-intensive and suffers from the fact that harvested individuals cannot be used for further study. As a non-destructive alternative, the repeated monitoring of surrogate variables for plant biomass, such as plant height or twig and branch length, have been applied for estimating changes in plant biomass over time using allometric relationships (e.g. Jarvis and Leverenz, 1983; Bartelink, 1997). However, the recording of these surrogate variables for a large number of tree saplings can also be time-consuming.

The technique of 3D-laser scanning (also known as terrestrial LIDAR) has advanced in the last decade to become a common method for the optical measurement of the three-dimensional extensions of distinct objects. The measurement principle of terrestrial 3D-laser scanners is based on laser distance measurements between the scan unit and any object in the surroundings of the instrument that could possibly reflect the emitted laser beam. As the scanner stores the polar coordinates (direction and distance) of a reflected laser hit, it is assumed that this technique can deliver detailed structural information about a juvenile tree suiting to model the spatial structure of the plant. For this purpose, complex 3D-structures like plants require multiple scans from different directions in order to capture the present structure as accurately as possible. This is necessary as objects behind another object, that may reflect the beam, may be missed by the laser beam when measuring from only one position (Van der Zande et al., 2006). Takeda et al. (2008) presented a successful approach to extract the 3D-distribution of plant surface area density of Japanese larch (*Larix kaempferi*) trees. Other studies showed the potential to measure further structural parameters of trees such as LAI, lean, sweep and taper and others more (Pfeifer et al., 2004; Thies et al., 2004; Henning and Radtke, 2006; Danson et al., 2007). Hosoi and Omasa (2007) used a portable 3D-laser scanner to calculate canopy leaf area density profiles for deciduous trees. Studies focusing on mea-

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doi:10.1016/j.agrformet.2011.05.013

surements of the biomass mostly concentrated on forest trees so far and were usually rested upon allometric relationships between parameters that can easily be measured with terrestrial laser scanners, e.g. diameter at breast height or total tree height, and the trees biomass (e.g. Watt et al., 2003). Airborne laser scanners have also been used to derive trees biomass (e.g. Lim and Treitz, 2004) but will not be discussed in this paper as we focus on ground-based measurements as used in small areas, greenhouses or common garden experiments. Studies on the use of terrestrial laser scanners for direct plant biomass estimations which are not based on allometric relationships between easy to measure parameters and biomass, are rare (Keightley and Bawden, 2010). In our study we used a new approach which is based on the relationship between the number of laser hits detected for a tree and the trees biomass. Tackenberg (2007) presented an approach based on digital image analysis that focuses on the determination of the vertical distribution of above-ground biomass of plants. Tackenberg depicts the need for such non-destructive methods for biomass determination for specific plant individuals, especially in common garden experiments. In contrast to the method invented by Tackenberg, where the real 3D structure cannot be measured but is calculated based on the assumption of symmetry with the erect stem being the axis of symmetry (Tackenberg, 2007), our study aims to provide a biomass determination based on real 3D-data obtained from a laser scanner. Similar to Tackenberg our study was motivated by the potential of a reduction of plant individuals which need to be grown in common garden experiments.

Although registered multiple-scan datasets represent reliable copies of the 3D-scene they captured, it is not trivial to automatically derive the accurate volume of plant stems and branches from these data, since gaps in the dataset, variable point grid resolutions due to non-uniform distances of the objects to the scanner, and possible measurement artefacts on curved edges may confound the volume calculation and therefore the allometric estimate of plant biomass. As an alternative to the automated formula-based volume calculation, we tested in our study the performance of a calibration approach based on known biovolumes and related biomasses of a subset of experimental plants.

The specific aim of our study was to test the potential of this improved non-destructive 3D-laser scanning approach for measuring the above-ground biomass and seasonal growth of potted juvenile trees against biomass harvests and other established allometric estimates of biomass.

2. Materials and methods

2.1. Experimental setup

A growth experiment with beech (*Fagus sylvatica* L.) saplings in the Experimental Botanical Garden of the University of Goettingen served as the study object to test the applicability of 3D-laser scanning as a non-destructive method for growth analyses in juvenile woody plants. The experiment was established in 2007 to investigate the response of juvenile European beech trees to the combined effects of soil drought, as is expected to occur under climate change in parts of Central Europe (IPCC, 2001), and nitrogen availability. Sixty-three juvenile beech trees, each four years of age, were planted individually into buckets of 45 l volume in April 2007. The buckets were arranged in a randomised block design in an outdoor area under a mobile acrylic-glass roof which excluded rainfall and allowed both exposing of the plants to the outdoor environment and growing them under a defined soil moisture regime. To protect the beech saplings from full sunlight, which could be harmful at this stage of life, we installed a shadow net that excluded ca. 50% of the solar radiation. Our comparative growth monitoring study was carried out in the vegetation period of 2009, starting in July and ending with the last harvest in September (see Table 1), when the sapling trees were about six years old.

2.2. Terrestrial laser scanning

The terrestrial 3D-laser scans were made with a Zoller and Froehlich Imager 5006 (Zoller und Froehlich GmbH, Wangen, Germany). The instrument uses the phase difference technology, meaning that a continuous light wave is emitted and the difference in the phase of the wave between the emitted and received signal reflected by an object is measured. This difference between the instrument and the object which reflected the beam can therefore be used for precise ranging to the object (e.g. Wehr and Lohr, 1999). The Imager 5006 is battery powered and can be used as a stand-alone unit in the field. The scanning resolution was set to an angular step width of 0.036° resulting in about 86 Mill. points for a field of view 360° horizontally and 310° vertically $((310°/0.036°) \times (360°/0.036°) = \sim 86$ Mill.), which equals a point to point distance of 0.6 mm on a surface perpendicular to the laser beam in 1 m distance in both horizontal and vertical direction if measured from beam centre to beam centre. The emitted beam is circular with a diameter of 3 mm and a divergence of 0.22 mrad, and the viewing range of the scanner is 1–79 m due to the ambiguity interval of the modulated light wave used to determine the distance to objects. The wavelength of the emitted light beam is visible green (532 nm, Zoller and Froehlich, 2007). Scanner settings were chosen to give a good balance between scanning resolution and required time per scan. Even though it was necessary to reduce the scan data to only the sixteenth part of the original (see below) we would still be able to make additional studies with the full resolution as soon as stronger hardware will be available. As reducing the original data resolution is always possible we decided for the highest resolution available in an arguable amount of time per scan (in this study 3 min 22 s per scan).

The scanner positions were not fixed at the different scan sessions during the growth monitoring to allow for a fast and flexible instrument setup. Scanner positions were therefore chosen in a way to give a comprehensive view to all buckets from at least three sites and with at least two scans in the vicinity of each bucket (~4 m) to ensure good resolution. As the trees were less than 2 m in total height including the bucket, we did not expect to face problems related to reduced data point density in the upper part of the trees as it was encountered in studies with taller trees in the field (Hosoi and Omasa, 2007). The registration of the scans of each session was based on 24 artificial targets fixed to wooden pillars that were installed between and around the potted trees. A target consists of a DIN A4 paper with two white and two black quadrates arranged in chessboard-style and a number printed under it for identification. The centre of the chessboard, that area where all four quadrats have a common corner, is the point marked manually in all scans where the target with the same number is visible. These fix points are than used for registration of multiple scans. All scans made were successfully registered with all other scans of the scene due to the small overall area of the study site (around 20 by 20 m). The great number of targets used for the relatively small area to be scanned ensured very low dilution of precision in the position of elements in the combined scans (low registration error). All scans of each scanning campaign were fully combined according to their field of view.

The first scanning campaign covering all 63 trees was conducted on July 13, 2009 (monitoring event #1, M1). Scanning was repeated on four occasions (M2–M5) over the subsequent 77 days (Table 1). The number of scans per session was 20 or 21 to ensure a complete capture of the scene of all experimental plants. Because 23 of the trees were harvested during the vegetation period to validate the