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

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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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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

Table 1
Experimental protocol with the number of scanned and harvested young beech trees per monitoring event.

Date	Monitoring event	No. of scanned		No. of harvested trees
		Trees with leaves	Without leaves	
July 13, 2009	M1	63	0	0
July 27, 2009	M2	63	0	0
July 27, 2009	M3	40	23	23
Sept. 7, 2009	M4	37	0	0
Sept. 28, 2009	M5	37	0	0
Sept. 28, 2009	M6	0	37	37

scanner measurements and three trees died, 37 of the initially 63 trees were measured continuously until final harvest on September 28. The 23 trees harvested on July 27 were selected by random. They were scanned first, then subsequently defoliated by hand and scanned in leafless state again to record the structure and volume of the axes (stems and twigs). Forty trees, which have been scanned on the M2 occasion, were scanned again only a few hours later (M3 scanning event) without any alteration of the tree position (see Table 1). With these two repeated scans of the same objects, we tested the reproducibility of the laser scan results.

After scanning the ensemble of 23–63 trees from the 20 or 21 scanner positions, the data was transferred to a computer with the Z+F LaserControl 7.3.5 Software (Zoller und Froehlich GmbH, Wangen, Germany). The same software was used to register the 3D position of every visible artificial target in each scan manually and to combine the scans based on these common target positions.

Once the scans were all arranged in the same coordinate system, the data was filtered for erroneous data points. We applied the filters with predefined settings as implemented to ZF Laser Control which are focusing on five main types of erroneous points:

- Points created halfway between the first and the second reflection from a single splitted laser beam (Mixed pixel filter),
- points with no neighbours within a certain distance (single pixel filter),
- points that are of too high (>100% of the emitted signal, e.g. caused by direct sun) or too low (<0.6%, very low reflectivity) intensity in the reflected signal (intensity filter),
- points that are out of the calibrated range of the scanner (1–79 m, range filter) and finally,
- points that are closer to each other than 0.16 mm which can therefore not be the result of accurate measurements as 0.16 mm is below the minimum distance that can be measured by the scanner even at highest resolution (thinning filter).

Filtered scans were than exported as zfs-files (instrument-specific file type). These files were imported to Cyclone Software 5.8.1 (Leica Geosystems GmbH, Munich, Germany) and the data was reduced to the sixteenth part of the original size of the point cloud to cope with hardware restrictions. The 3D-view of the point cloud of a single tree as produced by the Cyclone Software allowed visual checking for erroneous points (e.g. dust, insects, measurement errors) and for twigs and leaves from neighbouring trees in the image. Those points were erased manually from the point cloud as they were not detected by the software filters completely. The separation of point clouds from neighbouring trees was the only subjective part in the data-processing procedure, which did not require an experienced person.

Once a point cloud was assigned to a single tree, an algorithm was written in the software Mathematica (Wolfram Research Inc., Champaign, USA) and used to create a 'regularly spaced point cloud'. Thereby the point cloud of the tree was transformed to a regular spatial grid with equal distances between neighbouring points. This was necessary for obtaining a homogeneous spatial resolution for the single-tree point cloud regardless of the varying distances of the scanned objects to the scanner position.

As 3D-laser scanners tend to produce less data points with increasing distance from the scanner position, which is a result of the constant divergence of two neighbouring beams emitted with a certain angular step width, it is necessary to generate regular spatial grids in order to achieve comparable results throughout the whole point cloud. In this study, the grid spacing was set to be 0.5 cm (i.e. 0.5 cm point cloud grid, PCG). Fig. 1 shows three images of an exemplary tree based on the original point cloud (Fig. 1a), a 0.5 cm point cloud grid (Fig. 1b) and a 1 cm point cloud grid (Fig. 1c).

We used the coefficient of variation (CV) to compare the results of repeated measurements on the same trees (M2 vs. M3 monitoring event; $n = 40$) based on 0.5-, 1-, 2-, and 3 cm PCGs to evaluate whether already the smallest grid was suitable to eliminate the measurement-dependent differences in the point clouds of two independent scan sessions or not.

When the point cloud grid was created, a linear regression model was established based on the relationship between the dry weight of a tree and the corresponding number of points that represented the tree in the 0.5 cm grid. The dry weight data was obtained by a traditional harvest approach for the time steps M2, M3, M5 and M6 and was used as reference data. We had to establish two models, one for the trees that were foliated (M2; M5) and one for those that were defoliated (M3; M6) to embrace the fact that a model for the foliated condition would fail for the defoliated condition and vice versa. From the number of points in the PCG, that represented a certain amount of biomass (e.g. 113 points ~1 g) we calculated the absolute biomass of the scanned trees. Furthermore, comparisons of PCGs created before the defoliation of the trees (M2 and

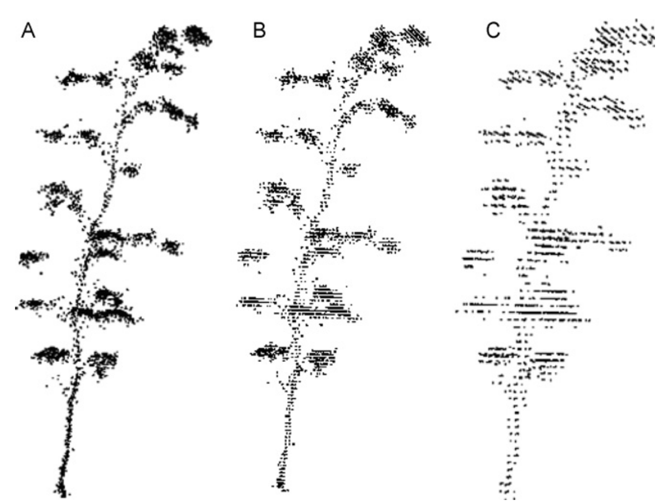

Fig. 1. Tree point clouds of an exemplary juvenile beech tree. With increasing grid space the resolution of the tree model decreases and finer contours disappear. Tree height was about 41 cm. (A) Point cloud as created from the original scanner data (3411 points). (B) 0.5 cm point cloud grid computed with Mathematica (2296 points). (C) 1 cm point cloud grid (1105 points).

M5) with PCGs created after the defoliation (M3 and M6) served to calculate leaf biomass and leaf area (*cf.* Hosoi and Omasa, 2007) as the difference in the number of points in the two PCGs. This was done to test whether the time-consuming scanning of the leaves with a flatbed scanner after their harvest could be abandoned in the future in favour of the laser technique.

2.3. Biomass harvest of the experimental plants for validation

The trees were harvested in groups of randomly chosen individuals on different days as detailed in Table 1, and their total height and the diameter at the soil surface were measured. To determine the volume of the stem above-ground biomass, we used an immersion bath. Each tree was cut into 5–10 cm long pieces and submerged in a graduated cylinder with a volume of 250 ml or 500 ml filled with 150 ml or 400 ml of water, respectively, depending on the dimension of the tree. The compartments of the above-ground biomass were then dried at 70 °C for at least 48 h to constant weight.

In order to measure leaf biomass, the leaves were stripped from the trees before harvesting the shoot. The leaf area of every single leaf of a tree was subsequently analysed with a flatbed scanner and the computer program WinFOLIA (Régent Instruments, Quebec, Canada) in order to calculate the total leaf area. The leaves were dried (70 °C, 48 h) and weighed.

Finally, we compared the results from the laser scanning approach with the non-destructive allometric biomass measurements that allowed estimating the total woody biomass of the trees. The R^2-values of the relationships between total woody biomass and the parameters total tree height and total number of leaves were compared to those gained from the laser approach.

3. Results

All scans were registered with an average deviation between two registered points of less than 2.7 mm. The maximum registration error was less than 8 mm for all monitoring sessions (data not shown). For those scan sessions with a synchronous biomass harvest for validation (M2, M3, M5, M6), highly significant relations between the number of points derived from scanning and biomass data obtained by harvest were found. The best result was achieved using the 0.5 cm point cloud grid (Table 2).

For leaf biomass, we also found a tight correlation ($R^2 = 0.81$) between estimated (scanner) and measured (harvest) values (Fig. 2). As is visible in this scatter plot, the leaf biomass of larger tree individuals can be predicted by the laser scanning method with a somewhat lower certainty than that of smaller ones. This problem is less obvious when the biomass of the stem and twigs is derived from the laser scans (Fig. 3). The correlation between laser-derived and harvest-based leaf area values was similarly strong as for leaf biomass in the 0.5 cm point cloud grid ($p < 0.001$; $R^2 = 0.83$; $n = 60$, Fig. 4). Again, it is visible in the scatter plot that the biomass of larger trees is predicted with a slightly lower accuracy than that of smaller ones (Fig. 3).

Even though the 0.5 cm point cloud grid gave the best results with respect to leaf biomass and leaf area, the results of repeated laser scans of the same plant showed a higher consistency between two subsequent datasets when conducted with the 2 cm PCG, as is indicated by a lower coefficient of variation (Table 3). It appears that the 2 cm-resolution is optimal for scanning tree saplings because the resolution is not too coarse to catch even small increases in biomass, nor is it too fine-scaled to produce data which do not match when repeated with a different scan setup (and scanner position) later on the time axis.

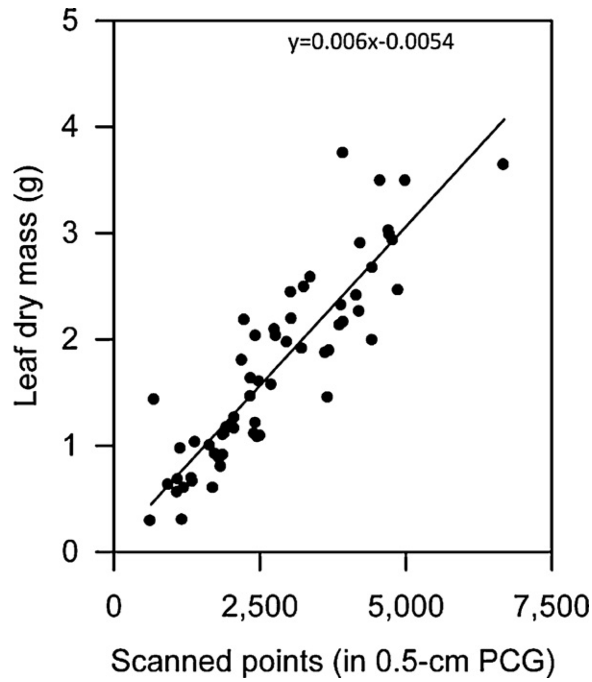

Fig. 2. Relationship between leaf dry mass per tree measured by harvesting and the number of points in a 0.5 cm point cloud grid created by laser scanning ($p < 0.001$; $R^2 = 0.81$; $n = 60$; slope = 0.0006; offset = −0.0054).

Comparing the laser-scanning approach with another non-destructive method of biomass estimation resulted in no better accuracy if both approaches are referenced against the biomass harvest. Using allometric relationships between total tree height or total leaf number and total tree biomass (leaves, stems, twigs) gave coefficients of determination of 0.54 ($p < 0.001$) and 0.67 ($p < 0.001$), respectively, which is similarly, or less tight than the laser scan - harvest relationship (Figs. 5 and 6 and Table 2).

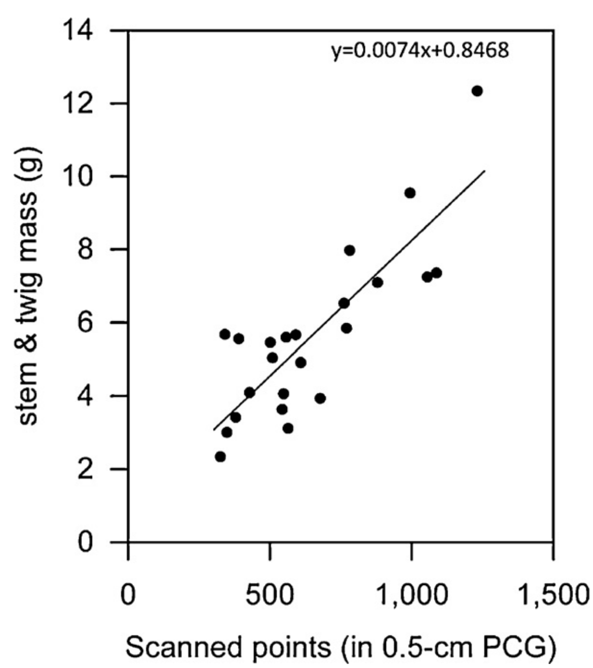

Fig. 3. Relationship between the total stem and twig biomass of a tree measured by harvesting and the number of points in a 0.5 cm point cloud grid created by laser scanning ($p < 0.001$; $R^2 = 0.70$; $n = 60$: slope = 0.0074; offset = 0.8468).

Table 2
Coefficient of determination for the relationships between plant biomass (total above-ground biomass with or without leaves) as derived from laser scans and that obtained by harvest using three different point cloud grids (0.5 cm PCG, 2 cm PCG, 3 cm PCG). All relationships were significant at $p < 0.001$.

Monitoring event	Above-ground biomass	R^2			n
		0.5 cm PCG	2 cm PCG	3 cm PCG	
M2	With leaves	0.83	0.85	0.83	23
M3	Without leaves	0.70	0.62	0.60	23
M5	With leaves	0.66	0.69	0.67	37
M6	Without leaves	0.61	0.51	0.48	37

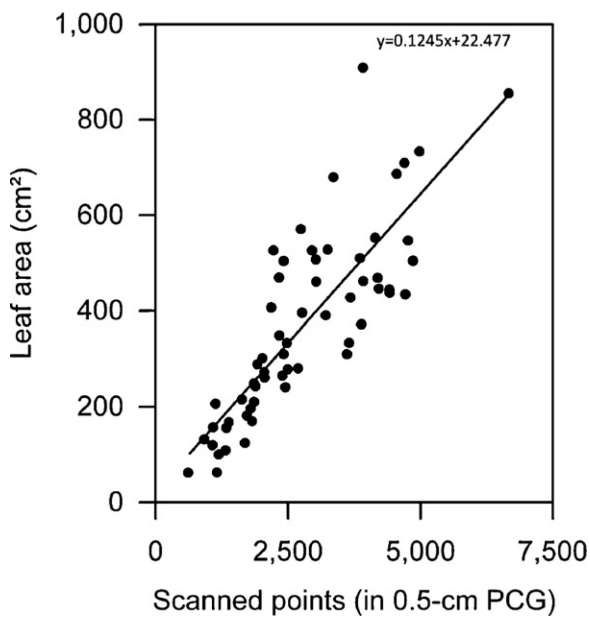

Fig. 4. Relationship between the total leaf area of a tree measured by harvesting and the number of points in a 0.5 cm point cloud grid created by laser scanning ($p < 0.001$; $R^2 = 0.83$; $n = 60$; slope = 0.1245; offset = 22.477).

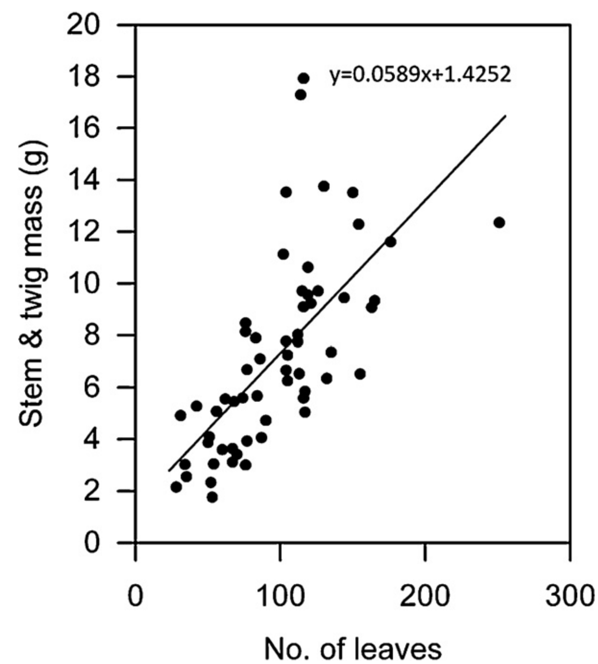

Fig. 5. Relationship between the total stem and twig biomass of a tree measured by harvesting and the number of leaves counted ($p < 0.001$; $R^2 = 0.67$; $n = 60$; slope = 0.0589; offset = 1.4252).

4. Discussion

This investigation showed that laser scanning is a useful method to measure above-ground biomass and growth of juvenile beech trees non-destructively in outdoor experiments. We found tight correlations between the amount of above-ground biomass derived from laser scans and that obtained by traditional biomass harvest, with the correlation being closer for plants with leaves (R^2 0.66–0.85) than for defoliated plants (biomass of stems and branches only; R^2 0.48–0.70). On average a foliated tree was represented by around 3800 points, while a defoliated one was detected by "only" 850 laser hits. We assume that the high percentage of round surfaces being present in the defoliated representation of the trees caused an increased number of erroneous pixels due to measurement errors. The quality of the correlations between the number of laser hits and the biomass for the defoliated plants therefore decreased compared to the foliated ones which had more flat surface being detected by the scanner. While earlier studies on laser scan-based biomass estimation in mature trees regularly were confronted with a reduced density of data points in the upper part of the canopy (e.g. Hosoi and Omasa, 2007), we did not face this problem in our study with juvenile trees. This is not only a size effect, but is also a consequence of introducing the concept of the point cloud grid (PCG) when analysing the data, because PCGs reduce the heterogeneity in the point density in all sections of the 3D-image. It should be stated here that this effects can only be achieved if large oversampling of the plants is ensured, which is easily done by performing a large number of scans for small areas as was done in our study. In case of intensive shadowing within the point clouds due to obstruction effects the use of a PCG could cause a false image of the scene.

The correlation between the biomass values obtained either with the laser method and the harvest was stronger when smaller grid distances were selected in the PCG which indicates, that the most accurate biomass estimate should be obtained with the highest resolution PCG (0.5 cm). In Table 2 it is shown that the 3 cm PCG

Table 3
Coefficient of variance of the number of points in point cloud grids of different resolutions for two subsequent measurements on the same trees (M2 and M3; $n = 37–40$). The root mean square error (RSME) was calculated from the differences in the number of points of the same tree resulting from the two subsequent scan sessions M2 and M3.

PCG resolution	Mean number of points per tree[a]	RMSE (in points)	Coefficient of variation (%)
0.5	4354 ± 1766	649	14.3
1	1645 ± 651	129	7.7
2	510 ± 184	35	6.8
3	247 ± 85	19	7.8

[a] Trees scanned during the monitoring events M2 and M3.

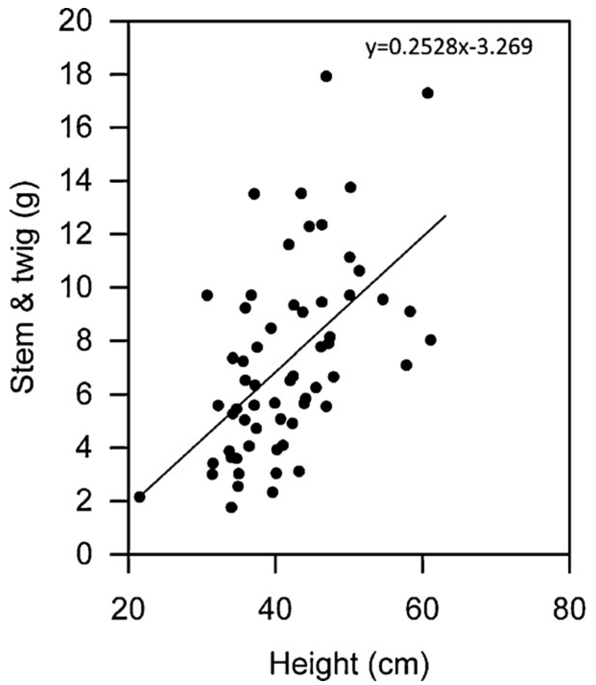

Fig. 6. Relationship between the total stem and twig biomass of a tree measured by harvesting and the height of the trees ($p < 0.001$; $R^2 = 0.54$; $n = 60$; slope = 0.2528; offset = −3.269).

will gave less good correlations when compared with the 2 cm PCG, while the differences between 1 cm and 2 cm seemed to be not that clear (no trend obvious). Only shadowing due to obstruction effects could explain the weaker model quality of a 1 cm PCG for M2 and M5 when compared to the 2 cm PCG (Table 2). A higher resolution will represent the plant more detailed than a lower resolution which is a logical consequence of the greater number of "samples" (laser hits) in relation to the study object (plant). At the same time the effects of obstruction became less important with increased grid cell size. However, choosing very small point distances will introduce other sources of error when using laser scanning for growth analyses. In fact, it may be impossible to achieve sufficient congruency in the point clouds that represent the same tree individual in two subsequent scan events because laser scanner measurements are sensitive to small changes in the scene itself, which can result in different numbers of data points for the same object in two different scan sessions. Further small differences in the instrument position during two scan sessions, wind-induced movement of the scanned object, and the registration process itself may cause a certain inaccuracy in the shape of the resulting point cloud which makes analyses of the growth process difficult. This kind of bias will be encountered when living objects such as plants are scanned in the field and a high point cloud density is chosen (Pfeifer et al., 2004; Takeda et al., 2008). Thus, larger point distances are advantageous when a time series of images is to be analysed (e.g. for growth analysis), even though accuracy will decrease. We found a PCG with 2 cm point distance to represent the best compromise between a satisfying resolution of the image and a high consistency between repeated measurements of the same object, as it is evident from the coefficient of determination in Table 2 and the coefficient of variation in Table 3. One approach to increase the accuracy of the laser scan images to the level of a 0.5 cm PCG in repeated measuring programs would be to place artificial objects between the trees into the scene. These objects should not change in size or position during the experiment so that they can serve as 'reference units' in all scan sessions. By using the number of points, that represented the reference objects as a calculation basis, it should be possible to achieve a higher congruency between subsequent scan images of a plant even at higher point densities as in a 0.5 cm PCG. This approach should be tested in future investigations.

We found the laser scanning method to be less time-consuming than the traditional harvest in measuring the biomass of juvenile trees. From the first preparation prior to the scanning it took not more than 2 h to the final calculation of data points in the PCG. To scan additional trees will add a few minutes per individual as all points representing each tree need to be selected from combined point clouds. While the data acquisition in the field is much faster than conducting a harvest, the post-processing procedure of the scan data requires more time and is dependent on the purchase of expensive hard- and software. However, we found that the scanner data post-processing required not significantly more time than the computer processing of the harvest data took.

The laser scanning approach of biomass measurement requires always a calibration of the scanner data by a set of biomass data from harvests of selected trees of the experiment in order to be able to convert the relative units obtained by the scans (number of points in the point cloud grid) into mass or volume units (in g or cm^3 of biomass). It is recommended to harvest trees of all important size classes; the quality of the model will necessarily increase with the number of sampled trees. Further studies have to show whether species-specific calibration functions, that relate scanner data to biomass, can be generalized to cover structurally similar tree species as well.

A second goal of this study was to compare the laser scanner approach to other existing methods of non-destructive biomass estimation, in particular allometric relationships between parameters such as total tree height, total leaf number or stem diameter with total plant biomass. While these measurements can be rapidly conducted in a large number of juvenile trees, they require a similar calibration effort as in the case of laser scanning, i.e. a set of harvested trees. While the stem diameter may not be a particularly useful predictor of biomass in juvenile trees, we obtained fairly good relationships between tree height and the total number of leaves with above-ground biomass (R^2 0.54 and 0.67) which were similar to the coefficients of determination obtained for the laser scan-biomass relationship (R^2 0.66–0.85). Given that the labour effort is not higher and the precision of the biomass estimate is similar to conventional non-destructive biomass estimates through allometric relationships, we conclude that the laser scanning approach is a suitable and promising alternative in the field of non-destructive biomass measurement techniques for young trees, which provides a wealth of additional information beyond the biomass estimate, including data on canopy structure, branching patterns, total twig length, the spatial distribution of leaves in the canopy, and others more (e.g. Watt et al., 2003; Thies et al., 2004; Henning and Radtke, 2006; Bucksch and Fleck, 2009). A further advantage is that this approach offers the possibility for monitoring the growth of tree juveniles over time without the need for extra harvests.

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