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Dominik Seidel

Terrestrial laser scanning

Applications in forest ecological research

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– GÖTTINGEN CENTRE FOR BIODIVERSITY AND ECOLOGY –

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Summary

The increasing relevance of the three-dimensional (3D) structure of forest canopies for current research tasks, especially in ecology, generates a rising need for instruments offering detailed spatial information (Lovell et al., 2003; Parker et al., 2004; Tageda and Oguma, 2005; Pretzsch and Schütz, 2005). If a fast measurement of high resolution and real 3D-information (xyz-coordinates of all objects) is of highest priority, terrestrial laser scanning can offer such data with a reasonable effort. Destructive methods are not an alternative due to the non-arguable effort they would require for mature forest canopies, especially if the high-resolution 3D-information is in the focus. Research is facing the challenge that surrogates for the three-dimensional distribution may be no longer needed as comprehensive 3D-data becomes available from terrestrial laser scanning (TLS). Now, algorithms and programs are needed to extract suitable parameters from the virtual forests. The present thesis aimed to contribute to this research. We conducted our studies in the mixed forest of the Hainich National Park (Thuringia, Chapter 3,4) and also analyzed tree saplings in a pot experiment in the New Botanical Garden in Goettingen (Lower Saxony, Chapter 5).

We found that modelling the three-dimensional structure of a species-rich temperate broad-leaved forest stand based on ground-based 3D-laser scanner data and extracting ecologically relevant parameters, such as canopy openness or gap size distribution, is possible when the calculation is based on volumetric pixels (voxels). Independently taken hemispherical photographs of the canopy were successfully simulated based on the scanner data. It was shown that laser scanners can face problems in the identification of rather small canopy gaps, especially in combination with wind-induced movements of canopy elements. Being able to model hemispherical photographs for any position under the canopy offers new opportunities for functional research in tree and forest canopies. We showed that the analysis of species-specific patterns of canopy space occupation and their effect on light competition and light availability on the ground will be possible based on LIDAR data. A future application would be canopy models of growth and photosynthetic carbon gain in mature trees.

We also presented a model of competitive pressure that is able to predict the direction of crown asymmetry of a focal tree caused by competitive effects at the neighbor trees with remarkable accuracy. Our approach of a precise laser-scan-based canopy analysis

and the derivation of competitive pressure vectors using the crown centre distance (between focal tree and neighbor) and DBH as importance values offers a considerable potential for competition research in mixed forests. Multiple-aspect laser scanning of tree canopies can help to achieve a better understanding of the dynamics of canopy space exploration and may lead to an optimization of silvicultural management activities in mixed stands. A higher accuracy in canopy shape analysis is also useful to test the suitability of conventional crown measures (such as crown depth or crown projection area) as estimates for crown volume and their importance in competitive interactions.

Furthermore, we found laser scanning to be a suitable and less time-consuming method for measuring the biomass of juvenile trees. The post-processing of the scanner data required not significantly more time than the computer processing of the data obtained with a traditional harvest approach. 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 pattern, total twig length, the spatial distribution of leaves in the canopy, and others more. A further advantage is that this approach offers the possibility for monitoring the growth of tree juveniles over time without the need for subsequent harvests.

All studies presented above profited from the high accuracy and resolution of the structural information obtained with the laser scanning technology. We tested and evaluated the quality of the data produced with an exemplary scanning system and showed a selection of possible applications in the field of forest ecological research. The future use of laser scanning in forests depends on further simplifications in the field of data processing and automatic parameter extraction via standardized calculation protocols, respective algorithms. The automated separation of tree individuals from point clouds would be an example for such an useful and long-needed algorithm future work should focus on.

Chapter 1

Introduction

1. Scientific motivation

A society benefits from a forest not only aesthetically, but also from its function in regulating the climate in general and mitigating climate change by sequestrating carbon in particular, as well as from the direct harvest of wood, fuel, fibres and pharmaceuticals (e.g. Daily 1997; Canadell and Raupach 2008). To guarantee the vitality and integrity of our forests and their functioning under the prediction of a changing climate, a large scale forest conversion became a new forest management policy in Germany and Central Europe (Lindner 2000; Kenk and Guehne 2001; Noss 2001). According to this policy monospecific forests are to be converted into species-rich mixed stands that are ecologically and economically more beneficial. Therefore, the interest of scientists in the understanding of the complex structure of forests is growing (Mosandl and Küssner 1999; Loreau 2000). To enable a successful management and modelling of the future development of a forest, the chemical, biological and physical interactions within these complex ecosystems need to be understood. Hence, the consequences of a large scale forest conversion on biodiversity, biogeochemical cycles and biotic interactions, as well as on the growth and carbon gain of a stand are one main focus of the research in forest sciences (e.g. Pretzsch 2002). As the three-dimensional distribution of leaves, twigs, branches and stems is probably the most important of all characteristics controlling the future growth and development of a forest stand (Pretzsch 1997), detailed information on the spatial distribution of biomass within a forest patch is needed.

Due to the scarcity of wood as fuel resource in the late Middle Ages, maps of forested areas were drawn to allow for an estimation of the total growing stock and to enable for planning the utilization of the harvested wood (Brack 1997). In the 19th century, foresters in Central Europe used ocular estimates of volume and stocking of small forest areas (Pfeil 1858). This approach was still used for the planning in the State Forest of Saxony in the early 1940's (Loetsch and Haller 1964). While the forest inventory of the 19th century was characterized mainly by the use of experience, simple measurement techniques and early statistical knowledge for small area inventories, the technological development of the 20th century rapidly increased the spatial scale. Advanced statistical methods (e.g. stratified sampling) were applied around 1911 and the first aircrafts allowed aerial survey on the landscape level in the

1920's (Schreuder et al. 1993). The need for forest inventories in large countries such as Canada and Australia enforced the development of these new techniques.

At the beginning of the new millennium sophisticated statistical methods, combined with new remote sensing technologies have become a powerful tool for forest inventory on the regional as well as on the global scale (Brack 1997). However, there is still a need for the measurement of ground-truth data. In addition, structural data is sometimes needed in a higher resolution than those currently available from air- or space-born platforms. Finally, there are still some parameters which cannot be measured with remote sensing instruments (Gong et al. 1998; Lovell et al. 2003; Hopkinson et al. 2004; Naesset et al. 2004; Pfeifer et al. 2004; Korhonen et al. 2006).

While the stem of a tree is a rather simply structured object which can be defined as cylinder or cone based on parameters that can easily be measured (e.g. position of the stem, diameter at breast height, length of the stem), the crown of a tree is a much more complex study object. As intricate as the structure of a tree crown, or the combination of more than one crown to an extensive forest canopy, are the biological, physical and chemical interactions that take place in these ecosystems (e.g. Pretzsch 2002; Lowman and Rinker 2004). Foresters, focusing on extractable wood volume, log sizes or the amount of residues wood, as well as researches, who aim to investigate ecological processes and interactions in a forest canopy, profit from high resolution spatial information on the distribution of biomass on a tree.

In the past, scientists used a variety of devices to enable direct access to the forest canopy, such as rope techniques, ladders, cherry pickers, canopy walkways, construction cranes, towers or even hot-air balloons and inflatable rafts as reviewed by Lowman (Lowman 2001). Beside the direct contact some ground-based remote sensing technologies have been used in the past to measure canopy parameters without actually 'going' into the tree crowns. Examples are binoculars, hemispherical cameras, spherical densiometers and many others more (for extensive review see Chapter 2). Among these so called 'non-contact methods' the ground-based three-dimensional laser scanning is one of the most promising technologies for high resolution measurements on the spatial dimensions of trees (e.g. Fleck et al. 2004).

This technique, also known as terrestrial laser scanning (TLS), allows to describe the tree structure comprehensively and thereby offers new opportunities for investigations dealing with canopy processes or tree interactions (e.g. Lovell et al. 2003; Henning and Ratdke 2006; Takeda et al. 2008). Nowadays, a number of companies sell 3-D laser scanner instruments with data acquisition rates off more than 500.000 measurement points per second, measured in almost all directions (e.g. FARO Focus 3D, FARO Technologies Inc., Lake Mary, Florida, USA; Zoller and Froehlich Imager 5010, Zoller and Froehlich GmbH, Wangen, Germany).

The progress in the development of these instruments is immense. Within the three years of this PhD study the size of comparable laser scanner instruments decreased by more than 50 %, the weight was reduced to almost a third and the data acquisition rate has nearly doubled (e.g. when comparing the Z+F Imager 5006 with the Z+F Imager 5010). At the same time the prices are decreasing constantly.

In parallel to the fast developments on the hardware side (scanners, computers), there is an ongoing research motivation for software-solutions and algorithms for the data handling and parameter extraction from forest laser scans (e.g. Aschoff and Spieker 2004; Hopkinson et al. 2004; Thies et al. 2004; Watt and Donoghue 2005). The present PhD study aims to contribute to this field of science by developing new algorithms and methods for the extraction of structural parameters of forest canopies from laser scanner data and evaluating them based on the use of conventional instruments.

2. Objectives of the study

This study was conducted within the framework of the Research Training Group ("Graduiertenkolleg") 1086: *The role of biodiversity for biogeochemical cycles and biotic interactions in temperate deciduous forests*. Since 2005 senior and fellow scientists, graduated and undergraduate students of more than ten departments work in this project, bringing together the knowledge of biology, forestry, ecology, agroecology, economy and other fields of science. Eleven PhD-students belong to the staff of the second phase of the project, initiated in 2008, and are organized in three groups working on the topics "biodiversity and biotic interactions" (group A), "matter turnover" (group B), and "synthesis" (group C). As a member of the subproject C1 my main study objectives are:

- to model the above-ground stand structure of the study sites,
- to develop a method to characterize the canopy structure, and
- to investigate competition between trees at the study sites.

In order to fulfill these tasks the application of a terrestrial 3-D laser scanner was in the focus of my research. The following hypotheses were tested:

(1) 3-D laser scanning is a useful method to model the above-ground stand structure of species-rich mixed forests (Chapter 2, 3, 4).

(2) 3-D laser scanning data can be used to simulate hemispherical photographs in a forest in order to characterize the canopy structure (Chapter 3).

(3) The influence of competition on the shape of a tree can be measured based on 3-D laser scanning data (Chapter 4).

(4) Estimations of the above-ground biomass and growth rate of young trees are possible based on 3-D laser scanning data (Chapter 5).

3. Study site- The Hainich National Park

The Hainich National Park, located in Thuringia, Central Germany, was chosen as study site as it is the largest area of unfragmented temperate broad-leaved forest in Germany, sheltering up to 14 tree species per ha. All study plots are located in the south-east of the National Park, close to the village of Bad Langensalza (51°06' N, 10°30' E) and are situated about 330 m a.s.l. within two sub-areas named "Lindig" and "Thiemsburg" (Fig. 1). The meteorological station Weberstedt recorded a mean annual precipitation of 590 mm and a mean annual temperature of 7.5 °C (1973-2004, Deutscher Wetterdienst, Offenbach, Germany).

The dominant forest communities are *Galio-Fagetum*, *Hordelymo-Fagetum* and *Stellario-Carpinetum* (Mölder et al. 2008) and all plots are located on a stagnic Luvisol according to the World Reference Base for Soil Resources (WRB).

The mean tree age in the hundred tree diversity clusters is between 70 and 200 years (Schmidt et al. 2009). Since the establishment of the National Park in 1997 a natural stand development was ensured. Prior to that date parts of the forest served as military training area, which allowed at least for a near-natural stand development (Mölder et al. 2008). Further back in history multiple-aged forest (Plenterwald), high forest (Hochwald) and initial coppice with standard systems (Mittelwald) could be found in this area. However, for at least 200 years the area was bearing deciduous forest and can therefore be described as an ancient woodland (Mölder 2009; Wulf 2003).

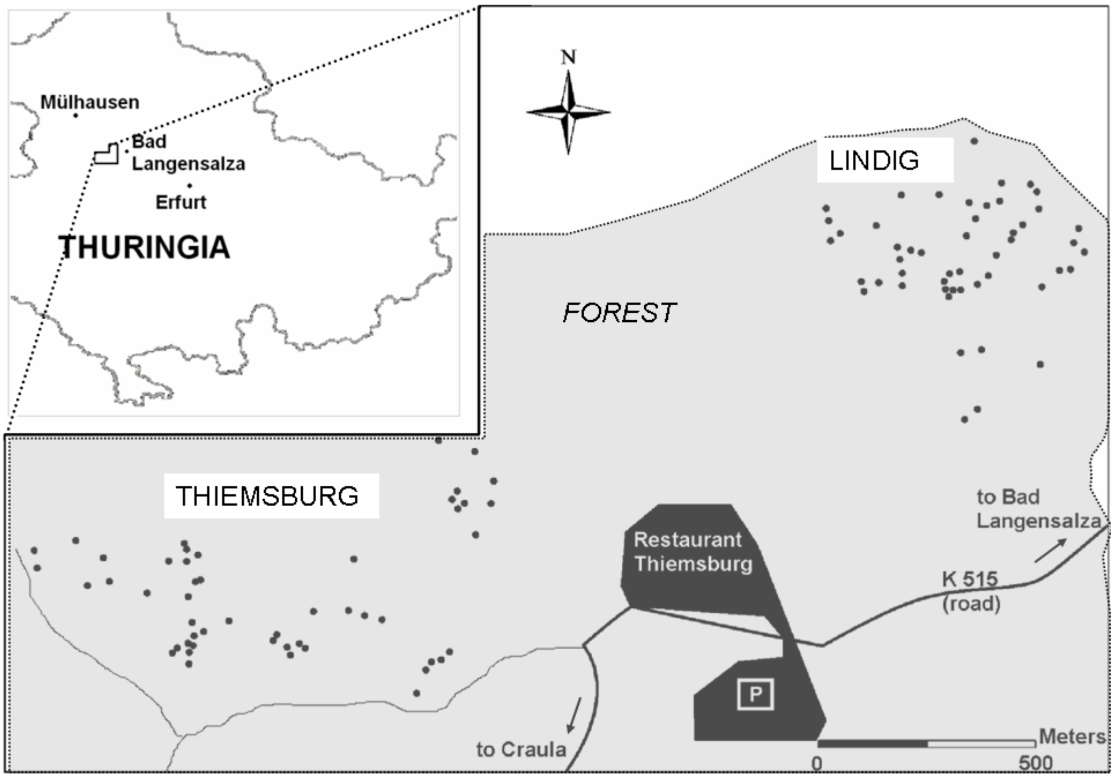

Fig. 1: Map of the research area with black dots indicating the location of the hundred tree diversity clusters.

4. Study design- The 100 tree diversity clusters

The main studies of the PhD students participating in the second phase of the Research Training Group 1086 concentrated on the effects of tree diversity on the biogeochemical cycles and biotic interactions. 100 plots of 4 m² size were selected each in the centre of a group of three trees, forming a so called 'tree diversity cluster'. All possible neighbourhood combinations of the five tree species *Fagus sylvatica* L., *Acer spec*., *Fraxinus excelsior* L., *Carpinus betulus* L., and *Tilia spec.* were selected in the forest, resulting in five one-species, ten two-species and ten three-species clusters (overall 25 different combinations). The three trees forming a triangular shaped cluster with a fenced plot in the centre (Fig. 2) were chosen to be of comparable size, evaluated based on the diameter at breast height, and to be members of the top canopy layer. Each of the 25 species combinations was replicated two times in both sub-areas yielding a total of hundred tree diversity clusters. The mean area encircled by the imaginary lines connecting the three trees was 23.8 m². Overall 300 study trees with a mean diameter at breast height of 44.3 cm were selected based on this study design.

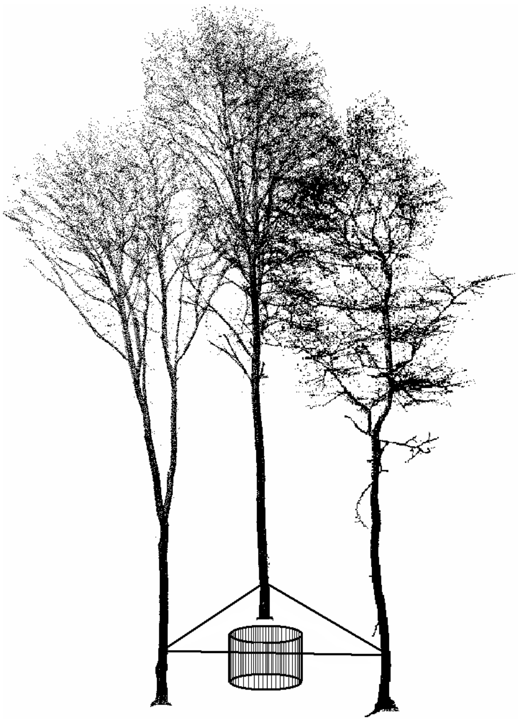

Fig. 2: An exemplary tree diversity cluster consisting of three trees. The location of the study plot in the centre of the cluster is indicated by a fence.

The plots in the centre of the tree diversity clusters were subject to a variety of measurements taken by the members of the Research Training Group 1086 (GK 1086) in the years 2008 to 2010 covering both biotic and abiotic parameters. In addition, a weather station was installed on top of the 'Baumkronenpfad Hainich' (canopy walk way Hainich), located in the middle of the two study areas, providing data on the wind speeds, wind directions, multiple radiation parameters, precipitation and temperature.

5. The Zoller and Fröhlich Imager 5006

All laser scans performed during this study were obtained using the Zoller and Fröhlich Imager 5006 (Zoller und Fröhlich, Wangen, Germany). The instrument is a stand alone laser scanner covering a field of view of up to 310 degrees in vertical and 360 degrees in horizontal direction. With a minimum angular step width of 0.0018 degrees the instrument emits a laser beam with a wave length of 532 nm (green light) which is deflected by a turning mirror into vertical directions, reflected by an arbitrary object in the surroundings of the scanner, and finally detected by a sensor in the instrument. While the turning mirror determines the vertical direction of the emitted beam the entire instruments performs a 180-degree rotation on the horizontal axis to cover all azimuthal directions. As the mirror deflects the beam in all directions on the vertical axis during each horizontal rotation step, only 180 degrees of horizontal rotation allow to cover the full 360 degrees on the azimuth. The green laser beam is circular, 3 mm in diameter and diverges with only 0.22 mrad (ZF 2010). Based on the time-of-flight between the emission of the laser beam and the detection of the reflected signal by the sensor, the internal processor calculates the distance between the instrument and the reflector (any object that could possibly reflect light with 532 nm wave length). The time-of-flight is thereby determined based on the so called 'phase difference'- or 'continuous wave'- technology, in which the difference in the phase of the light wave of the reflected beam compared to the emitted beam is measured. The emitted light beam consists of modulated light waves, that allow to measure a wider range of distances. This is necessary as non-modulated waves would only be useful for measuring distances between two recurring phases of the light wave (Deumlich and Staiger 2002). By modulating a changing wave amplitude on the light wave the ZF Imager 5006 is able to measure distances up to 79 meters, which is the so called ambiguity interval. The calculation is based on the formula

(1) $$d = \text{time of flight} * c/ 2$$

with 'd' being the distance between the sensor and the object that reflected a beam and 'c' being the speed of light (~299,792,458 m/s). The minimum distance that can be measured to an object is one meter. With a weight of 14 kg and battery power for up to 4 h the Imager can be carried by one operator with no need for a laptop or electricity in the field (ZF 2010).

In my studies, focusing on the tree diversity clusters, I performed about 800 scans, each lasting 3 min and 22 sec covering the full field of view of the instrument that was adjusted to an angular step width of 0.036 degrees. This scanning resolution was considered to produce data of a satisfying resolution without causing problems concerning the data storage capacity. A reduction of the data density due to hardware restrictions would still be possible at any stage of the data processing.

6. Scan design and registration process

In order to scan each cluster from five to thirteen perspectives using the ZF Imager 5006 we distributed 24 artificial targets as spatially homogeneous as possible within the area to be scanned defined by the tree diversity cluster and its surrounding trees. These targets represent fix points that are needed to combine multiple scans of the same scene by converting their local coordinate systems (valid for one scan) into a global coordinate system (valid for all scans, see below). Twenty targets were made of simple DIN A4 chessboard-like papers that have been laminated to be protected against water. By simply installing these papers with a dash-board pin at the tree stems around the centre of the plot, fix points are created and can bee seen in multiple scans. Four targets were mounted on telescope sticks and leaned on the trees in up to ten meters height to ensure for a spatial distribution that is as homogeneous as possible over all three spatial dimensions. The first scan was always started in the centre of the triangle formed by the cluster trees and was used as so called 'Masterscan', building the reference for the combination of all scans of the same scene. The number and positions of the following scans were chosen depending on the overall structure of the forest patch. In a cluster with dense understorey vegetation and extensive branches at the lower part of the stems more scans were performed than in case of a rather open cluster. The positions of the laser scanner were chosen in the field to enable an adequate visibility on as many targets as possible. To ensure a complete capture of the whole cluster scene the first row of trees behind the cluster trees (if seen from the cluster centre) was encircled with scanner positions (Fig. 3).

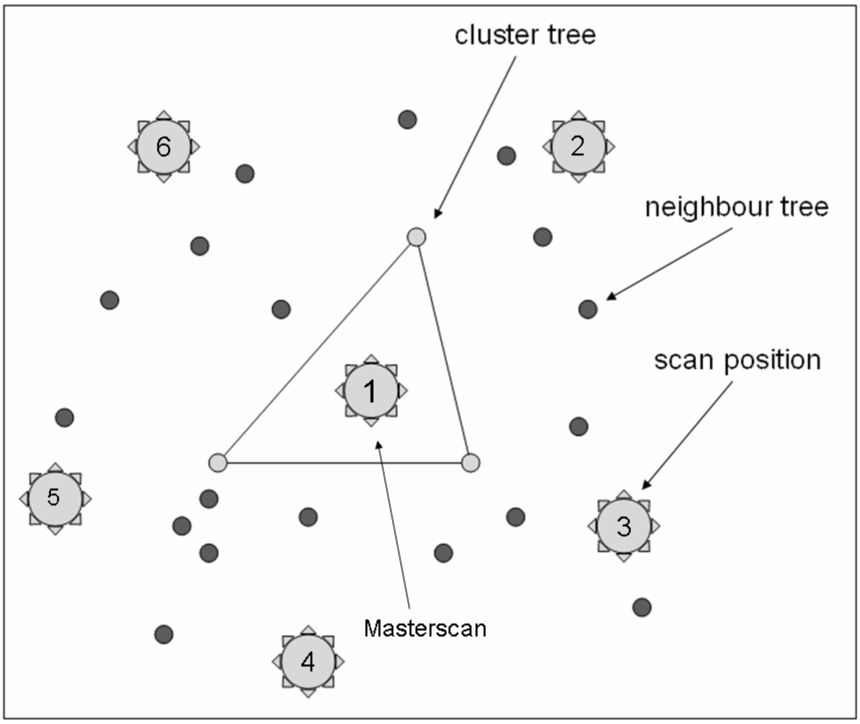

Fig. 3: Scan design as performed on all hundred tree diversity clusters.

Transferring the data to a computer was the next step required to perform the semi-automatic registration process which is needed to enable a real three-dimensional view on the combined scan-data of all scans. By using the software Z+F Laser control (Zoller und Fröhlich, Wangen, Germany) each scan can be examined like a black and white photograph. The scan data is in fact an intensity information for each direction the laser beam was emitted to combined with the distance to the object that caused the reflection. By showing the distorted image, being the two dimensional projection of the scanned three-dimensional forest patch, the position of the centre of each unobstructed artifical target (polar coordinates) can be selected. With a minimum number of three targets being visible in two different scans the information of both scans can be combined. The 'Masterscan', acquired in the centre of the plot is the basis for the coordinate systems of all registered scans, meaning that all scans will be transformed into the coordinates-system of the Masterscan (global coordinates). Based on mathematical rotation and translation of the coordinates of all target-centres found in two scans the registration process itself is performed by the Z+F Laser control software. The virtual replicate of whole forest patch is than available in a single pts-file, storing the polar coordinates and the intensity of all laser points obtained for the scan session, which is the basic information type for all investigations presented here.

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Chapter 2

Review of ground-based methods to measure the distribution of biomass in forest canopies

Annals of Forest science, in press

Review of ground-based methods to measure the distribution of biomass in forest canopies

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Abstract

Ecological research and an effective forest management need accurate information on the structure of forest canopies to understand the biochemical, physiological and biogeochemical processes within a forest. This paper reviews the currently available instruments for measuring the distribution of biomass within forest canopies. We compare the most well-established approaches and present the different measurable parameters. A special focus lies on the resolution of the obtained data. It was found that only 3D-laser scanners offer data with the resolution required by ecologists, private landholders, the forest industry and the public to detect trends in tree growth patterns and canopy interactions in all three spatial dimensions. But, data validation, data analysis and parameter extraction are still under development, and the price of the instrument is quite high. Research should focus on the parameter extraction from terrestrial laser scanner data as this could allow for the calculation of functional attributes for different sections of a canopy on a high spatial resolution. It could also help ecologists to characterize the structure of forest stands in a quick and precise way.

Keywords: forest canopies / biomass distribution / 3D-information

1. Introduction

Forests cover about 30% of the earth's mainland and the surfaces of forest canopies are the main gateways regulating the exchange of energy, carbon and water vapour between terrestrial ecosystems and the atmosphere (FAO, 2001; Law et al., 2001; Parker et al., 2004). The structure of a forest canopy influences the quantity, quality, spatial and temporal distribution of light in the stand, which in turn affects the presence or absence of ground vegetation, influences temperature, relative humidity, and the physiological activity of tree organs (leaves, fruits, woody organs) and many other organisms within a forest (Jennings et al., 1999; Kobayashi and Iwabuchi, 2008).

Because of the complexity of the three-dimensional forest canopy structure, most canopy measurement research has focused on parameters that may serve as a surrogate for the two- or three-dimensional canopy structure, such as leaf area index (LAI), average leaf inclination angle (ALIA), above-ground biomass (AGBM), canopy clumping index (Ω) or foliage density (Chen and Black, 1992; Kucharik et al., 1999; Gower et al., 1999; Drake et al., 2003; Jonckheere et al., 2004; Takeda and Oguma, 2005).

Some of these variables, e.g. LAI or AGBM, can be obtained from airborne platforms (Running et al., 1986; Chen and Cihlar, 1996; Lefsky et al., 1999; Hyyppä et al., 2008). However, for an effective forest management, especially for ecological research, it is desirable to obtain information about the distribution of the biomass in a forest plot at a higher resolution, especially higher than that currently available from remote sensing (Watt et al., 2003). Such data could be used to detect trends in the commercial and biodiversity conservation values of forests and might serve for the purpose of carbon accounting (Tickle et al., 2006). Additionally, there is a need for methods collecting ground truth data and for obtaining detailed information on canopy stand structure where remote sensing technologies are 'blind' (Gong et al., 1998; Lovell et al., 2003; Hopkinson et al., 2004; Naesset et al., 2004; Pfeifer et al., 2004; Korhonen et al., 2006).

Until now sampling of the complete spatial heterogeneity of a canopy has been difficult as it can neither be directly measured nor can it be estimated with indirect approaches. The main reasons are that the number of needed measurements is large and errors are too high (Jennings et al., 1999; Jonckheere et al., 2004). Hence parameters that could serve as surrogates are still important. While it is significant to integrate or simplify descriptors in all those cases where a direct relationship to total biomass or volumetric density is given, the suitability of these parameters is questionable especially during an assessment of forest functions. Functional processes such as gas-exchange or radiation interception are often species-specific and can usually not be explained by vegetation density on its own (Larcher, 2003).

Since forest management concentrated on converting monocultures into diverse mixed-species stands, which are economically and ecologically more beneficial (Olsthoorn et al., 1999; BMBF, 2003; Spiecker, 2003; BMBF, 2004; Lüpke et al., 2004; Schraml and Volz, 2004), forests and their canopies became more heterogeneous and therefore their three-dimensional structure became more relevant. The hitherto prevalent assumption of vertical or horizontal canopy homogeneity as used in forest models needs to be revised for trees in a forest stand, as there are shade and sun leaves as well as young and old leaves (Boardman, 1977; Ashton, 1978; Koike et al., 1990; Canham et al., 1994; Parker et al., 2004). Even the sunlight penetration and thereby the distribution of direct and diffuse light, cannot be explained on the two-dimensional level (Pretzsch and Schütz, 2005). As Pretzsch and Schütz (2005) pointed out, "the fact that sunlight does not come vertically from above but is absorbed or modified when passing through canopy layers, calls two-dimensional concepts into question" (Pretzsch and Schütz, 2005, p.631).

In the literature, some promising results of modelling the spatial distribution of light or biomass in a canopy in two (2D) or three (3D) dimensions are presented (Aber and Federer, 1992; Canham et al., 1994; Lovell et al., 2003; Hopkinson et al., 2004; Tageda and Oguma, 2005). But a number of methods are suggested which are simply not practical for evaluating biomass distribution for large areas (Koike, 1985; Kurachi et al., 1986; Sumida, 1995).

The objective of this paper is to review the major direct and indirect terrestrial methods for measuring the distribution of biomass in forest canopies and to identify gaps in the technology. Precise information on the distribution of the biomass is needed to increase the quality of models of radiation, interception or wind velocity within a stand. Having detailed information on the structure allows scaling from branch to tree level, or from tree to stand level. This will help to understand processes within the canopy and interactions between forests and the atmosphere as well as between forest and the pedosphere. Furthermore we depict the needs for future research on instruments allowing to gain these information. A discussion of the advantages and disadvantages of the various approaches, as well as the expectations of the future applications will be given. A classification of two groups was used: (i) direct methods (destructive) and (ii) indirect methods (non-destructive). Prior to the introduction of the methods we will present the parameters that can be measured and how they are defined.

2. Suitable parameters and their definitions

In this review we do not focus on the mathematical procedures used to derive all parameters introduced but we will briefly present their definition. For those who are interested in the mathematical sources, we will cite appropriate literature. One of the most important parameters is the *leaf area index* (LAI, see Fig. 1). It has been redefined many times as reviewed by Jonckheere et al (2004). Hence it is important to point out which definition is used in a study. According to Jonckheere et al (2004) LAI is defined as one half of the total leaf area per unit ground surface area in current literature. A number of studies recommended the use of the term *plant area index* (PAI, see Fig. 1) to separate data gained from indirect LAI-measurements from those of direct measurements. Indirect approaches do not allow separating between photosynthetically active and inactive biomass and therefore the actually measured parameter is the whole plant area (woody and non-woody plant material) instead of the photosynthetically active area alone (Parker et al., 2004; Henning and Radtke, 2006; Van der Zande et al., 2006). PAI can be considered as one half of the total area of all plant surfaces per unit of ground area (Henning and Radtke, 2006). Walcroft et al (2005) suggested using *effective LAI* (L_e) to distinguish between woody and foliage surfaces if measured with optical methods, and foliage alone when measured directly. In this review we used the term PAI when talking about optically (indirect) retrieved "LAI"-data that included woody and non-woody plant material. *SAI, surface area index*, is the total foliage surface area per canopy volume (Wells and Cohen, 1996, p.1336). *Canopy closure* is defined as percentage of ground shaded by overhead foliage (Daubenmire, 1959 cited in Ganey and Block, 1994). Confusion about similar parameters has been clarified by Jennings et al (1999). *Canopy gap fraction*, which is the fraction of view that is unobstructed by the canopy in any particular direction (Welles and Cohen, 1996) is similar but not identical to canopy closure (see Fig. 1).

The term *leaf area density* (LAD, see Fig. 1) is useful if the volumetric density of a canopy is to be described. It is defined as total leaf area per canopy volume (Welles and Cohen, 1996). The *foliage density*, defined in Koike (1985) as the expected value of leaf number penetrated by a straight line within a unit distance, is identical with the *relative frequency* or *percentage frequency* in Wilson (1959; 1960; 1965) or the *density of foliage* in MacArthur and Horn (1969).

Detailed information about the orientation of foliage objects is given by the *average leaf inclination angle* (ALIA, see Fig. 1) which describes the angle between the leaf surface and a horizontal plane (Takeda and Oguma, 2005). The randomness of the distribution of foliage in a canopy can be quantified with the *clumping index* (**Ω**, see Fig. 1), which was first affiliated by Nilson (1971) and is used to describe the degree of systematic arrangement of foliage in a canopy (Nilson, 1971). As a comprehensive description of the amount of the existing biomass above the ground, the *above-ground biomass* (AGBM, see Fig. 1) does not distinguish between green and non-green biomass or between herb- or tree-layer vegetation (Drake et al., 2003). Figure 1 gives a graphical overview of the major characterises of a forest canopy and important biomass parameters.

It is obvious from the great variety of parameters that we need various methods to describe and measure all these different canopy characteristics. In the following we present ground-based methods to determine the mentioned parameters.

3. Direct methods

Direct methods use instruments that have direct contact to the material of investigation (e.g. a leaf) and that are able to determine the desired parameters without using mathematical derivations. The term '*destructive methods*' is also used as the investigated objects are usually damaged during the measurement.

As these methods are of high accuracy they were often used as reference for other approaches (e.g. Jonckheere et al., 2004; Thimonier et al., 2010). Although nowadays there are already other techniques used for validation (Lovell et al., 2003; Hopkinson et al., 2004; Morsdorf et al., 2006), the direct methods are still regarded the best choice.

Allometrics

Allometric relations are based on the determination of a relationship (correlation) between characteristics of two different plant organs, e.g. the diameter at breast height and the total height of a tree. Thereby one parameter is measurable and the other one is the non-measurable (or difficult to measure) parameter of interest. If the biomass distribution is the parameter to be estimated, allometric relations could be based on the destructive collection of the foliage of certain branches with known diameter. The characteristics of the sampled plant material, e.g. the leaf area of a branch with a certain basal diameter, can then be assigned to the entire tree, and even to other trees of the same species if the diameters of the according branches can be measured. It is crucial to develop a statistical model that describes the relationship between branch diameter and the leaf area of this branch exactly enough (Bartelink, 1997). Therefore one can say that it can be laborious and time consuming to establish an allometric formula with a satisfying degree of accuracy and many samples are needed (Gower et al., 1999). Many biomass formulas (allometric relations) are available to estimate difficult to measure parameters for different species based on easier to measure parameters, such as diameter at breast height (DBH, see Fig. 1), branch basal area, tree height or others (Whittaker and Woodwell, 1968; Hashimoto, 1990; Niklas, 1994; Gower et al., 1999; Porte et al., 2002; Pretzsch and Schütze, 2005; Pretzsch, 2006). Special software has been developed to predict biomass parameters based on existing equations (e.g. BIOPAK, Means et al., 1994). If not reconfirmed by case-specific calibration (e.g. leaf collection in the stand of interest) allometric relations could also be considered as an indirect method. However, the establishment of an allometric formula found in the literature has once been based on a destructive sampling, at least to achieve validation-measurements (Gower et al., 1999). Therefore we classify allometric relations as direct methods.

Stratified clipping and the scaffolding approach

'Stratified clipping' is based on a harvest of all plant elements within defined height-layers. The harvest is repeated for different height levels (canopy strata), to get a vertical profile of the foliage density (Monsi and Saeki, 1953; Fujimori, 1971; Aber, 1979). Here a horizontal analysis of foliage allocation, for instance to investigate clumping effects, would be possible. This method is time consuming (Aber, 1979) and thereby, especially in complex structured natural forests, it is only applicable to small canopies or single trees. Allometric relations are often based on such exhaustive measurements on single trees, which might not be feasible in protected areas. However, collecting all leaves of a tree is an exact way to determine its leaf area or biomass and the data can be used for further analysis, such as leaf age or health assessment of the tree. The extraction of vertical leaf-area distributions has been the main goal of stratified clipping as presented in the literature (Kira et al., 1969; Waring et al., 1982).

The scaffolding approach is a special form of stratified clipping. Fukushima and colleagues (1998) tested the accuracy of the 'MacArthur-Horn method' (MacAthur and Horn, 1969, see indirect methods) with a harvesting approach combined with allometrics by using a scaffolding in the forest. The scaffolding consisted of cells of defined size, spreaded over different height levels. All leaves inside each cell were counted and partly harvested. Allometric relations were then used to estimate the stand's foliage density. Here, as an improvement to stratified clipping, the horizontal biomass distribution can also be described (Fukushima et al., 1998). A big disadvantage is that the use of a scaffolding in a forest is strongly limited by the topographic conditions, understorey density and stand height (Barker and Pinard, 2001).

Most direct harvest approaches potentially fulfil the requirements for a reconstruction (in 2D or 3D) of the sampled tree- or stand-canopy structure even though the effort might not be worthwhile. In fact direct methods are extremely laborious if not impracticable if complete canopies of mature trees are to be investigated (Aber, 1979). But there is no other way for a validation of the indirect methods.

Litter traps

A widely used direct non-harvest method is the traditional litter trap which is at least 40 years old (Ovington, 1963; Marshall, 1968; Heller, 1971; Ellenberg et al., 1986). The litter fall of leaves or needles is collected in traps of various designs that are adequate to collect the litter and allow for water penetration to prevent decomposition (Daniel, 1975; Tanner, 1980; Neumann et al., 1989; Chason et al., 1991; Dufrêne and Bréda, 1995; Takeda and Oguma, 2005). What material is collected is determined by wind and gravity combined with the primary position of the leaf or needle in the stand. Researchers advice that this method should only be used in deciduous forests with autumn leaf fall (Jonckheere et al., 2004), as leaf age is an interesting factor when analysing the collected material (Lowman, 1988). The analysis of the collected material is rather easy but time-consuming. Leaf area is calculated by scanning the leaves with a flat-bed scanner and using software (e.g. WinFolia, RegentInstruments, Quebec, Canada) to calculate the area of exemplary leaves (Lendzion and Leuschner, 2008). Leaf weight and other parameters can be determined after drying the samples in an oven. The exact procedure is known as the 'gravimetric method' and is a tool to define the green-leaf-area-to-dry-weight ratio, which is crucial if litter trap data shall be assigned to the plot level (Jonckheere et al., 2004). Continuing the separation by species to analyze species-specific parameters is as well possible as an additional check for diseases, leaf age and other characteristics (Lowman, 1988; Luizao, 1989; Takeda et al., 2008). In contrast to the other direct methods, information on the spatial distribution in all three dimensions is insufficiently available by this approach, which is a big disadvantage, as a forest stand is not homogeneous in any direction. Setting up a large number of litter traps per area unit could solve as statistical solution to get information on a higher level of spatial resolution, but would not be feasible (Jonckheere et al., 2004). Litter traps are often used for validation of new methods (e.g. McIntyre et al., 1990; Thimonier et al., 2010) and are assigned to the direct methods even though they are not destructive (Sampson and Allen, 1995; Mussche et al., 2001; Jonckheere et al., 2004). However, litter traps are clearly different from the other direct approaches.

4. Indirect methods

In contrast to the direct methods, indirect approaches are based on mathematical derivations or assumptions which are used to calculate the desired parameter from another easily measured parameter (Jonckheere et al., 2004). Indirect methods are not based on an active collection of plant material and are therefore not destructive. They can be separated into indirect contact methods that require contact between the measuring instrument and the plant, and indirect non-contact methods that operate without any contact to the plant.

Indirect contact methods

Point quadrat method and inclined point quadrats

The theory behind the indirect contact methods is based on investigations developed in the 1930's. Levy and Madden (1933) introduced the point quadrat method whereupon thin needles were passed through grassland or low-vegetation canopies (up to 1.5 m height) in an upward direction. The contacts between the needle and the green foliage were recorded and the ratio of non-contact-shots to contact-shots was then used as a measure of the leaf area above a predefined quadrat of ground area (Levy and Madden, 1933).

In 1960, Wilson (1960) published an improved model, the inclined point quadrats approach. Extensive tests lead Wilson to the conclusion that only sloped needle-shots which are perpendicular to an inclined ground area quadrat, were able to estimate the LAI with satisfying accuracy. He recommended an inclination angle of 32.5° at which LAI became equal to 1.1 times the average number of leaf- contacts per needle (Wilson, 1960; Jonckheere et al., 2004). It is important that either the needle or the leaves had to be randomly distributed according to the compass direction (Barkman, 1988), as the mathematics would otherwise be limiting. Suggestions and practical evidence on how to further improve the inclined point quadrat were given and reviewed by Jonckheere and colleagues (Jonckheere et al., 2004). Dufrêne and Bréda (2005) compared the use of a sharp and a blunt needle and found the results to be significant linearly related to litter trap data but systematically lower in a range of 6 to 37%. Measuring biomass distribution by counting contacts and non-contacts with a measurement tool in a manual way is difficult to conduct, time-consuming and labour intensive work. In addition it is difficult to retrieve contact- or non-contact data even for small canopies, such as grass (e.g. Knight, 1973). First, it is not easy to bring a needle or something similar into the canopy without disturbing it and secondly it is difficult and thereby subjective to determine whether there is a contact or not. Jonckheere et al (2004) pointed out that there is still the problem that at least 1000 insertions should be done to achieve reliable results. As long as the insertions are to be done manually all improvements according to the used instruments or even automated contact detection (Jonckheere et al., 2004; Weiss et al., 2004) will not significantly increase the applicability of the method to tall forest canopies.

Indirect non-contact methods

Non-contact methods are also known as 'optical' methods (Fassnacht et al., 1994; Chen and Cihlar, 1996; Kucharik et al., 1998; Walcroft et al., 2005) as they are based on optical measurements. Typically retrieved parameters are foliage density, ratios of photosynthetically active radiation (PAR) between above and below the canopy, canopy closure, and many others (Koike, 1985; Koike, 1989; Welles and Norman, 1991; Stenberg et al., 1994; Guevara-Escobar et al., 2005). The canopy gap fraction is an important surrogate for LAI or PAI, and it can also be determined based on indirect non-contact methods (Welles and Cohen, 1996). Canopy gap fraction is essentially identical to the parameter derived from the inclined point quadrat methods (ratio of non-contact shots to contact shots when observed in skyward viewing direction).

MacArthur and Horn'- photographic method

The "MacArthur and Horn"-photographic method allows the determination of the ratio of sky to plant area in a photograph made in an upward direction from under the canopy. The photograph is covered with a grid of lines and the percent cover of the canopy is estimated by the percent of grid squares with more than 50% covered (MacArthur and Horn, 1969). Originally the method was developed to estimate vertical foliage profiles by recording the heights where a plant element intersects with a vertical line virtually drawn to infinity above the intersecting points of the grid on the camera. The camera is usually moved randomly along a transect. PAI and the vertical distribution of the AGBM can finally be calculated from these data (Fukushima et al., 1998; MacArthur and Horn, 1969). Aber (1979) further improved the method and named it "optical point quadrat method". Both, the "MacArthur and Horn"-photographic approach and the optical point quadrat method used by Aber (1979) have some similarities to the methods presented in the chapter "LIDAR and optical point quadrat methods" but are treated separately in this paper due to their photographic character.

Hemispherical photography

Hemispherical photography is another photographical approach which actually predates the "MacArthur and Horn"-photographic method. In the 1890's there were suggestions to use photographs to assess 'the effect of obstruction on irradiation at a site' (Riblet, 1951 cited in Anderson, 1964). These thoughts were the basics for the invention of the hemispherical or 'fisheye'- photography. In 1924 Hill published his idea of "a lens for whole sky photographs" and created a lens with a simple equidistant (polar) projection (Hill, 1924). In the following years advancements of Hill's lens with a field of view of up to 180 degrees were brought to the market and used widely (Evans and Coombe, 1959; Anderson, 1964; 1966; Madgwick and Brumfield, 1969; Bonhomme and Chartier, 1972; Pope and Lloyd, 1975; Nilson and Ross, 1979; Herbert, 1987). Equidistant polar projections thereby prevailed against competitors with mathematically more difficult projection types (Anderson, 1964; Rich, 1990; Jonckheere et al., 2004). Still, distortions caused by the lens may introduce errors in the results and should be corrected (Herbert, 1987). Anyway, hemispherical photography enables the analysis of many other parameters more than LAI, such as light penetration or leaf angle distribution (Rich, 1990). In an analogy to the before mentioned non-contact method, hemispherical photographs can offer gap fraction data (canopy openness, see Fig. 1) that allows for the estimation of PAI, transmitted radiation and other parameters (Koike, 1989; Hardy et al., 2004). The images need to be processed to separate pixels representing plant material and pixels representing the sky according to their grey values and a simple threshold procedure (e.g. Frazer et al., 1999; Englund et al. 2000). Therefore, hemispherical photographs need to be transformed to grey scale when made as colour images and are to be taken in upward direction with the camera being levelled. Camera settings should be optimized for high contrast between plant and sky. To get a workable black-to-white-contrast there should be a uniformly overcast sky to prevent direct radiation causing illumination effects in the picture and thereby leading to misclassifications between sky and plant material, which is the basis of the analysis of hemispherical photographs. Only pictures with high contrast allow successful, automated, less subjective and fast image processing. Analysis software is available from several manufacturers, (e.g. WinScanopy (RegentInstruments, Quebec, Canada), CanEye (www.avignon.inra.fr/can_eye) or Gap Light Analyzer (Simon Fraser University, Burnaby, B.C.) and others more. Discussions on suitable camera settings (Chen et al., 1991; Macfarlane et al., 2000; Jonckheere et al., 2004; Zhang et al., 2005) as well as on the thresholding procedure and its subjectivity (Anderson, 1964; Guevara-Escobar et al., 2005; Zhang et al., 2005) can be found in the literature. In addition there are publications available on the differences between the results from analogue and digital cameras (Frazer, 2001). The 3D-biomass distribution can be estimated from hemispherical photographs if the sampling design is appropriate (Ondok, 1984). A type of hemispherical photography with similar characteristics but with an included software that directly processes the images is the digital plant canopy imager (CI-110, CID Bioscience, WA, USA). It is not treated as an extra method here as it is basically identical to hemispherical photography in the way of generating the data, but doing the analysis in real-time (Bréda, 2003; Keane et al., 2005).

In the past, data retrieved from such photos were useful for ecological studies and were often used as a validation for novel measurement techniques, such as LIght Detection And Ranging (LIDAR, see next chapter) instruments (Brunner, 1998; Lovell et al., 2003; Hopkinson et al., 2004; Morsdorf et al., 2006).

LIDAR and optical point quadrat methods

LIDAR instruments have recently been used as 'optical point quadrat' methods and were tested for giving reliable gap fraction data. Optical point quadrat sampling means that the traditional needle as used in the (inclined) point quadrat method to detect contact and non-contact shots is substituted by a laser beam (Vanderbilt et al., 1979; Lovell et al., 2003; Parker et al., 2004; Takeda et al., 2008). Until now the method was mainly used for small canopies or crops (Vanderbilt et al., 1979; Walklate, 1989) but attempts to measure forest canopies are also reported (Lovell et al., 2003). The LIDAR unit emits a laser beam in a certain direction and receives a signal if the beam was reflected by an object. Consequently, contact shots are equivalent to reflected laser beams that reach the receptor unit of the instrument and non-contact shots are equivalent to non-received shots. Systems provide a range from simple single-direction laser pointers to 2D- or even complete 3D-laser scanners whereas tripod-based approaches exist as well as portable ones (Welles and Cohen, 1996; Blais, 2004; Fleck et al., 2004; Dias, 2006; Hosoi and Omasa, 2007). Not all of these instruments have been successfully applied to tall forest canopies.

3D-laser scanners can be used in a multiple scan design to create 3D-models of the scanned scene based on more than one perspective. The scanner is moved to different positions in and around the investigated scene, in which artificial targets are fixed to allow the combination of the scans in the computer into one common coordinate frame (Hopkinson et al., 2004; Pfeifer et al., 2004; Dold and Brenner, 2006; Henning and Radtke, 2006; Van der Zande et al., 2006; Fleck et al., 2007). The scanning procedure is usually fast and can be done in a few minutes for a full hemisphere with a state-of-the-art scanner, e.g. the Z+F Imager 5006 (http://www.zf-laser.com/-e_index.html) or the FARO Laser scanner photon (http://laser-scanner.faro.com/faro-laser-scanner-photon/) and others more. However, the transformation of all scans into one coordinate system requires a time-consuming registration process and strong computer hardware which can make the post-processing rather expensive.

The use of terrestrial laser scanners (TLS) is usually restricted to what is visible from the ground even if different perspectives are used. Approaches mounting the scanner on a mobile lift to get a better overview are rather seldom (Loudermilk et al. 2007). Anyway, obstruction effects can never be totally eliminated. This causes a general trend of less data in the uppermost part of the investigated scene as the laser beams are already reflected by lower canopy elements (Chasmer et al., 2004; Hosoi and Omasa, 2007; Takeda et al., 2008).

Publications show that TLS is en route to become a powerful tool to measure the 3D-distribution of the biomass of a forest in a never seen resolution, speed and comprehensiveness (Lovell et al., 2003; Henning und Ratdke, 2006; Takeda et al., 2008). Automatical measurements of length and diameter of tree trunks and individual branches including the changes in their radii (Pfeifer et al., 2004) are as well possible as tree lean, sweep and taper (Watt et al., 2003; Thies et al., 2004), gap fraction, PAI and LAI (Lovell et al., 2003; Chasmer et al., 2004; Henning and Ratdke, 2006; Danson et al., 2007; Takeda et al., 2008). Most of these applications are still under development and validation remains a problem (Pfeifer et al., 2004; Van der Zande et al., 2008).

Radiation measurement

The LI-Cor Line quantum sensor LI-191 (LI-Cor Bioscience, Lincoln, NE) and other linear sensors measure the ratio between the photosynthetic active radiation (PAR) under the canopy and above the canopy, usually with a two-sensor sampling allowing for simultaneous measurements. The sensor itself consists of a meter-long quartz rod covered with a glass that filters non-PAR radiation. Canopy closure (see Fig. 1) and LAI can be estimated from this data as they are related to the gap fraction of the canopy that allows PAR to penetrate (Martens et al., 1993; Stenberg et al., 1994; Welles and Cohen, 1996; Guevara-Escobar et al., 2005) and thereby conclusions on the biomass distribution can be drawn. This is done based on the Lambert-Beer-law and was described in detail by Monsi and Saeki (1953), including formulas and derivations which will not be repeated here.

Other PAR line quantum sensors are the Sunfleck Ceptometer (Decagon Devices, Pullman, WA, USA), in the modified versions called SunLink and AccuPAR, and the SunScan SS1 (Delta- T devices, Cambridge, GB) (Dufrêne and Bréda, 1995; Welles and Cohen, 1996). The Sunfleck Ceptometer and its descendants consist of 80 small sensors spaced one cm apart on a linear probe, all measuring the incoming PAR independently from each other allowing the estimation of a sunfleck distribution. The SunScan SS1 reads data from two ceptometer-like sensors parallel to calculate LAI via a light model (Welles and Cohen, 1996).

Kucharik and colleagues (1998) pointed out that the assumed random distribution of foliage elements, underlying the theory to derive LAI (or PAI) from indirect measurements, is frequently called into question (Kucharik et al., 1998). As the the Lambert-Beer-law (Jarvis and Leverenz, 1983; Marshall and Waring, 1986) and the one-dimensional inversion model (Norman and Campbell, 1989), which are usually used for the computation of the LAI (or PAI) from non-contact instruments (Monsi and Saeki, 1953), are only valid in homogeneous media, they have to be corrected with the clumping index (Ω). Ω is used to account for non-randomness at the shoot, branch, crown or canopy level that occurs in every canopy (Lang and Yueyuin, 1986; Stenberg et al., 1994; Chen and Cihlar, 1995b; Dufrêne and Bréda, 1995; Weiss et al., 2004; Leblanc et al., 2005; Walcroft et al., 2005; Morsdorf et al., 2006).

The hemispherical sensor LI-Cor LAI-2000 (LI-Cor Bioscience, Lincoln, NE, USA) is the consequent advancement of the LI-Cor Line quantum sensors LI-191. The indirect estimate of the biomass distribution is based on the theoretical relationship between leaf area and canopy transmittance, which is the actually measured parameter (Welles, 1990). LAI is calculated from measured radiation via inversed radiation models as introduced above (Jarvis and Leverenz, 1983; Marshall and Waring, 1986; Norman and Campbell, 1989). The LAI-2000, also named ‘plant canopy analyzer’, therefore uses five photo diodes which are arranged in concentric rings and measure the relative irradiance below 490 nm for different sky sections. The canopy transmittance is then computed for the different sections as the ratio of below-to-above-canopy radiation for each ring. Below and above canopy readings need to be done without a big time-delay and under overcast sky conditions that remain uniform

(Li-Cor, 1992; Wang et al., 1992; Stenberg et al., 1994; Welles and Cohen, 1996; Guevara-Escobar, 2005).

TRAC and MVI

In 1995, Chen and Cihlar invented the TRAC (Tracing Radiation and Architecture of Canopies)- instrument (Chen and Cihlar, 1995a) to give estimates of the clumping factor (Ω) as needed for reliable data from indirect non-contact measurements of PAI or LAI. Ω is calculated by analyzing the canopy gap-size distribution. Canopy gap fraction is thereby analyzed as a function of solar zenith angle (Chen and Cihlar, 1995b; Kucharik et al., 1998; 1999). The TRAC uses three Li-Cor LI-190 SB PAR-sensors, two facing the sky, one facing the ground and calculates the ratio of total PAR to reflected PAR. For coniferous tree species it is not yet possible to determine Ω on a scale larger than the shoot level, neither with the TRAC nor with the MVI (see below), as mentioned by Chen et al. (Chen et al., 1997).

Shortly after the TRAC was brought to the market, Kucharik et al. (1998) presented the MVI (Multiband Vegetation Imager). The MVI allows to distinguish leaves from branches by using a two-band (Visible, 400-620 nm and Near-Infrared, 720-950 nm) image pair of the investigated scene (Kucharik et al., 1998), which is a unique and useful feature. The spatial relationship between branches and photosynthetically active foliage can thereby be measured with this instrument as well as Ω, the clumping factor (Kucharik et al., 1998).

Both, TRAC and MVI, are based on measurements of the net radiation and have been intended to measure Ω, but not LAI, PAI or other canopy parameters, which makes them different from the other instruments presented here. However, they were included into this review as the clumping factor is also regarded as an important parameter to determine biomass distribution information.

DEMON

The DEMON (Assembled Electronics, Yagoona, NSW, Australia) is an instrument used to measure the direct beam transmission of the sun in canopies. Calculations are thereby also based on measurements of the canopy gap fraction as a function of zenith angle. The DEMON is faced directly to the sun while the operator is standing under the canopy and the incoming radiation is filtered to a band near 430 nm and then captured in a photocell. The acceptance angle of the photocell is limited to only 0.302

steradians and thereby diffuse radiation from 95% of the upper hemisphere is eliminated. The measurements have to be repeated and results are averaged over different sun angles requiring some knowledge about Ω from other instruments, such as MVI or TRAC to give reliable results (Lang et al., 1985; Lang, 1990; Welles and Cohen, 1996; Kucharik et al., 1998).

Spherical Densiometer

The classical 'Spherical Densiometer' is widely used to retrieve forest canopy parameters, such as canopy closure and hence the forest light environment, optically (Knowles et al., 1957; Englund et al., 2000). It is an inexpensive and simply constructed instrument invented in the 1950's (Lemmon, 1956; 1957). Consisting of a convex or concave mirror with an overlaid grid of squares, the spherical densiometer is hand-held horizontally at elbow height while the operator takes at least four sampling positions (Cook et al., 1995; Fiala et al., 2005). Some authors classified the spherical densiometer as a quick and reasonably precise method to determine the long-term light environments even though it is faced with the problem of subjectivity (Englund et al., 2000). Others stated that results of the spherical densiometer are weakly correlated to other instruments but not influenced by subjectivity (Engelbrecht and Herz, 2001), while again others say that the accuracy of the obtained data is often questionable *especially due to subjectivity* (Ganey and Block, 1994). Cook et al (1995) even named their paper: "spherical densiometers produce biased estimates of forest canopy cover." (Cook et al., 1995). However, to minimize operator effects, measurements should be done by only one experienced operator and with a densiometer fixed on a tripod and being levelled (Lemmon, 1956; Strickler, 1959; Vales and Bunnel, 1988; Ganey and Block, 1994). Many instruments exist that are similar to the spherical densiometer and that allow visual estimates of canopy closure and we will name them for the sake of completeness: Line intercept (Canfield, 1941), non-spherical-densiometers (Stumpf, 1993) or the vertical tube (Johansson, 1985). Other ocular estimates exist but they are usually used to define canopy characteristics of the understorey vegetation (Walters and Soos, 1962; van Hees et al., 2000).

The Moosehorn

The Moosehorn is a simple handheld instrument which can be used to measure the canopy density and the crown closure. Basically it consist of a long box with a glass on the top end and a grid printed on this glass. The box is to be held vertically in a way, that the glass faces directly the sky (a bubble level is useful). On the bottom end of the box is a sighting aperture that allows seeing the glass with the grid via a mirror. The operators head is thereby in a natural orientation with the eyes being parallel to the forest floor which makes it easier to count the number of dots in the grid not covering canopy material. The proportion of dots covering canopy material and those covering the sky is related to the canopy density. Repeated measurements are necessary to get reliable results. Out of 25 dots in the grid only the central one is projected vertically. The remaining dots are projected in angles between 1.8 and 5.1 degrees from vertical which could cause some bias, as well as the difficulty to hold the whole instrument vertically for the period needed to count all grid points (Robinson, 1947; Garrison, 1949; Bonnor, 1967).

5. Comparison of techniques and discussion

After the introduction of the most well established methods, we found that depicting 'the best' approach is difficult. Indirect approaches were shown to be less laborious than direct methods but the type of data gained from indirect approaches is quite different in terms of what is actually measured. In addition, due to a less straightforward measurement, the data is often more difficult to interpret. The fact that all indirect methods, except of the TLS, tend to underestimate the LAI due to foliage clustering is well known (Nackaerts et al., 1999). Another contributing factor is that optical approaches are more or less blind for what is behind the first object in each and every viewing direction (Aber, 1979; Watt et al., 2003; Watt and Donoghue, 2005; Van der Zande et al., 2006) which could also result in an underestimation of the present biomass (Breda, 2003). So, each method has its advantages and disadvantages. We used a catalogue of criteria that enabled us to evaluate the quality of the methods and their suitability to fulfil the given task: providing three-dimensional biomass distribution data for forest canopies in a comprehensive way. The criteria were:

- where or under which conditions are measurements possible
- what weather conditions are required
- how accurate is it and what is the spatial resolution
- what computer resources are needed
- how long does it take

- how much does it cost
- how much effort is the post-processing of the data and

finally: what are the general advantages and disadvantages?

These criteria were evaluated based on experiences reported in the literature. Giving concrete numbers, e.g. for the price of an instrument, would fail. Prices change, they differ between countries, depend on configurations. If the amount of time needed for a measurement is to be compared for different instruments it depends on many more aspects than the instrument alone. How easy is the access to the object of investigation and how big is it? What kind of transportation is available? Which level of accuracy is desired? How experienced is the user?

Hence, we decided to use relative ranges for prices, the time required for a measurement, accuracy and resolution and the needed computer resources. This allowed for a comparison of the methods relative to each other. We will not discuss the topographical restrictions of the instruments, such as measurement errors due to slope effects, because most of these restrictions are of rather theoretical nature. It is more a question of the amount of additional effort that is necessary to use a method on a slope that decides whether it will be done or not, than actually the overall applicability. An example would be the scaffolding approach, that would be more complicated on a steep terrain, but it is not generally impossible. For indirect methods often mathematical solutions exist to correct for topographic effects in the data, such as those presented by Schleppi et al (2007) for hemispherical photographs. The decision if a method is used for a study is to a certain extent dependent on the topography as one factor characterizing the study site, but there are others more that have to be taken into account, such as infrastructure (road access, electricity) or available time. Such a priori limitations should not be incorporated into a review of the methods.

Where or under which conditions were measurements possible

In this chapter we compare the applicability of the different approaches. We found that the direct methods, even though they featured data with the highest accuracy, faced the biggest limitations according to the spatial information of the extracted data, especially if 3D-information is of importance, as it is difficult and expensive making a complete harvest of a mature tree (Aber, 1979). To protocol the origin of the collected material on a high spatial resolution (e.g. cm) is extremely laborious. The access to the canopy itself could be limited as dense understorey vegetation would hinder the complex instrument setup, such as the installation of a scaffolding (Barker and Pinard, 2001). In addition, the destructive character of some direct methods does not allow repeated measurements and can be problematic in National Parks due to nature protection polices. Using allometric relations from the literature could be a solution to the problem of the destructive character of the method and the hampered canopy access. But it would still be difficult to separate the characteristics of individuals from those that are species-specific. A large number of statistically independent samples would be necessary to solve this problem which would be laborious (Jonckheere et al., 2004). However, there would still be a lack of information on the three-dimensional distribution of the biomass as it would not assign a position (xyz-coordinates) to the material.

The point quadrat approaches in their traditional form were designed for shrub or grassland canopies and can only be applied to rather small and simply structured trees, as the operator needs to see whether there is a contact between the needle and the canopy (Groeneveld, 1997). For taller canopies the instrument itself is impracticable, as an easy to carry telescope stick would be hard to handle once they exceed a certain length. Using optical point quadrat measurements would solve this problems for two reasons. First, there is no longer a stick (with the needle on top) which could bend or swing and secondly, there is no need to see the object hit by the laser beam (Lovell et al., 2003). Anyway, some optical point quadrat methods were invented rather for crops than for large trees (e.g. Vanderbilt et al., 1979; Walklate, 1989).

The indirect non-contact methods were regarded to be applicable to a broader range of forest canopy types. Limitations are rare. The Li-Cor Line quantum sensors and the LAI-2000 require simultaneous above or beneath canopy measurements (Welles and Cohen, 1996; Machado and Reich et al., 1999). Either an open field or a tower/stick reaching above the canopy are therefore needed, what should not be a problem in most cases.

Required weather conditions

A complex forest canopy is difficult to describe in detail even without wind induced movements. Hence, the absence of wind or gusts is the most crucial precondition for a successful measurement of the biomass distribution in a forest canopy. All presented approaches require calm wind, even though the tolerance against constant breezes or gusts might be different for each method. TLS is one of the methods that is very sensitive to wind induced movements of the study object as it has a very high spatial resolution (mm) detecting even small changes during the scanning (e.g. Haala et al., 2004). Traditional point quadrat methods are also strongly hindered by wind as movements of the leaves make contact-detections difficult (e.g. Radtke and Bolstad, 2001). Litter traps have to work under any weather conditions. The theory used to gain results from litter traps, which is based on the assumption that the leaves do not fall far from their origin in the canopy, tends to fail under windy conditions. Anyway, Staelens and colleagues (2003) found that "prevailing wind directions during leaf litter fall affected leaf dispersal in a broad-leaved deciduous forest" (Staelens et al., 2003).

Precipitation (rain as well as snow) might be disadvantageous for most field work but is totally intolerable for those methods based on optical measurements: TLS, photographic approaches, MVI, densiometer and Moosehorn. Raindrops may also cause errors in the light measurements and some instrument even need direct sunlight. The photographical approaches (MacArthur and Horn-method, hemispherical photos) require a uniform overcast sky to prevent high contrast in the brightness of the sky (Zhang et al., 2005) but measurements are also possible during dawn and dusk of a day with clear blue sky (e.g. Welles and Cohen, 1996). Instruments measuring the radiation (Quantum sensors, ceptometer, SunScan SS1), canopy reflectance (TRAC, MVI) or direct beam transmission (DEMON) require constant direct sunlight for reliable results. The LAI-2000 is best to be used under uniform overcast sky conditions (e.g. Wang et al., 1992). Litter traps have the highest tolerance for any kind of precipitation as long as drainage is ensured.

Accuracy and resolution

While the accuracy of a method can be high (results correlate with an accepted validation method) the resolution can be low at the same time. An example would be the litter traps. The method is well established and used for validation of other methods (Mussche et al., 2001). The accuracy is therefore regarded to be high, but the resolution of the method is rather low as there is no information for a *certain* tree or branch that could be extracted. As all direct methods are of high accuracy, the indirect methods can only be evaluated using direct methods for validation (Fukushima et al., 1998; Arthur et al., 2000; Mussche et al., 2001). Their direct character may be laborious (Aber, 1979) but it is the only way to gain reliable validation data. In Table 1 we listed appropriate literature that allows to evaluate the accuracy of each indirect method. The resolution of the methods was classified based on the level of detail in the spatial data that can be from the methods, e.g. "tree level" would mean that the measured parameter can be extracted for a single tree, but not for a certain branch.

Point quadrat methods showed a satisfying accuracy (e.g. Wilson, 1960; Dufrêne and Breda, 1995) but offer only a low resolution as the number of contacts within the total number of shots to the canopy is a spatial average (Levy and Madden, 1933; Goodall, 1952) and is useful on the canopy level only, even though heights at which contacts occur can also be protocolled (Wilson, 1963).

Indirect non-contact methods have a wide variety in their accuracy and resolution as they are based on a variety of measurement techniques and sensors (Jonckheere et al., 2004). Low precision in the spatial assignment (resolution) of 3D-information can already be gained with the Line quantum sensor, the Ceptometer and the SunScan SS1 as these instruments are strongly averaging over the measured area. Measured radiation values are always related to a certain part of the canopy depending on the field of view of the instrument (Lang and Yueqin, 1986; Welles, 1990). The accuracy of estimated biomass values is thereby dependent on the used light model and its assumptions (Welles et al., 1996) as well as on the accuracy of the determination of some input parameters required, such as the extinction coefficient, which are often not measured but estimated (Welles, 1990).

Hemispherical photographs and images taken with the MacArthur and Horn-method are only used to describe certain parts of a canopy (low resolution, only canopy level). They have been shown to be a reliable LAI source and they were used for validation of other methods (Brunner, 1998; Lovell et al., 2003; Hopkinson et al., 2004; Morsdorf et al., 2006). A higher resolution might be possible when using cameras with a finer image resolution (e.g. Leblanc et al., 2005) but results can still not be assigned to certain elements of the canopy as the 3D-forest structure is transferred to the 2D photographic information and thereby one dimension is lost. A special sampling design at least allows a limited 3D-data extraction from hemispherical photographs (Ondok, 1984). TRAC, LAI-2000 and MVI offer data on a similar level of resolution and accuracy as hemispherical photographs do (Welles and Cohen, 1996; Rhoads et al., 2004; Leblanc et al., 2005) whereas some authors see the LAI-2000 to be in favour (Machado and Reich, 1999).

DEMON, spherical densiometer and Moosehorn offer data of rather low spatial information content (resolution) as results are given for the tree or canopy level and vertical information is not available. (Bonnor, 1967; Welles and Cohen, 1996; Englund et al., 2000; Engelbrecht and Herz, 2001). This is true for all indirect non-contact methods except of the terrestrial laser scanner. TLS is able to give complete 3D-models (resolution: very high) of the scanned forest (e.g. Watt et al., 2003; Hosoi and Omasa, 2007), but there are still problems in the use of the data. Modelling algorithms and data extraction is difficult and obstruction effects in the upper part of the canopy as well as validation are still challenging (Chasmer et al., 2008; Van der Zande et al., 2008). However, the accuracy of parameters derived from TLS is promising (e.g. Danson et al., 2007; Hosoi and Omasa, 2007).

Needed computer resources

Most of the instruments (line quantum sensors, point quadrat sampling, densiometers, Moosehorn) need none or only simple computer resources. MVI, TRAC, DEMON and LAI-2000, as well as hemispherical photography, need some additional soft- or hardware. The required hardware is today's standard and the software is in many cases available as freeware. The only instrument that needs powerful processors, large RAM and lots of free hard disk space, as well as a strong graphic adapter and expensive software is the TLS. Moreover, the use of 3D-laser scanner data is limited due to problems in the processing of the large datasets (e.g. Pfeifer et al., 2004).

Expenditure of time

While hemispherical photographs and MacArthur and Horn-images can be taken in less than a minute, direct methods usually take days or weeks. The laborious character of direct measurements and point quadrat methods implicates a greater time requirement. Except of the litter traps, which are used over a certain period of time (e.g. autumn leaf fall), all indirect measurements can be done within minutes or hours for a complete canopy. Whenever measurements have to be done periodically it is easier to use indirect methods. Especially imaging instruments, such as photos, the TLS or the MVI are useful in the monitoring of changes over time. The time ranges presented here are valid under the presumption that one single experienced operator is using the technique, but this might be unrealistic for the harvest methods labour effort. Anyway, the time needed for a measurement differs from operator to operator, depends on the weather and even changes with the experience a single operator makes by using an instrument. In addition, measurements might not be possible for days due to rain, snow, frost, wind or hindered by transport problems or the general accessibility of the study site. Hence, the time ranges given here are only rough and approximate values.

Price for the instruments

Comparing the prices of a certain measurement, e.g. the price of a LAI information for a forest plot would not be useful. First, the different resolutions of the instruments would have to be brought in conformity, which is very difficult. Secondly, the price of time and work needed to gain the data differs with the operators qualification and boundary conditions, such as carrying cost and the consumption of expendable materials. Instrument prices are subject to change but using relative price-classes will help to get an overview on the necessary investments.

The most inexpensive instruments are the Moosehorn (Smith et al., 2008), densiometers (Englund et al., 2000), the cameras for the photographical approaches (Englund et al., 2000), the equipment for the point quadrat methods (Aber, 1979) and allometric approaches especially for large areas using formulas from the literature (Botkin et al., 1993). Using litter traps is already more expensive. Not because of the material needed to construct them but due to the fact that they require inspection and service by an employee throughout the year. The harvest approaches are expensive more due to their laborious character than because of the instruments needed. The instrument price increases in relation to the employee´s wages when using the MVI, DEMON, TRAC or the instruments measuring the radiation. Even more expensive is the LAI-2000. By far the biggest investment is the TLS, which is about 50 to 80 times the price of a hemispherical camera.

Post-processing effort

When comparing the post-processing effort of the techniques it can be difficult to separate the actual sampling from the post-processing for some instruments. We decided to call post-processing only what is "usually" done in the office/lab after the actual field measurement. Of course, nowadays, portable computers allow viewing and processing the data directly at the location of the measurement but this is not necessarily to be done in field. Hence, it is not sampling anymore but "post-processing" in our definition.

Using allometric equations requires some post-processing, since the data acquisition in the field is only the input data for the equations that need to be processed later on (Whittaker and Woodwell, 1968; Hashimoto, 1990; Niklas, 1994; Porte et al., 2002; Pretzsch and Schütze, 2005; Pretzsch, 2006). The harvest techniques as well as the litter trap method need a rather laborious and time consuming post-processing, as plant compartments need to be sorted, dried, weight, scanned etc. (Monsi and Saeki, 1953; Fujimori, 1971; Aber, 1979; Lowman, 1988; Luizao, 1989; Lendzion and Leuschner, 2008). Less time consuming are the point quadrat methods, as they need only simple calculations and statistics to build the ratio of hits to non-hits between the needle and canopy objects what can be automated (Wilson, 1960; Barkmann, 1988; Jonckheere et al., 2004).

The MacArthur and Horn-photography approach also requires some mathematics but has its emphasis more on the field work than in the post-processing (MacArthur and Horn, 1969).

Hemispherical photography analysis is done using software-packages that require input parameters for the calculation (e.g. WinScanopy (RegentInstruments, Quebec, Canada), CanEye (www.avignon.inra.fr/can_eye) or Gap Light Analyzer (Simon Fraser University, Burnaby, B.C.)) and some interventions by the operator that may be time consuming. While it takes only seconds to make a hemispherical photograph it can take a couple of minutes to calculate LAI values or other parameters based on the image.

Terrestrial laser scanning is probably the indirect method that is most post-processing intensive. While high resolution full-hemisphere scans can be taken in less than four minutes (e.g. ZF Imager 5006, Zoller and Froehlich GmbH, Wangen, Germany) the extraction of biomass parameters might take a day due to the registration process and the large amount of data that is to be processed. Generally spoken, the more automated the analysis is, the less time is needed for post-processing. The lack of standards in the extraction of parameters from terrestrial laser scanning is therefore currently the main reason for the above-average time-demand of this young technique (Thies et al, 2004; Thies and Spieker, 2004). The analysis of data obtained with Line quantum sensors is also less standardized and may therefore take some extra time for the user specific post-processing. Data loggers are to be red out and mathematics have to be applied to calculate the desired parameters (Welles, 1990; Leblanc et al., 2002). Using the LAI-2000, the TRAC, the SunScan or the Ceptometer (and its modifications) makes the post-processing obsolete, as the measured parameter (LAI) is directly represented on a screen since all calculations are automatically derived by the internal software. Strongly reduced manual post-processing is also given with the incorporated canopy image analysis techniques of the MVI (Jonckheere et al., 2004). The DEMON has an incorporated parameter calculation as well. However, both instruments need to be red out with a computer for the final data evaluation even though their is no "real" post-processing (Jonckheere et al., 2004). The last two instruments, the spherical densiometer and the Moosehorn, do not require post-processing. The ratios of obstructed and unobstructed grid cells can be evaluated directly in the field and their is no data logging available (Bonner, 1967; Englund et al., 2000).

Advantages and disadvantages

In this chapter we present the general advantages and disadvantages of each method.

Allometric relations showed good results in the past (e.g. Bartelink, 1997; Porte et al., 2002) and once established they do not require a lot of field work. Disadvantages are the mean resolution and the fact that characteristics from individuals are difficult to separate from those that are species-specific (Jonckheere et al., 2004).

Stratified clipping or a scaffolding harvest are also methods of high accuracy but only mean resolution. The assembling in the field can be difficult for the methods that require the active collection of plant compartments and they are too laborious to be used for practical applications in tall canopies or over large areas. Additionally, an excessive disturbance of the studied forest plot is often not tolerable.

Litter traps have a big advantage: literature offers lots of reference data from studies in the past as it is an old and simple method. The passively collected material allows to determine parameters such as the dry-weight-to-leaf-area ratio and results can be compared to those of older studies. The accuracy in the estimation of such parameters might be high, but the resolution is weak. Information on a certain point in time is not extractable as well as single tree related data or precise 3D-information. It is impossible to prevent leaves from distant trees to be blown into a trap far away (resolution: very low). In addition the analysis of the collected matter in the lab is laborious. As a matter of completeness the low price of this method should be mentioned as an advantage.

All indirect methods are rather fast and non-destructive which is a general advantage for these kinds of measurements. However, disadvantages are as manifold as the approaches. Both point quadrat methods are unfortunately not suitable for large canopies. The assumption of random distribution of the foliage elements is also a drawback (Whitehead et al., 1990; Chason et al., 1999).

Hemispherical photography and the MacArthur and Horn-method are fast, they produce permanent image records and they are rather inexpensive and easy to carry. The problems are more in detail. Camera settings are sensitive to the weather and the image analysis is not free of subjectivity. Mac Arthur and Horn images are prone to distortions in the images, which is not completely eliminated in the hemispherical lenses as well (Herbert, 1987; Schwalbe, 2005).

The TLS applications to extract 3D-biomass distributions is in an early stage of development. Therefore prices are extremely high and standardized ways of data extraction in form of algorithms are rare. However, TLS may offer unique spatial information in a comprehensive way and with a unique resolution. The image character of the data allows analyzing a variety of architectural parameters and their number increases with the ongoing research. However, validation is still a problem as the destructive sampling of a complete laser scan scene is difficult. Standardized protocols for TLS data interpretation are also rare. Portability and expenditure of time needed to capture a canopy are additional TLS-benefits to be mentioned here.

An easy portability is a key benefit of the Moosehorn and the spherical densiometer. Others are their extremely low prices and the usage independently from any computer accessibility. Anyway, these simple instruments are prone to subjectivity and they are of low resolution according to the 3D-character of the canopy structure data that can be obtained. Again, as for the point quadrat methods, a random distribution of foliage elements is assumed (Barkmann, 1988), which is another con (Whitehead et al., 1990; Chason et al., 1991).

An advantage of the Line Quantum sensor, the Sunfleck Ceptometer and the SunScan SS1 is mainly their portability. The extraction of 3D-data, especially of those which is single tree related, is impossible due to the low resolution. The assumption of random foliage distribution is again a simplification of the reality and considered to be a disadvantage.

The LAI-2000 also uses this theoretical restriction with the same negative consequences in the analysis. Anyway, it offers comprehensive information on the canopy light climate in one measurement which can be used to derive sophisticated LAI values, unfortunately the reference is difficult to be extracted thereby (low resolution).

TRAC and MVI can be used to gain clumping data, which is a unique advantage. Both instruments are easy to carry and the MVI can even be used to extract information on the photosynthetically active material alone. Again a big disadvantage is the non given possibility to assign the results to a certain part of the canopy (low resolution).

Table 1 gives a summary of the characteristics of each method in the compared categories.

6. Conclusions

Depending on the aim of the study different compromises concerning the used methods appeared to be inevitable. Each method has proved to be useful and has shown its advantages and disadvantages. The demand for new methods is always connected with open research questions, new fields of investigation or new findings.

The increasing relevance of the three-dimensional structure of forest canopies for current research tasks, especially in ecology, generates a rising need for instruments offering detailed spatial information (Lovell et al., 2003; Parker et al., 2004; Tageda and Oguma, 2005; Pretzsch and Schütz, 2005).

If a fast measurement of high resolution and real 3D-information (xyz-coordinates of all objects) is of highest priority the TLS should be chosen, as it is the only method that could offer such data with a reasonable effort. Destructive methods are not an alternative due to the non-arguable effort they would require for mature forest canopies, especially if the high resolution 3D-information is in the focus. The price of a TLS is a hindrance, so is the still difficult and less standardized data analysis. However, studies showed the big potential for the instrument (Lovell et al., 2003; Watt et al., 2003; Hopkinson et al., 2004; Thies et al., 2004; Watt and Donoghue, 2005) especially if destructive methods are not applicable due to forest protection policies. Rental of the instruments could alleviate the financial burden as well as a shared purchasing by different institutes or organisations.

Research is facing the challenge that surrogates for the three-dimensional distribution may be no longer needed as comprehensive 3D-data becomes available from TLS. Up to 500.000 measurements throughout a canopy can be done in one second when using a state-of-the-art 3D-laser scanner. Now, algorithms and programs are needed to extract suitable parameters from the virtual forests.

Research should focus on this data acquisition as they would enable the calculation of functional attributes such as canopy carbon gain, transpirative water loss and processes for different sections of a canopy. Ecologists would be able to characterize the structure of forest stands faster and more precisely than ever.

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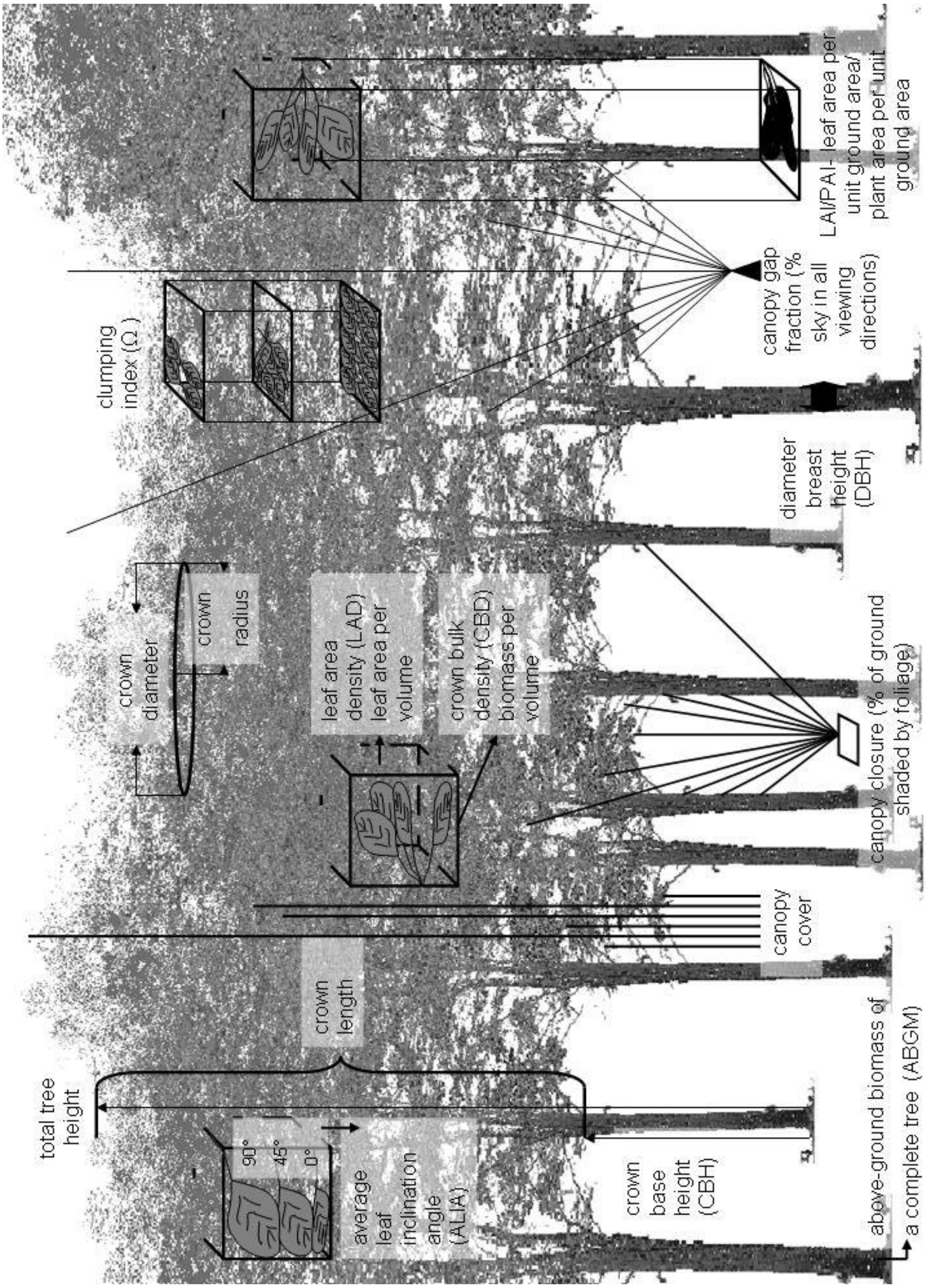
Table 1: Overview of the methods referred to in the text and their characteristics, advantages and disadvantages (in three parts).

	Approach group	Measured parameters	Requirements according to the investigated object	Accuracy / resolution	Needed computer resources	Required weather conditions	Expenditure of time	Post-processing effort	Price for instruments	Advantages	Disadvantages
Allometric relations	Direct	LAI, PAI, individual tree biomass; AGBM; tree height; DBH; biomass repartition; crown form; vertical changes in branch inclination; vertical changes in foliage density;	enough statistically independent samples available; small destructions must be allowed	high/ middle (usually not finer than tree or branch level)	low (simple calculations)	calm wind during the destructive part	long (days)	middle	low	once established formulas can be applied to other trees/ canopies	sometimes statistical requirements can not be met (e.g. number of samples); characteristics of individuals hard to separate from species-specific; laborious
Stratified clipping / Scaffolding harvest	Direct	three-dimensional foliage distribution; AGBM	no dense understory; small area of interest; not protected area	high/ middle (usually not finer than tree or branch level)	low (simple calculations)	calm wind	long (days)	very high	middle	accuracy	destructive; not suitable for large areas; difficult setup; not usable in dense understory; laborious
Litter trap	Direct	LAI; dry-weight-to-leaf-area ratio; leaf decay	none	high/ very low (canopy level)	low (only simple calculations, scanner)	no snow cover; no frost	very long (autumn leaf fall)	very high	low	simple instruments	geographically averaging; analysis is laborious; difficulty to relate the data to a single tree; no data for a certain point in time
Point quadrat	Indirect contact	LAI; Green area index; PAI; cover percentage; approximated vertical foliage distribution	low-vegetation canopies; only small trees	e.g. Levy and Madden, 1933; Dufrêne and Breda, 1995/ low (usually not more than canopy level)	low (simple calculations)	calm wind	long (days)	middle	low	no postprocessing; not based on inversion formulas	laborious; limited to low vegetation canopies; assumes random distribution of foliage elements
Inclined point quadrats	Indirect contact	LAI; Green area index; PAI; cover percentage; approximated vertical foliage distribution	low-vegetation canopies; only small trees	e.g. Wilson, 1960/ low (usually not more than canopy level)	low (simple calculations)	calm wind	long (days)	middle	low	no postprocessing; not based on inversion formulas	laborious; limited to low vegetation canopies; assumes random distribution of foliage elements

	Approach group	Measured parameters	Requirements according to the investigated object	Accuracy / resolution	Needed computer resources	Required weather conditions	Expenditure of time	Post-processing effort	Price for instruments	Advantages	Disadvantages
MacArthur and Horn`-photography	Indirect non contact	foliage profile; canopy cover; three dimensional foliage distribution	none	e.g. Fukushima et al., 1998; MacArthur and Horn, 1969/ low (canopy level)	low (only simple calculations, flatbed-scanner)	calm wind; no rain; uniform sky conditions (overcast; dusk; dawn)	short (minutes)	middle	low	fast; permanent image record; portability	lens distortions; camera settings difficult; analysis sometimes subjective
Hemispherical photography	Indirect non contact	PAI; canopy cover; transmitted light; 3D-biomass distrubution	none	e.g. Welles and Cohen, 1996; Jonckheere et al., 2004/ low (canopy level)	middle (special software, advanced calculations)	calm wind; no rain; uniform sky conditions (overcast; dusk; dawn)	short (minutes)	high	low	fast; permanent image record; portability	lens distortions; camera settings difficult; analysis sometimes subjective
Terrestrial 3D-laser scanners (TLS)	Indirect non contact	architectural information (DBH; height and others); 3D-structure; Light interception; PAI; ALIA; AGBM	none	e.g. Lovell et al., 2003; Henning und Ratdke, 2006; Takeda et al., 2008/ very high (precise leaf level)	high (strong PC, large RAM and Harddisk, strong graphics, special software)	calm wind; no rain	middle (hours)	very high	very high	comprehensive data; permanent image record; resolution	expensive instrument; early stage of development (less experience), less standardized ways for the data analysis
LI-Cor Line quantum sensor	Indirect non contact	canopy transmittance; PAR; canopy closure; LAI	above/ beneath canopy data must be available (tower or open field close to the study side)	e.g. Welles et al., 1996; Martens et al., 1993/ low (canopy level)	low (only simple calculations)	calm wind; no rain; direct sunlight (clear sky)	middle (hours)	middle	middle	simple instrument; portability	above canopy data sometimes hard to get; accuracy; single tree related data difficult to extract; additional data needed for analysis; assumes random distribution of foliage elements
Sunfleck Ceptometer	Indirect non contact	canopy transmittance; PAR; canopy closure; LAI; sunfleck distribution	none	e.g. Welles et al., 1996; Fasstnacht et al., 1994/ low (canopy level)	low (only simple calculations)	calm wind; no rain; direct sunlight (clear sky)	middle (hours)	none	middle	portability	single tree related data difficult to extract; assumes random distribution of foliage elements
SunScan SS1	Indirect non contact	canopy transmittance; PAR; canopy closure; LAI; sunfleck distribution	none	e.g. Dufrêne and Breda, 1995; Welles et al., 1996/ low (canopy level)	low (only simple calculations)	calm wind; no rain; direct sunlight (clear sky)	middle (hours)	none	middle	portability	single tree related data difficult to extract; additional data needed for analysis; assumes random distribution of foliage elements

	Measured parameters	Requirements according to the investigated object	Accuracy / resolution	Needed computer resources	Required weather conditions	Expenditure of time	Post-processing effort	Price for instruments	Advantages	Disadvantages
TRAC	clumping index; canopy reflectance; LAI	none	e.g. Chen and Cihlar, 1995a; Leblanc et al., 2005/ low (canopy level)	low (only simple calculations)	calm wind; no rain	middle (hours)	none	middle	portability, offers clumping data;	single tree related data difficult to extract
MVI	clumping index; canopy reflectance; foliage-to-woody-plant material ratio; LAI; PAI	none	e.g. Kucharik et al., 1999/ low (canopy level)	middle	calm wind; no rain	middle (hours)	middle	middle	differentiation of photosynthetically active foliage and woody plant material possible; permanent record (image); offers clumping data; does not assume random distribution of foliage elements	single tree related data difficult to extract
DEMON	direct beam transmission	none	e.g. Dufrêne and Breda, 1995; Fasstnacht et al., 1994/ low (canopy level)	middle	calm wind; no rain; direct sunlight (clear sky)	middle (hours)	low	middle	portability	single tree related data difficult to extract; additional data (e.g. Ω) needed for analysis; many measurements needed; assumes random distribution of foliage elements
Spherical Densiometer	canopy closure; light conditions	none	e.g. Englund et al., 2000; Engelbrecht and Herz, 2001/ low (canopy level)	none	calm wind; no rain	middle (minutes to hours)	very low	low	simple instrument; portability	subjective; unprecise; single tree related data difficult to extract; assumes random distribution of foliage elements
Moosehorn	canopy closure; light conditions	none	e.g. Vales and Bunnel, 1988; Robinson, 1947; Garrison, 1949; Bonnor, 1967/ low (canopy level)	none	calm wind; no rain	middle (minutes to hours)	very low	low	simple instrument; portability	subjective; unprecise; single tree related data difficult to extract; assumes random distribution of foliage elements

Figure 1: A forest canopy, its major characteristics and the main biomass parameters presented in the text.



Chapter 3

Analysing forest canopies with ground-based laser scanning: potentials and limitations

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Analysing forest canopies with ground-based laser scanning: potentials and limitations

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Abstract

We tested ground-based high resolution laser scanning as a tool for analysing the complex canopy structure of temperate broad-leaved forests. The canopies of 35 groups of trees (each consisting of three trees with variable species identity) were analyzed by laser scans from various positions inside a mixed stand to generate three-dimensional point clouds of the axes and leaves. The scan data was used to produce hemispheric views of the canopy that were compared to synchronously taken hemispherical photographs of the same part of the canopy. We conclude that terrestrial laser scanning in mature forests can overcome several of the methodological problems inherent to conventional canopy analysis with optical methods and thus may soon offer a promising tool for functional research in complex forest canopies. Certain limitations of the LIDAR apporach are encountered, in particular when wind hits the canopy, and hardware limitation (computation capacity), which may soon be overcome.

Keywords: 3D-laser scanner/ canopy structure/ hemispherical photography/ voxel-approach

1. Introduction

The structure of tree canopies exerts a major control on the energy and mass exchange between forests and the atmosphere. The distribution of light and photosynthetic activity in the canopy and the source strength for water vapour depend not only on total leaf area but also on the spatial distribution and exposure of leaves and needles in the canopy. Competition for light and canopy space is influenced by the branching patterns of the trees and the investments in terms of new leaves and structural organs necessary to occupy canopy volume (Reiter et al. 2005).

Thus, a deeper understanding of tree crowns and canopy interactions in forests requires profound knowledge of the spatial structure of tree canopies. However, precise data on the distribution of leaf area and axes in the crown, leaf clumping and canopy gaps is difficult to obtain for adult trees, simply because of the sheer size of the plants and difficulties in canopy access.

In the past, analyses of the spatial structure of tree canopies and the associated light climate were mostly based on photographs with wide-angle (fish-eye) lenses taken from the ground vertically upwards that allowed calculating the fraction of diffuse and direct radiation reaching the camera viewpoint (Anderson 1964; Evans and Coombe 1959). Such photographs may also be used to characterize the light climate along a height gradient inside the canopy. A major shortcoming of this approach is that it is nearly impossible (or at least extremely time consuming) to perform this kind of measurement along a dense grid of camera positions in the canopy. In addition, there is an ongoing discussion on the accuracy of the information obtained with canopy photography and on necessary improvements of the technique. Most problematic are the effects of different sky conditions on the images and subjective interventions in the processing of the data (Anderson 1964; Zhang et al. 2005; Guevara-Escobar et al. 2005).

3D-laser scanner measurements conducted on the forest floor (terrestrial LIDAR) offer opportunities to overcome most of these problems. Recently, terrestrial LIDAR has been employed in attempts to calculate canopy openness and LAI in forest stands. When compared to conventional hemispheric photos taken from the ground, a good agreement was found (Danson et al. 2007; Lovell et al. 2003). A major advantage of calculating the desired structural parameters from scanner data is the non-subjective character of the data processing which would represent a large step forward in the direction of objective methods for canopy analysis. However, a profound analysis of the potentials of this promising technique for forest canopy analysis does not yet exist.

In this study, we used a ground-based high-resolution laser scanner to test the accuracy of this technique in a set of forest patches that differed in tree species richness, species identity and overall canopy structure. We applied a multi-scan approach to increase the scanning resolution in particular in distant parts of the canopy and thus to eliminate certain shortcomings of the application of LIDAR technology to complex forest canopies. Conventional hemispherical photographs of the canopy were used as reference for assessing the accuracy of hemisphere views that were simulated from the 3D-laser data for a large number of canopy positions in a diverse set of forest patches.

The two main goals of the study were (1) to test the accuracy of laser-scan data in a diverse set of old-growth forest patches against an independent method (hemispheric photographs), (2) to identify the potentials and also the major limitations of this approach when used in complex forest canopies, and (3) to assess this method in terms of practicability, i.e. the balance between labour effort and quality of data.

2. Methods

2.1 Study area

The study was conducted in Hainich National Park in the federal state of Thuringia in Central Germany (51°05'N; 10°31'O). The National Park was established in 1997 and covers a total area of 16,000 ha of semi-natural mixed deciduous forest with up to 14 tree species per ha. The investigations concentrated on two old-growth forest patches in the eastern part of the National Park close to the village of Weberstedt with five abundant tree species: European beech (*Fagus sylvatica L.)*, lime *(Tilia cordata P. Mill.)*, sycamore maple (*Acer pseudoplatanus L.*), common ash *(Fraxinus excelsior L.)* and hornbeam (*Carpinus betulus L.)*. We chose 35 tree clusters that were composed of each three adult trees of one, two or three tree species. 15 clusters were selected in a forest area named "Lindig", 20 in an area called "Thiemsburg". The trees in the clusters had an average DBH of 44.04 cm and were 28-32 m tall.

2.2 Field measurements

The canopies of each of the 35 clusters and the crowns of the next directly adjacent trees were scanned with the terrestrial laser scanner Z+F Imager 5006 (Zoller und Froehlich GmbH, Wangen, Germany) between June 2008 and September 2008. Resolution was set to 'High' which is equal to a horizontal and vertical angular step width of 0.036 degrees. This resulted in a 10.000 pixel resolution for 360 degrees (Z+F Imager 5006 Manual). The range of view of the scanner was limited to 310 degrees vertically and full 360 degrees in horizontal direction. The scanner uses the phase-difference measurement technique to measure the distance to an object that is reflecting the emitted laser beam. It is a stand-alone instrument with no need for a laptop or electricity in the field.

In each cluster, 24 artificial targets (20 cm by 30 cm) were used in the scene, 20 of which were fixed between ground level and 2.2 m above ground. The remaining four targets were used as 'canopy-targets'. We constructed a device to mount the target on a 6 to 16-m long aluminium telescope stick and to allow for leaning this stick against a tree below the basis of the canopy. This device consisted of a board to fix the target on and an adaptable clip facing the tree trunk to prevent slide movements on the bark. The telescope sticks were fixed to a length of 10 m and leaned against selected trees. This procedure took only a few minutes and allowed for registering the scene with targets more homogeneously distributed in space. The 24 artificial targets were distributed around the centre point of each tree cluster as homogeneously as possible. Weather conditions were considered to be appropriate for measurements when wind velocity was less than 5 $m*s^{-1}$ on average and no rain fell . Scanning was then started by making a first scan of the entire hemisphere at the centre point. This scan was later used as master scan for registration. Between five and twelve additional scans at surrounding positions 5-10 m distant from the cluster centre were performed to capture the entire cluster and the neighbouring trees depending on the density of the understorey and the overall dimensions of the tree cluster. Figure 1 shows an exemplary cluster and the according scan design. Due to the substantial differences in species compositions, species diversity, crown structure and canopy openness of the 35 tree clusters, we were able to test the LIDAR-system in a broad variety of temperate forest canopies.

In addition, more than 100 hemispherical photographs were taken from the canopies from the forest floor at various positions within the scanned scene in summer 2008. These positions were chosen in different ways. The first group of photographs was positioned at 40 cm height above the forest floor at positions determined systematically (Fig. 1). A line from each cluster tree to the cluster centre was virtually drawn and at the middle of each line a stick was fixed to the ground. The second group of photos was recorded at randomly placed positions inside or in close vicinity outside the clusters using a random number generator that gave the x,y-coordinates. In this group of photos, the height above ground varied between 1.5 and 1.7 m. A third group of hemispheric photos was taken at characteristic points such as pieces of dead wood as well as installations of other research groups in the stands.

All photographs were recorded with a Nikon Coolpix 8400 Digital Camera (8 Megapixel) and a Nikon Fisheye Converter FC-E9. The camera was set to Fisheye-mode and adjusted to be 1 to 2 steps overexposed as recommended by Chen et al. (1991).

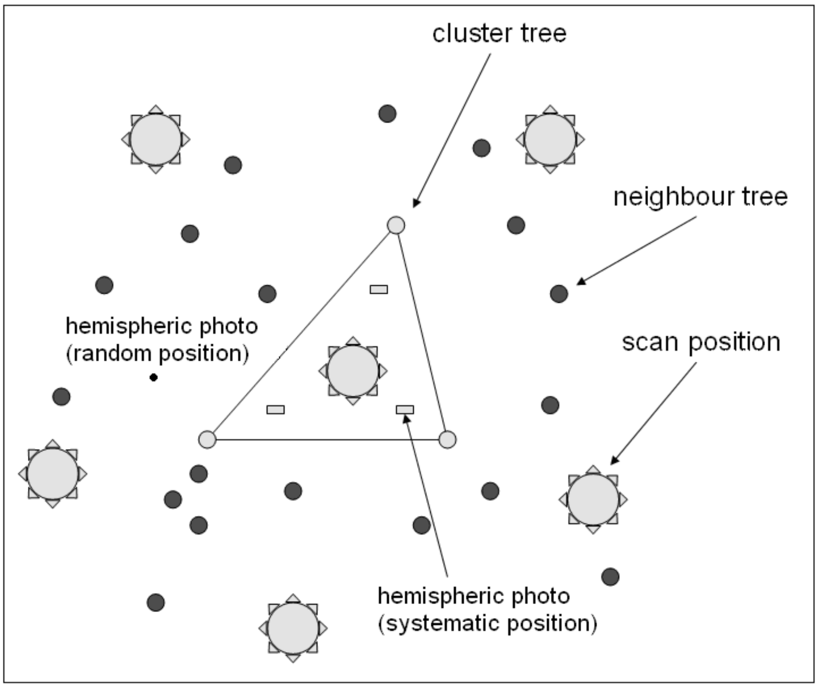

Fig. 1: Example tree cluster with the three cluster trees and additional surrounding trees and position of laser scans and hemispheric photos.

2.3 Data processing

All laser-scan data were filtered in the ‘Z+F Laser control’ software (Zoller und Froehlich GmbH, Wangen, Germany) to erase data points that were most likely not accurate (too far away, low quality of the reflected signal etc.). Registration was performed based on the 24 targets that were identified manually in each scan. By using algorithms that rotate and translate the determined fix points (targets) the software brought the positions of the targets in the best possible accordance with all scans of the same cluster. The remaining error in the transformed data, which is due to target movements, inaccuracy in the measurements or mistakes in marking the targets, is expressed as deviation of the fix-point position between two related scans of the same object (unit: mm). Due to hardware restrictions the resulting point clouds needed to be reduced to the sixteenth part of the scanned data. After compiling all data of a given tree cluster and its close surrounding, a three-dimensional visualisation of the canopy structure was generated (Fig. 2) with the data being available as .xyz-file for further computations. This format included the coordinates of each point detected by the scanner given in a cluster-wide coordinate system.

Fig. 2: Exemplary point cloud of a tree cluster and its immediate vicinity, based on six scans (10^6 points).

2.4 Hemispherical photographs

The digital hemispherical photographs were analyzed with the Gap Light Analyzer (GLA) Software (Simon Fraser University, Burnaby, Canada). For each tree cluster, the precise positions, where hemispherical photographs were taken, were identified in the 3D-laser point cloud and three centimetres were added in vertical direction to prevent parts of the marker being visible in the image. This would have caused big voxels being present very close to the camera position.

Canopy openness and LAI of the photograph were calculated using 24 azimuth and 10 zenith bands. In a second step, simulated hemispherical photographs were generated from the laser-scan data based on a polar projection conducted at the position of the camera in the voxel space. The simulated photographs were analyzed with the software Mathematica which was much faster than using the GLA software. However, we calculated all images a second time with GLA to enable comparison.

The image processing in GLA included the selection of the area representing 0 to 30 degrees zenith angle (0-360 degrees azimuth), selecting the optimal grey-value threshold to separate vegetation from sky pixels and finally calculating the openness for each image. The frequently disputed subjective adjustment of the threshold or the application of complex thresholding procedures (Jonckheere et al. 2004; Frazer et al. 2001; Hardy et al. 2004; Morsdorf et al. 2006; Guevara-Escobar et al. 2005) were not necessary during the analysis of the simulated images, as they only contained black and white pixels. This allowed us to use always the same threshold of 128 (half of a 256 bit image) and to overcome the problems of subjectivity in the selection of a suitable threshold (Jonckheere et al. 2004; Nobis and Hunziker 2005; Cescatti 2007). Further, analysis of the simulated photographs was also possible with the GLA software as Mathematica produced .jpg- images that could be imported easily.

To test whether significant differences between the canopy structure existed when analysing either by LIDAR or by hemispherical photography we first tested for normality of the data distribution with a Shapiro-Wilk-test and subsequently applied either the Welch t-test or the Wilcoxon rank sum test depending on the data distribution patterns.

The impact of wind during the scanner measurements on the quality of a simulation was investigated with a simple correlation analysis between maximum wind speed and the quality of the simulated image using the difference in the canopy openness between original and simulated image as a criterion. The wind speed data was obtained from a climate tower located only 100- 800 meters from the test sites that logged 10-min averages of wind speed.

Furthermore, we analyzed the gap structure with a simple Mathematica algorithm that identified gaps in the photograph and calculated the gap size based on the number of pixels. For each photograph the percentage of the cumulative openness caused by the ten largest gaps was calculated, as well as the size of the biggest gap alone. Significant differences in the canopy structure of the Lindig and Thiemsburg patches were found based on this method (see Table 1).

Table 1: Some characteristics of the canopy structure and the related gap patterns according to hemispherical photographs in the Lindig and Thiemsburg study areas.

	Lindig	**Thiemsburg**
Average number of species in the three-tree clusters	2.0	2.4
Average canopy openness (%)	7.0	5.7
Average number of stems (>20 cm circumference) in a 20 m radius around the centre of the tree clusters	46	61
Average size of the largest gap in the photo (No. of pixels)	13826	6065
Average contribution of the ten largest gaps to the total openness of a photograph (%)	56.7	44.2
P-value of the correlation and R^2 of the correlation between simulation and photograph	<0.001, 0.88	<0.01, 0.43
Number of simulations	15	20

3. Results and Discussion

3.1 Registration

All 35 scan sessions of the canopy structure were registered with only small registration errors. The average number of data points recorded per tree cluster was 14.5 M for a forest patch size of about 7800 m² (radius of 50 m).

On average, eight scans proofed to be a useful number to capture a cluster from all sides. The average registration error of the data ranged from 2 mm to 7.5 mm.

3.2 Voxel-model of canopy structure

The point clouds obtained directly from the laser-scans represented the structure of the scanned forest patches with high accuracy but turned out not to be a suitable data base for calculating the openness values of the canopy or to simulate hemispherical photographs. This is because points do not have an area or a volume. In addition, we faced two other problems regarding the laser scanner data. First, the volume density of data points decreases with increasing distance from the scanner, as the scanner emits the laser beam in a fixed step width of 0.036°. Hence, two neighbouring beams diverge more and more with distance. We calculated a beam distance of 3.14 cm at 50 m distance from the scanner position which represents the minimum distance between two data points (resolution). Consequently, the objects in the upper part of the canopy were represented by much fewer points or less accurately than those closer to the scanner. This distance effect existed even though the multiple scan design of this study reduced the effect. A second problem arises due to the structure of the forest: the obstruction of the upper part of the canopy by tree organs (leaves and axes) in lower strata. Again this effect was reduced by realising various scanning positions but certain parts of the canopy often appeared to be too dense for accurate laser-scan analysis.

Hence, in several tree clusters, the uppermost canopy was visualized by only very few data points. To overcome these problems in the point cloud data we used a voxel ('volumetric pixel') model of each tree cluster developed by S.Fleck and D.Seidel (pers. communication). All volumetric elements of the scene that contained scanned points were accepted as voxels of the 3D-scene, while the remaining volumetric elements were considered to be empty space. By defining the size of the voxels the resolution of the simulation was set (Fig. 3).

As all voxels were identical in volume and shape, regardless of the number of points they contained, they represented the stand structure much better than the untransformed point cloud. The voxel-approach reduced strongly the two mentioned drawbacks and also allowed assigning a volume to each data point. A disadvantage was the reduced resolution of the model. While many levels of resolution (mm^3 to m^3) are theoretically possible we encountered that too small voxels (1 cm^3) required very much computation time and minimized the homogenizing effect on point density, while large voxels decreased the resolution of the model. Voxels of 3 x 3 x 3 cm represented a reasonable compromise between the demands of resolution, computability and homogeneity.

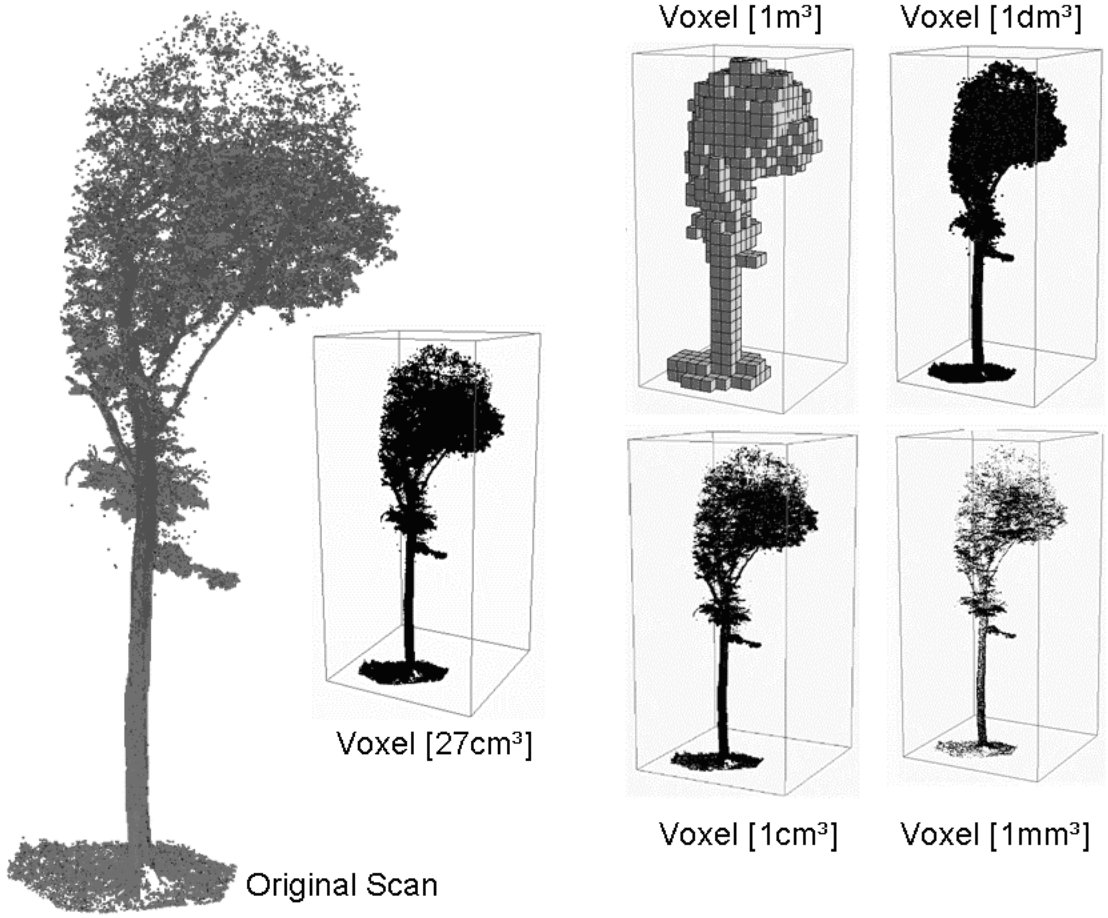

Fig. 3: (left) Point cloud of a single tree *(Fagus sylvatica)* as produced by six laser-scans. (right): Models of the same tree based on voxel sizes from one m^3 to one mm^3. (centre): voxels of 27 cm^3 as used in the simulation.

3.3 Hemispherical canopy views: photographs vs. laser-scan derived simulations

When the simulated hemispherical views of the canopy based on the laser-scan data were contrasted with the fish-eye photographs taken from the same position on the forest floor (Fig. 4), we found a satisfying agreement. This is demonstrated by the rather close correlation (R^2= 0.76) between canopy openness calculated from laser scans and openness obtained from hemispherical photographs (Fig. 4).

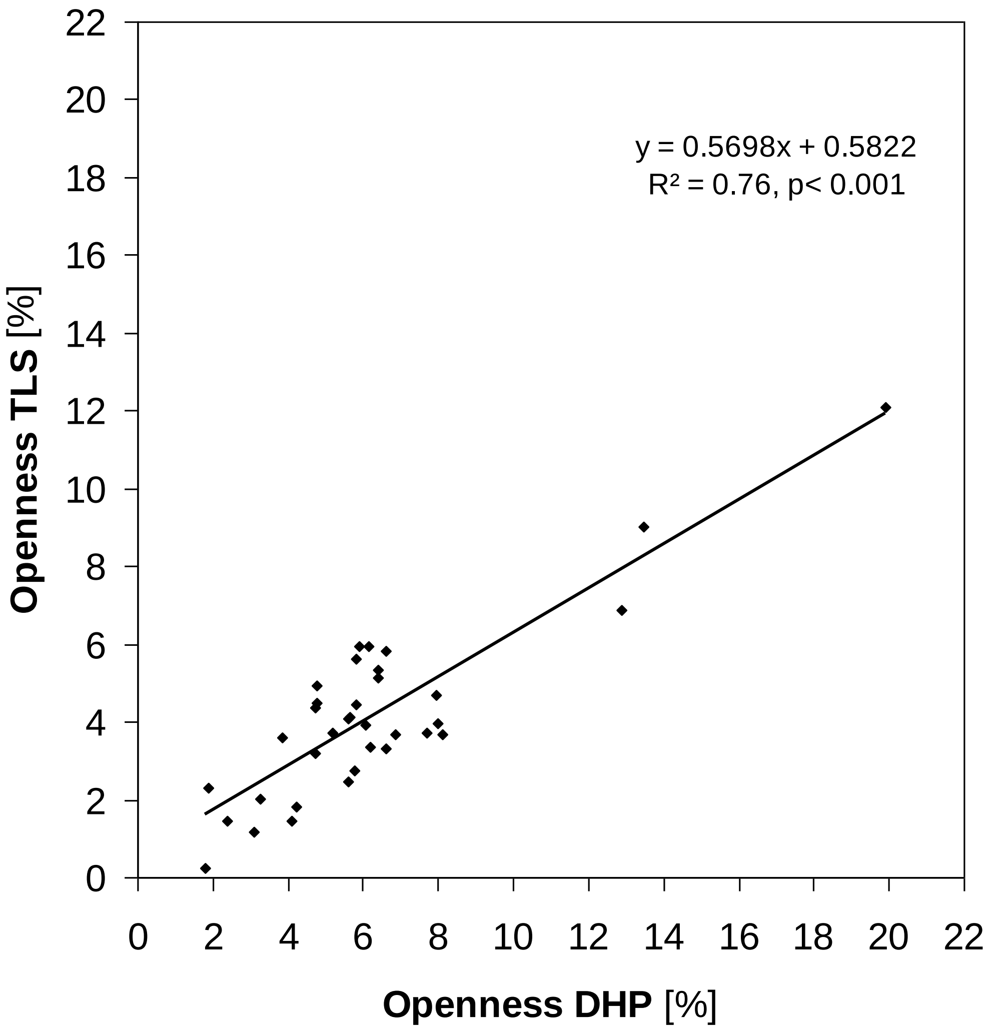

Fig. 4: Relationship between the calculated canopy openness obtained from terrestrial laser scanning ('TLS', calculated with Mathematica) and openness calculated from digital hemispherical photography ('DHP', calculated with Gap Light Analyzer) for a set of 35 scan sessions taken in both study areas.

This indicates that the algorithm creating the graphics from the voxel model worked well in terms of the geometry of the mixed forest canopy. However, even though gap patterns of two image types showed strong similarities, there were obvious data gaps in the simulation derived from the data of the scanner. As the laser scanner has a limited range (79 m), data gaps occurred in the higher zenith angles (outer part of the image), which is caused by the fact that the visibility in the lower part of the forest exceeds 79 m. For this reason it is recommended to use a 3D-laser scanner with a longer range or to conduct more scans in the surroundings of the target patch in upcoming investigations. In our study we corrected for the data gaps in the lower part of the stand by assuming zero light penetration for the lower 60 degrees of the photographs. The whole analysis was therefore restricted to the zenith angles between

0 and 30 degrees. In Figure 5 (bottom), several irregularly distributed rectangles are visible in the simulation which appear to have no natural pendant. These virtual objects resulted from voxels that represent insects, birds, erroneous measurements or objects in the air (e.g. falling leaves, dust, pollen) detected by one of the scans and projected into the image.

Their considerable size results from the distance to the position of the 'photo-point' (xyz-coordinate of the point where the hemispheric photo was taken). If they were close to the photo-point they could have a remarkable size, while they were not more than a small dot if far from the photo-point. Obviously, filtering the point clouds for erroneous data points did not entirely prevent this virtual objects from being visible in a number of images.

The hemispherical photographs, taken with the camera in the forest and used as validation method here, also showed a number of characteristic weaknesses. First we faced the problem of subjectivity in the thresholding process. In fact we found a correlation between two different experienced operators in defining the threshold with a R^2 of "only" 0.75 ($p < 0.001$). Secondly, the background illumination from the sky caused in some images effects of blooming in those areas, where clouds were rather bright and where small twigs should have been visible as the connection between a leaf and a branch, but were not.

Calculating canopy openness using GLA software was easier in case of the simulation than for the photographs as no subjective adjustment of the threshold was necessary in the first case. The calculated openness in the example presented in Figure 5 was 18.0% for the hemispherical photograph and 14.0% for the simulation. The geometry of the canopy was well represented in both approaches but small gaps, visible in the photograph, appeared to be even smaller or absent in the simulation. This went along with a general trend to some kind of 'clumping'. Small objects like single leaves should have been distinguishable as they were in the photograph but they built lumps instead. Both effects could be found in many simulated images and were a direct consequence of the voxel-model itself.

Even though we avoided laser-scan measurements at wind speeds >5 $m* s^{-1}$ negative influences of canopy movement on the quality of the simulated images were nevertheless evident. In fact, we found a significant negative correlation between mean peak wind speed and the difference between simulated and photographic image ($R^2= 0.2$; df = 33; $p< 0.01$).

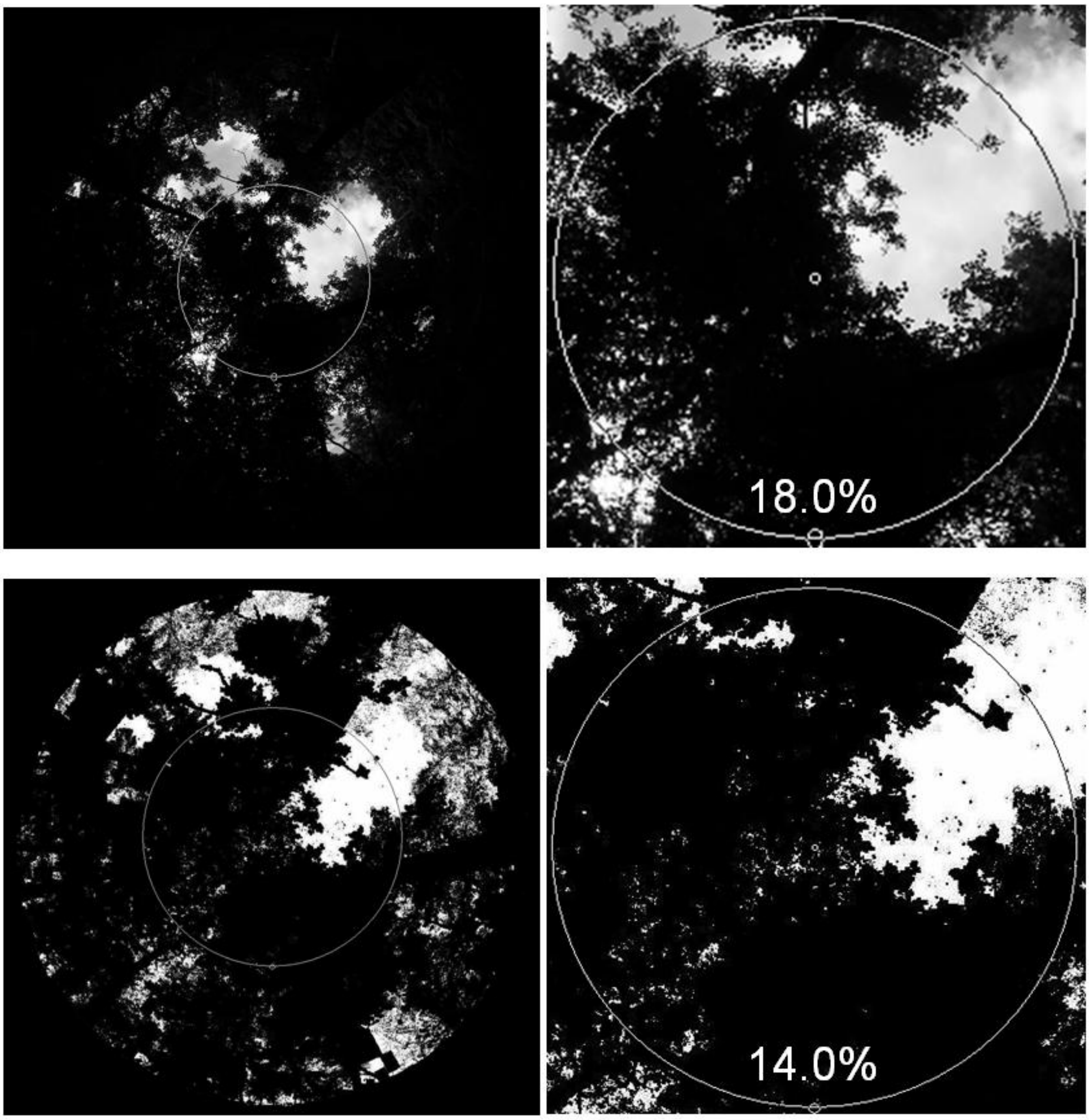

Fig. 5: Comparison of a hemispherical photograph taken from the ground (top) and its voxel-based simulation derived from six scans (below). On the left side is the whole scene, on the right the more restricted sections of the two images enlarged to allow for better comparison. Circles indicate the 30° zenith angle in which the analysis was done. Percent values indicate canopy openness within the analyzed circle.

3.4 Simulated hemispherical canopy views in different types of canopies

In total, we simulated 35 hemispherical views of the canopy in the Hainich mixed forest. We found the quality of the simulated images to be most dependent on the gap structure itself and also on wind speed. The more small gaps were present in the hemisphere, the more likely it was to have these tiny gaps closed in the scan due to wind-induced movement of canopy branches. Not surprising, higher wind speeds during the scanning period (up to 1 hr) enforced this effect. Clearly, a scanning procedure of 1 hr duration is more likely to be affected by canopy movement than a single camera snapshot of a fraction of a second. In multiple scanning approaches, wind effects decreased the calculated canopy openness mostly because branch movement, captured in one scan, closed gaps left from another scan.

While the clusters in the Lindig area had a rather open canopy with a large variance in openness values, those in the Thiemsburg area were found to have a rather dense canopy with a comparatively small variance in openness.

Indeed, a comparison of the taken hemispherical photographs revealed that the Thiemsburg canopy was characterized by a large number of very small gaps within a more or less homogeneous closed canopy, whereas the Lindig canopy had rather big gaps and a more heterogeneous canopy closure (see Fig. 6). Possible explanations could be the lower number of trees in the surroundings of the clusters (Lindig: 46, Thiemsburg: 61 stems per 1256 m^2), or the lower average number of species in the chosen clusters (Lindig: 2.0, Thiemsburg: 2.4 species in the three-tree cluster).

We hypothesized that decreasing the voxel size from 27 cm^3 to 8 cm^3 would reduce the gap closing effect due to an increased overall openness resulting from smaller voxels. Hence, the correlation between photographs and simulated canopy views was hypothesized to be more close, in particular in the Thiemsburg area with small canopy gaps. We simulated a dozen images based on this smaller voxel size but obtained no positive results. Other confounding effects, such as a reduced spatial homogeneity of the dataset, apparently gained in importance, resulting in less tight correlations between photographs and simulations when using 8-cm^3 voxels.(data not shown).

Table 1 shows some characteristics of the canopy structure and the related gap patterns according to hemispherical photographs in the two forest patches Lindig and Thiemsburg. It is evident, that photographs and simulations were more similar in the Lindig stand with larger gaps.

We explain the principal differences in the tightness of the correlations for the two stands (R^2= 0.88 and 0.43) by the differences in the gap structure between the two forest patches.

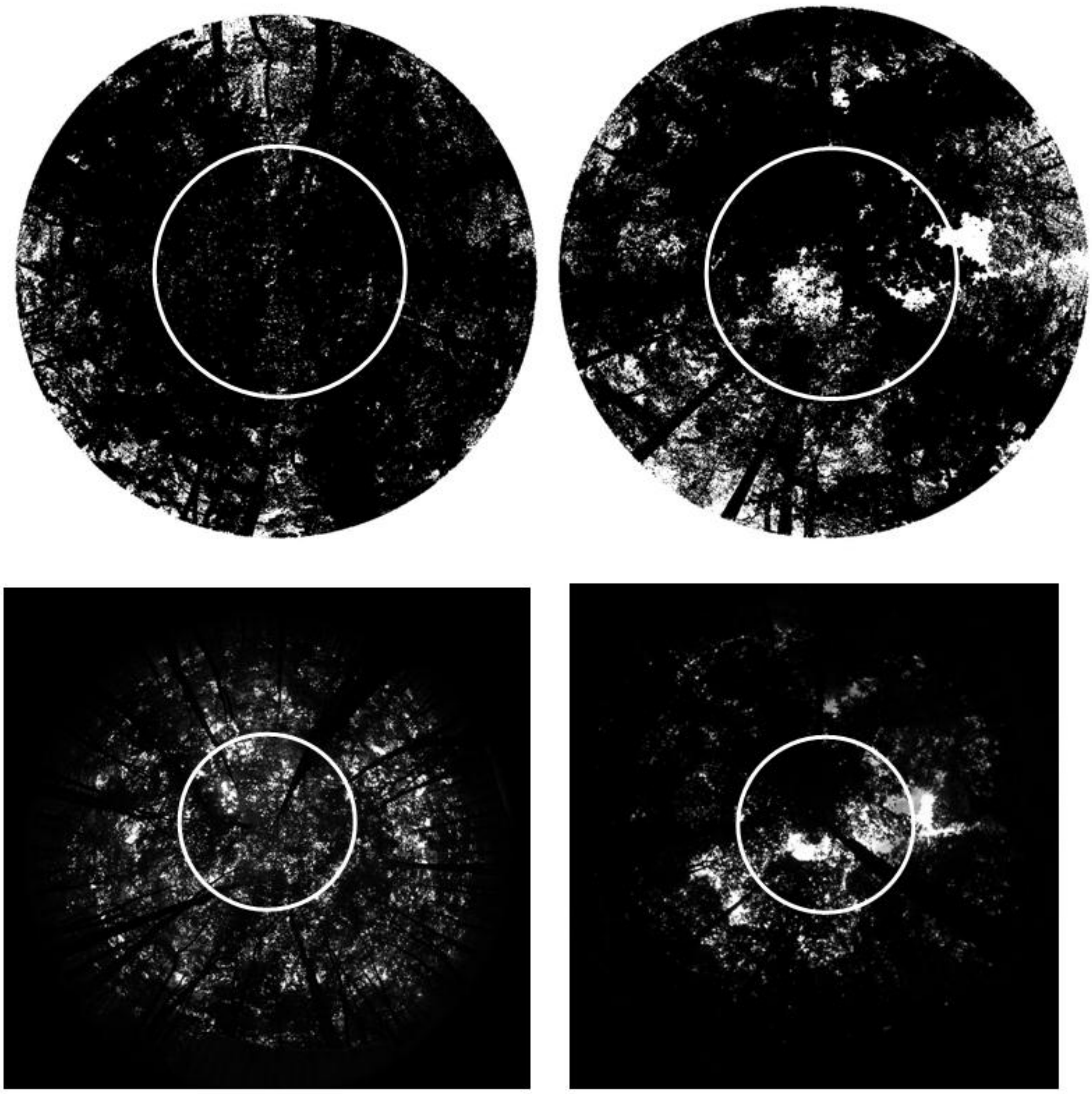

Fig. 6: Typical hemispheric view of the Thiemsburg (left) and the Lindig (right) canopies. Simulation (top) and photograph (bottom) are compared up to 30° zenith angle (indicated by the white circles).

A Welch-t-test revealed that the openness values of the two stands were significantly different, which was also true for the average size of the largest gap and the contribution of the ten largest gaps to the total openness of a photograph. Table 1 shows that the higher openness of the clusters in the Lindig area was to a greater percentage caused by the ten largest gaps (when compared to the Thiemsburg area).

Desirable improvements in the simulation algorithm are mainly limited by the computability of the datasets with recently available PC- hardware. Running a single simulation for a tree cluster took up to four hours but is expected to become faster with future processors. Thus, we expect that ground-based laser scanning will soon represent a valuable tool for analysing tree canopy structures with high accuracy in reasonable time. This may offer new opportunities for research on the functional ecology of tree and forest canopies, in particular with respect to the light climate, the resource economy of canopy space occupation, and canopy interactions in mixed forests.

4. Conclusions

We found that modelling the three-dimensional structure of a species-rich temperate broad-leaved forest stand based on ground-based 3D-laser scanner data and extracting ecologically relevant parameters, such as canopy openness and light penetration through the canopy layers, is only possible when the calculation is based on volumetric pixels (voxels). Hemispherical photographs of the canopy were successfully simulated based on the scanner data, but with some limitations.

The simulation of photographs taken close to a leaf, branch or stem failed due to inherent properties of the voxel-model, building volumetric pixels whenever there is an object found in the volume no matter how small or how close to the view point it may be. Future improvements of the simulation algorithm must focus on this problem. We recommend to avoid simulating photographs taken on positions where a large number of voxels (>1000) is situated within a hemisphere of one m radius over the simulation point, a situation that is easily detected with appropriate data analysis software such as Mathematica.

Data gaps that occurred in the more distal sections of the simulated images (high zenith angles), resulted from instrument limitations (maximum range of the scanner: <79 m). Reducing the analyzed area of the images to lower zenith angles as done in this study is one possibility to avoid this shortcoming, but not the most elegant solution. If enough scans from the ground can be combined, including some taken at greater distances from the area of interest, we assume that these problems can be minimized. Further, improvements in the measurement range of future scanners will help to overcome these limitations.

Future improvements on the algorithm used to transform the raw data will depend on the expected increase in the performance of processors which is needed to simulate hemispherical photographs much faster and based on more scans. This in turn will help to increase the zenith angle to be modelled (>30° zenith angle).

It was shown that laser scanners can face problems in the identification of rather small canopy gaps, especially in combination with wind-induced movements of canopy elements.

Being able to model hemispherical photographs for any position under the canopy offers new opportunities for functional research in tree and forest canopies. We showed that the analysis of species-specific patterns of canopy space occupation and their effect on light competition and light availability on the ground will be possible based on LIDAR data. A future application would be canopy models of growth and photosynthetic carbon gain in mature trees.

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Chapter 4

Crown deformations in mixed forests- quantifying asymmetric competition by terrestrial laser scanning

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Crown deformations in mixed forests-quantifying asymmetric competition by terrestrial laser scanning

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Abstract

Interspecific competition is a key process determining the dynamics of mixed forest stands and influencing the yield of multispecies tree plantations. Trees can respond to competitive pressure from neighbors by crown deformation, thereby avoiding competition. We employed a high-resolution ground-based laser scanner to analyze the 3-dimensional extensions and shape of the tree crowns in a near-natural broad-leaved mixed forest in order to quantify the direction and degree of crown asymmetry of 15 trees (*Fagus sylvatica, Fraxinus excelsior, Carpinus betulus)* in detail. We also scanned the direct neighbors and analysed the distance of their crown centres and the crown shape with the aim to predict the crown asymmetry of the focal tree from competition-relevant attributes of its neighbors. The horizontal distance of the crown centres and the diameter at breast height (as a surrogate of canopy size) were identified from a list of twelve canopy structural parameters to characterize the importance of a neighbor in competitive interaction best. By summing up the virtual competitive pressure of all neighbors in a single competitive pressure vector, we were able to predict the direction of crown asymmetry of the focal tree with an accuracy of 96 degrees on the full circle (360°).

The competitive pressure model was equally applicable to beech, ash and hornbeam trees and may generate valuable insight into competitive interactions among tree crowns in mixed stands, provided that sufficiently precise data on the shape and position of the tree crowns is available. Multiple-aspect laser-scanning proved to be an accurate and practicable approach for analysing the complex 3-dimensional shape of the tree crowns, needed to quantify the plasticity of growth processes in the canopy. We conclude that the laser-based analysis of crown deformations offers the opportunity to achieve a better understanding of the dynamics of canopy space exploration and also may produce valuable advice for the silvicultural management of mixed stands.

1. Introduction

During the last decades, forestry managers in the temperate zone often have favoured mixed stands over monocultures because they may be more resistant against herbivore attack (e.g. Jactel and Brockerhoff 2007) and tend to harbor a more diverse flora and fauna than pure stands (e.g. Moore and Allen 1999; Palik and Engstrom 1999). Interspecific competition is a key process determining the dynamics of mixed species stands. In the past, stem base positions have been used to study the spatial dynamics of mixed forests. More recently, there is a growing interest in analyzing stand dynamics through tree-crown patterns which may reflect the outcome of interspecific interactions between neighboring trees more sensitively. Predicting the consequence of interspecific competition is not only of academic interest in natural mixed forests, but economically important in planted mixed stands as well, because competition can reduce the yield and vigor of target species, and may eventually lead to their suppression and death.

Competition for light in the canopy is often asymmetric because radiation (at least its diffuse component) comes directionally from above so that taller trees can easily shade shorter ones while the reciprocal effect is less significant. However, asymmetry in light capture among coexisting trees may not only be caused by height differences among the tree species, but also by species contrasts in canopy shape and the three-dimensional structure and positioning of the foliage in the canopy space. Not only broad-leaved and coniferous trees differ largely in their crown shape and thus in their effect on direct neighbors (e.g. Kikuzawa and Umeki 1996), co-occurring broad-leaved trees of the genera *Fagus*, *Tilia*, *Acer*, *Fraxinus* and *Carpinus* in mixed stands were also found to differ markedly with respect to crown depth, crown base height, crown radius, and the height above ground of maximum crown projection area, despite similar total tree height (e.g. Frech et al. 2003). Thus, even in mixed stands with uniform canopy height, marked asymmetry of competition for canopy space and light is much more likely than quasi-symmetry. Heterogeneous light distribution in the canopy space due to partial shading by specific neighbors leads to canopy sections with slow growth while well sun-lit regions may show vigorous expansion growth, resulting in asymmetric canopy growth. Plastic modifications of canopy structure are a powerful response of trees to heterogeneous light regimes by growing towards areas with higher light availability and reduced competition, thereby avoiding neighbors (Muth and Bazzaz 2003). Because of this morphological plasticity, tree canopies are rarely positioned directly above the stem base.

A growing body of work in temperate and tropical forests suggests that tree canopy displacement is a common means of neighbor avoidance and that the magnitude of crown displacement increases with the degree of neighborhood asymmetry (Young and Hubbell 1991; Brisson 2001; Muth and Bazzaz 2003). Such a neighborhood approach may allow quantifying how the spatial attributes of neighbors influence the outcome of competitive interactions in mixed forests (Wagner and Radosevich 1998). A crucial step on the path to predictability of interspecific competition on the level of the individual trees is the selection of relevant spatial attributes characterizing the crown shape of the neighbors and focal trees. Neighbor distance, size and identity have most often been used to characterize the neighborhood of a target tree in terms of the total magnitude and prevailing direction of competitive pressure (Biging and Dobbertin 1992; Muth and Bazzaz 2003). While distance is undoubtedly a key factor with a strong negative correlation to competition intensity, the effects of neighbor size and identity on the magnitude of competitive pressure are more difficult to quantify. Muth and Bazzaz (2003) used basal area, tree height and canopy depth as canopy structural traits for characterizing the relative importance of neighbors in the net of competitive interactions within a patch of trees. In other studies, canopy projection area was utilized for the same purpose (Brisson 2001).

Due to several reasons, these canopy attributes are no ideal parameters for characterizing the shade effect on neighbor trees and thus the competitive pressure may not be deduced precisely. Indeed, Muth and Bazzaz (2003) concluded that most studies of canopy displacement have failed to detect clear relationships between neighbor size and distance, and the canopy displacement of a focal tree. One possible reason is that canopy projection area and canopy depth are only poor descriptors of canopy volume and the magnitude of light attenuation by the neighbor`s foliage because most tree crowns are irregularly shaped and deviate markedly from the idealized cylinder or cone bodies often used in models to analyze canopy interactions (e.g. Pretzsch 2002). A second reason is that coexisting tree species have been found to differ considerably in the height of maximum horizontal crown extension even when they achieve similar total height (e.g. Frech et al. 2003). This may result in a shift from a mostly one-sided to a more two-sided competitive interaction because inferior competitors for light in the upper canopy could be superior competitors in lower strata at the same time (Kikuzawa and Umeki 1996).

Here, we present results of a study of canopy displacement in a species-rich temperate broad-leaved forest, where ground-based laser scanning was employed for canopy analysis in order to overcome the shortcomings of crown shape analysis with conventional techniques. Multiple-aspect laser scanning allowed us to obtain much more precise models of crown shape, of the direction and magnitude of crown asymmetry of focal trees, and of the size and location of direct contact zones between neighboring trees. Our main study objective was to analyze how a tree`s competitive neighborhood influences the position and shape of its canopy.

2. Material and methods

2.1. Study site

The study was conducted in Hainich National Park in the federal state of Thuringia in Central Germany (51°05'N; 10°31'O). The National Park covers a total area of 16,000 ha of semi-natural mixed deciduous forest with up to 14 tree species per ha. The investigations concentrated on an old-growth forest patch in the eastern part of the National Park close to the village of Weberstedt with six abundant tree species: European beech (*Fagus sylvatica* L.*)*, lime *(Tilia cordata* P.Mill.*)*, sycamore maple (*Acer pseudoplatanus* L.), common ash *(Fraxinus excelsior* L.*)*, british oak *(Quercus robur* L.*)* and hornbeam (*Carpinus betulus* L.*)*. Mean annual temperature is 7.5 °C, annual precipitation is about 590 mm and all trees are growing on stagnic Luvisol according to the World Reference Base for Soil Resources (WRB). The forest communities present include mesic beech forests of the *Galio-Fagenion* type with dominance of *Fagus sylvatica* and species-rich stands of the *Stellario-Carpinetum* type, where lime, ash and hornbeam dominate. The forest has been subject to only low-intensity forest management with irregular single-stem logging during the past 40 years, and no forest use since 1997, when the Hainich National Park was founded. The forest patches selected in this study are located on level terrain showing no signs (i.e. stumps) of former forest use in their core areas, and thus must have experienced canopy growth and interaction processes free of human interference for at least 40 years.

2.2. Analysis of crown structure

We selected 15 trees, each five ash, beech and hornbeam trees, with a diameter at breast height (DBH) of at least 25 cm. All trees were part of the upper canopy layer with upright stem growth and no signs of inclination of the stem due to wind effects. All 15 trees and their direct neighbors (between 4 and 13) in a radius of at least 20 m were scanned with the terrestrial laser scanner Z+F Imager 5006 (Zoller und Froehlich GmbH, Wangen, Germany) in leafless condition in March 2009. The angular step width of the scanner was set to a resolution of 0.036 degrees in horizontal and vertical direction resulting in a 10.000 pixel image for a 360 degree scan (Z+F Imager 5006 Manual). The range of view of the scanner was limited to 310 degrees vertically and full 360 degrees in horizontal direction. The Imager 5006 uses the phase-difference measurement technique to measure the distance to an object; it is a stand-alone instrument with no need for a laptop or electricity in the field. Twenty-four artificial targets were installed at random locations in the scanned forest scene which were used as fixed points in multiple scans (eight on average) conducted of the focal trees and their neighbors from different aspects. All scans were made under low wind speeds (<5 m s^{-1}) to avoid wind-induced movements of the trees.

Using a map of the focal trees (target trees) and their surroundings created from the laser scans, the species identity of the neighboring trees was determined in the field and registered. We assumed that trees, which have been removed more than 40 years ago, do not have a lasting impact on tree shape today anymore. This was also assumed for the few tree individuals that fell during storm events. Nevertheless, to cope with the possible influence of lost trees on the canopy structure, we mapped all stumps in the wider surroundings of the focal trees, thus allowing for a statistical analysis of any effects of former competitors.

2.3. Data processing

2.3.1. Data preparation

The point clouds created by the laser scanner were filtered in the ‘Z+F Laser control’ software (Zoller und Froehlich GmbH, Wangen, Germany). We used the default settings of the filters that automatically erased all data points that were most likely not accurate (low quality of the reflected laser signal, etc.). The next step was the assemblage of all scans that were part of the same scan session, to create a single unified point cloud of the tree cluster, offering a real three-dimensional view of the scene. In this step, all information gained from the different scanner perspectives was combined, using the 24 targets, that were identified manually in each scan, as fixed points. The individual XYZ-coordinate system of every scan taken from a given scan scene was transformed into a 'global' coordinate system which was valid for all scans related to the same forest patch. The result was a point cloud offering comprehensive information on the three-dimensional distribution of the axes (stems, branches, twigs) of the focal tree and its neighbors. The subsequent step in the analysis generated individual three-dimensional data point clouds for every tree. Every focal tree and its corresponding neighbors were manually identified in the point cloud of the forest patch and extracted. This was a subjective procedure as their was no reliable algorithm available that identified trees in the point cloud on a higher level of accuracy than the human eye. As the trees were defoliated at the moment of the scanning, it was not difficult to separate the point clouds of two neighboring trees from each other. We decided to consider all those surrounding trees as possible competitors of the focal tree that were part of the upper canopy layer and were in direct contact with the crown of the focal tree. Whether a contact zone between two trees existed or not, was evaluated in a simple procedure using the software Cyclone 5.8. (Leica Geosystems AG, Heerbrugg, Switzerland). In Cyclone, the xyz-point cloud of the whole forest patch was made visible in a top view with the forest floor being erased. This made the outline of each crown clearly visible and every neighbor tree of a chosen focal tree was selected by hand if a common contact zone existed between the two crowns (Fig. 1). Every focal tree and its neighbors were saved with their point clouds in a single file per tree, with all trees belonging to the forest patch around the focal tree having one coordinate system in common.

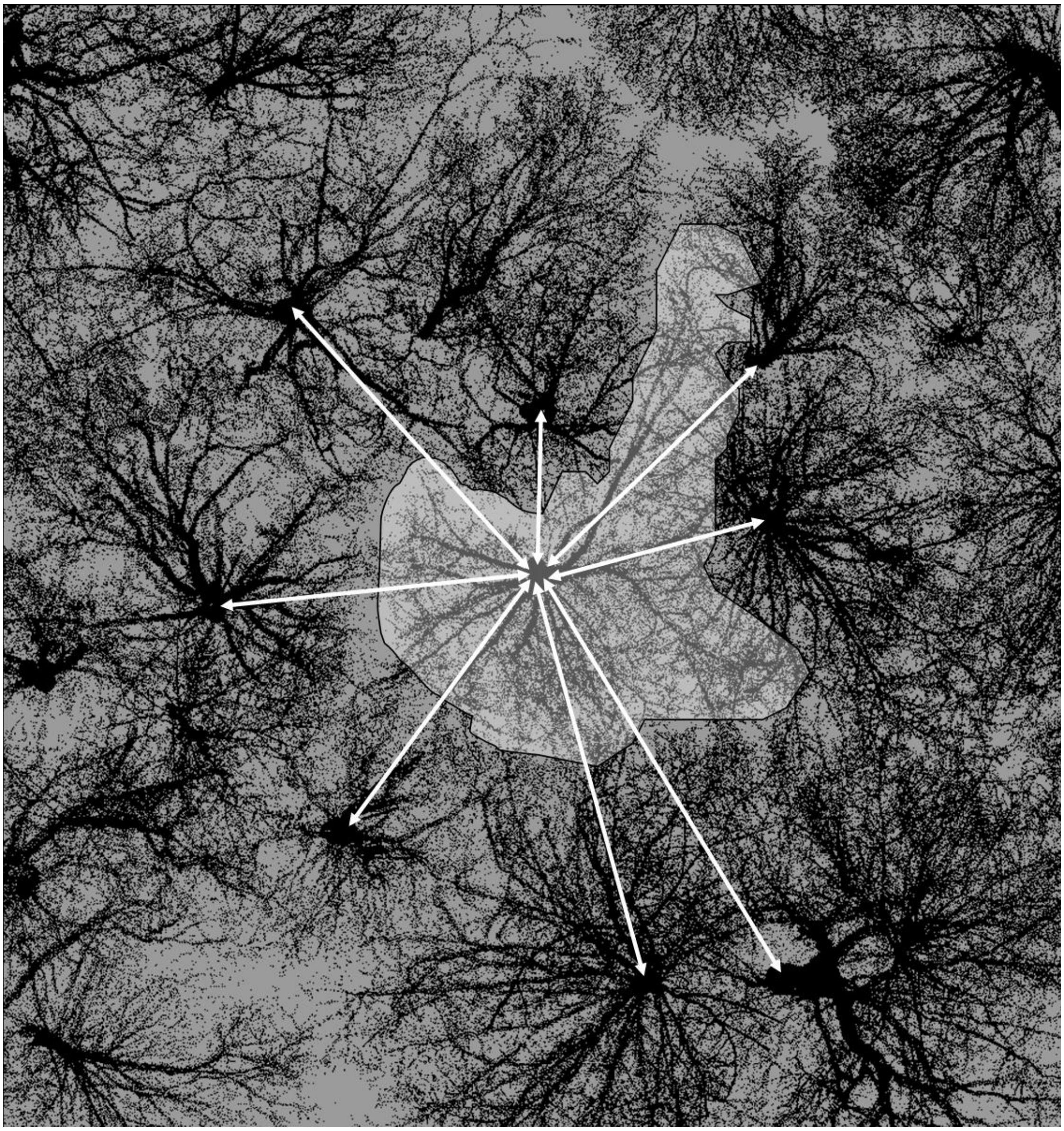


Fig. 1: A focal tree (centre) and its direct competitors as presented in a three-dimensional point cloud (top view, forest floor erased). The distance between the focal tree and its neighbors is indicated by white arrows. By evaluating optically which canopies do have a contact we selected the direct competitors of each focal tree. In this case we had eight competitors distributed around the focal tree.

2.3.2. Quantifying crown dimensions and asymmetry

Using the software "Mathematica 7" (Wolfram Research Inc., Champaign, IL, USA), we created an algorithm that allowed to parameterize various structural attributes of the crown and the stem from the xyz-data of each focal tree and its neighbors. To do so, the single tree-point cloud was transformed into a 'voxel-model' of the tree with a resolution of 10 cm (Fig. 2).

Fig. 2: Three-dimensional point cloud of a single tree as created by the scanner (left). Voxel-based representation of the same tree as used for the calculation of structural parameters with Mathematica based on voxels of 10 cm³ volume (right).

Every volumetric pixel (voxel) thus had a volume of 1000 cm³, which represented a good compromise between the goals of a short computation time (seconds) and satisfying resolution (10 cm). Assigning voxels to the data points is a crucial step in handling laser scanner data as it is necessary to eliminate the heterogeneity of the spatial density of points in the cloud which is caused by the variable distance of the objects to the laser scanner in the scene. The following crown structural parameters were determined for every focal tree:

- **t**otal **t**ree **h**eight (TTH)
- **d**iameter at **b**reast **h**eight (DBH)
- **c**rown **b**ase **h**eight (CBH)
- **c**rown **h**eight (CH)
- **c**oordinates of the **c**entre of the stem at **g**round level (CCG)
- **h**eight of maximum **c**rown **p**rojection **a**rea (HCPA)
- maximum **c**rown **p**rojection **a**rea (CPA)
- **c**entre of the **c**rown at the height of maximum **c**rown projection area (CCC)
- **c**rown **p**rojection **a**rea at the height of the maximum crown projection area of the focal tree (CPAcomp., only for neighbor trees)
- **c**entre of the **c**rown **at** the height of the **CPAcomp** (CCatCPAcomp, only for neighbor trees)
- degree of tree **asym**metry and its direction expressed as a vector (abbr. ASYM)
- **h**orizontal **d**istance between the CCC of the focal tree and the CCatCPAcomp of the neighbor tree (HD), and
- horizontal **d**istance between the **CCG** of the focal tree and the CCG of the neighbor tree (DCCG).

Figures 3a and 3b give a graphical presentation of these parameters and their location on the tree. TTH was calculated as the vertical distance between the uppermost point in the point cloud of the tree and the forest floor. For validation we also measured TTH of the study trees with an optical Vertex height meter (Haglof Madison, Miss., USA) in the field. For quantifying the DBH of the trees, we extracted all voxel centre-points in a height of 1.3 m above-ground and used the mathematical QR-decomposition procedure to fit a circle to the points. In this calculation, a 1-cm voxel-model was used instead of the 10-cm model to allow for a higher accuracy. In contrast to approaches of measuring the DBH with laser-scanning measurements published by Hopkinson et al. (2004) and Thies et al. (2004), we decided not to use a cylinder fitting process based on the point cloud of multiple height layers.

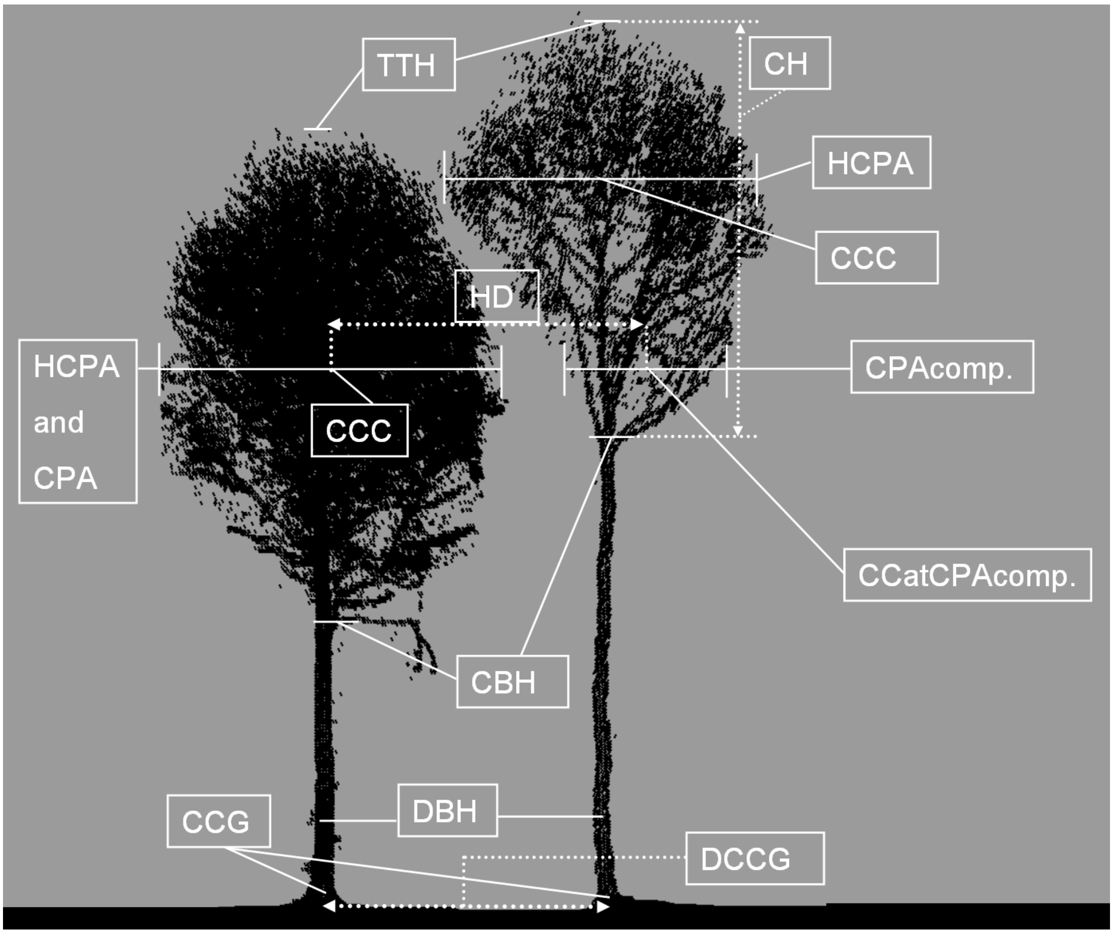


Fig. 3a: Graphical presentation of the most important structural parameters derived for an exemplary focal tree and an exemplary neighbor tree: **t**otal **t**ree **h**eight (TTH), **d**iameter at **b**reast **h**eight (DBH), **c**rown **b**ase **h**eight (CBH), **c**rown **h**eight (CH), **c**oordinates of the **c**entre of the stem at **g**round level (CCG), **h**eight of maximum **c**rown **p**rojection **a**rea (HCPA), maximum **c**rown **p**rojection **a**rea (CPA), **c**entre of the **c**rown at the height of maximum **c**rown projection area (CCC), **c**rown **p**rojection **a**rea at the height of the maximum crown projection area of the focal tree (CPAcomp, only for neighbor trees), **c**entre of the **c**rown **at** the **CPAcomp** (CCatCPAcomp), **h**orizontal **d**istance between the CCC of the focal tree and the CCatCPAcomp. of the competitor (HD) and horizontal **d**istance between the **CCG** of the focal tree and the CCG of the neighbor tree (DCCG).

Even though cylinder fitting methods usually give more robust results than simple circle approaches, we obtained better results with the circle fitting process due to extensive branching in the lower parts of some of our trees. In case of branching at the height of the layer of scanned data used for DBH-calculation, we used the next-highest layer. This correction was repeated if the problem was still obvious in the higher layer. To detect branching we plotted all points used for DBH-calculation including the fitted circle and performed an optical quality control. The laser scan-derived DBH-values were validated against conventional tape measurement data. A semi-automatized extraction of the parameter CBH, defined as the height of the lowermost leaf-bearing branch, was successfully performed based on the following procedure: 1) The points describing the centre of each voxel in every height layer (10 cm thickness as given from the 10-cm voxel-model) were taken to describe the convex hull of the tree crown in each height. 2) The difference between the area in one layer L_1 and its upper neighbor layer L_2 was expressed in percent of the area of layer L_1 to derive the gain or loss in area with height. 3) A cubic equation was fitted to the plotted curve describing the leaf area gain and loss with height. 4) The null positions of the first derivation of the cubic equation (between one and three are possible) were determined and the corresponding height layers were derived. Finally, an optical evaluation based on the 3-D point cloud of the trees was necessary to determine which of the heights represented the lower end of the crown in case more than one null positions existed. Again, the CBH values were validated against data obtained by traditional optical measurement. Vertical crown length (crown height, CH) was calculated as the difference between TTH and CBH. The centre of the stems at ground level (CCG, given in the coordinate system of the scanner) was derived by taking the average centre-position of the centre of the smallest rectangles that could be placed around the voxels in the lowest five to ten height layers of the tree. To determine the maximum crown projection area CPA, we created the convex hull polygons around the voxels in each height layer, calculated the area of the polygons and identified the area of the largest polygon (CPA) and its height (HCPA, see Fig. 3b). The centre of the polygon used to calculate CPA was determined by the same method as used in case of the CCG (centre of the smallest rectangle enclosing the voxel centre-points). CPAcomp for the neighbor tree was derived by applying the method described for CPA at the height layer determined by the height of maximum crown projection area of the focal tree. The horizontal distance (HD) between the CCC of the focal tree and the CCatCPAcomp of the competitor was obtained from the coordinates of the two points. A similar procedure was described by Rouvinen and Kuuluvainen (1997) based on structural data derived with a tachymeter. The horizontal distance between the centre of the stem at ground height of the focal tree and the neighbor tree (DCCG) was calculated as Euclidean distance between their coordinates.

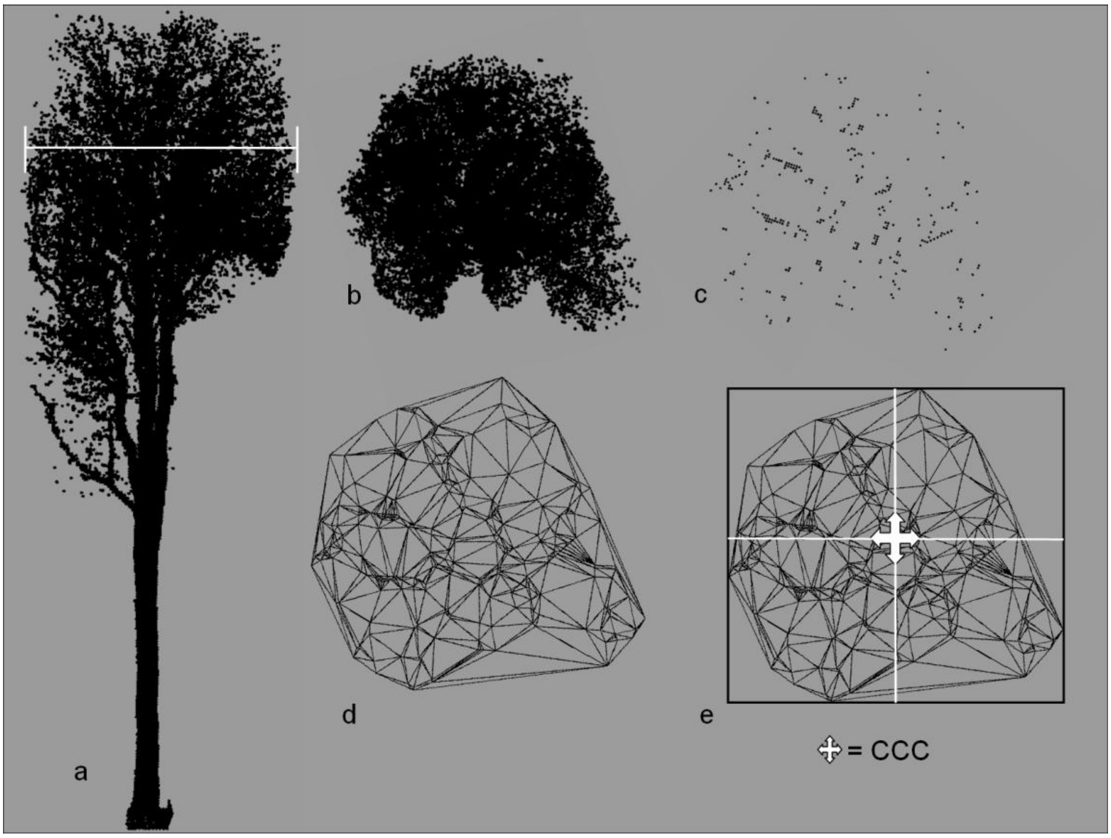


Fig. 3b: Graphical presentation of the maximum crown projection and the centre of the crown at the height of the maximum crown projection area. All images are based on the 10-cm voxel-model with only the centre-points of the voxels shown. a) 3-D point cloud of a tree with the height of the maximum crown projection area highlighted with a white line, side view. b) The same tree as in a) but in top view, showing the shape of the crown as visible from above. c) All voxel centre-points in the layer of the height of the maximum crown projection area. d) Outer hull of the point cloud in c. as used to calculate the maximum crown projection area. d) Centre of the crown at the height of the maximum crown projection area which is derived from placing a rectangle on the outermost edge points of the canopy volume and marking the centre of the rectangle.

In addition to these tree biometric key data we calculated a parameter which is based on the neighborhood situation of the focal tree. For each focal tree we calculated the number of voxels that are closer than a) three, b) two or c) one m (Euclidean distance) to a voxel of the neighbor tree. This was done in a pairwise calculation scheme. We performed the calculation for all voxels of both trees. This parameter may be used to quantify the size of the crown area with possible branch competition for light and space between neighbors (contact zone) by the number of voxels of two competing trees that are close to each other.

Table 1 shows a selection of the main structural parameters derived for the 15 focal trees and their competitors.

Table 1: A selection of some important structural parameters of the target trees and their competitors

Target tree	DBH (cm)	Height (m)	Maximum crown projection area (m^2)	No. of identified competitors	Species of the competitors						Competitors structural parameters		
					Ac	Fa	Fr	Ti	Ca	Qe	Mean DBH (cm) ± SD	Mean height (m) ± SD	Mean max. crown proj. area (m^2) ± SD
Beech 1	40.84	24.7	66.20	7	1	4	1	0	1	0	42.62± 15.36	26.07± 3.70	48.29± 22.31
Beech 2	48.70	26.8	57.77	6	1	4	0	1	0	0	51.46± 11.68	27.85± 1.32	50.84± 32.05
Beech 3	50.36	24.4	42.19	7	0	6	0	1	0	0	43.28± 17.95	26.47± 2.13	42.90± 47.89
Beech 4	61.01	27.1	88.19	7	1	1	0	3	1	1	41.12± 16.07	24.70± 2.52	45.49± 29.83
Beech 5	49.65	26.7	63.27	7	1	4	0	2	0	0	42.19± 19.86	26.46± 3.85	57.53± 34.72
Ash 1	41.16	26.0	39.85	6	0	4	1	1	0	0	39.47± 9.96	25.23± 1.21	28.18± 15.13
Ash 2	36.96	25.9	36.74	8	0	7	1	0	0	0	44.02± 8.74	25.66± 1.64	41.54± 22.27
Ash 3	35.22	25.3	42.82	5	1	3	1	0	0	0	38.82± 6.42	25.36± 1.44	32.52± 17.88
Ash 4	24.25	21.7	17.93	6	0	3	0	3	0	0	33.32± 13.73	22.70± 1.80	33.18± 30.07
Ash 5	40.68	26.9	49.31	4	2	0	0	1	1	0	32.59± 13.65	24.43± 1.18	29.41± 26.34
Hornbeam 1	35.15	21.8	56.88	13	1	8	1	3	0	0	36.68± 17.48	23.67± 4.33	32.34± 28.04
Hornbeam 2	36.41	23.3	48.86	9	0	9	0	0	0	0	44.61± 13.39	24.88± 3.11	35.58± 32.88
Hornbeam 3	59.94	26.6	80.25	5	1	2	0	2	0	0	43.62± 25.47	26.40± 3.77	43.17± 37.51
Hornbeam 4	51.88	26.2	121.99	9	1	3	1	4	0	0	37.44± 19.03	23.76± 3.67	39.98± 30.66
Hornbeam 5	45.95	25.6	59.98	6	1	0	0	5	0	0	27.86± 9.04	24.35± 1.10	16.10± 11.66

Ac = *Acer pseudoplatanus* L.; Fa = *Fagus sylvatica* L.; Fr = *Fraxinus excelsior* L.; Ti = *Tilia cordata* P.Mill.; Ca = *Carpinus betulus* L.; Qe = *Quercus robur* L.

The main characteristics of the shape of the crown of the focal trees are presented in Figure 4. All neighboring trees with a total height being lower than the height of maximum crown projection area of the focal tree (TTH of the competitor < HCPA of the focal tree) were skipped from the analysis as they are believed to be too small to be a relevant competitor.

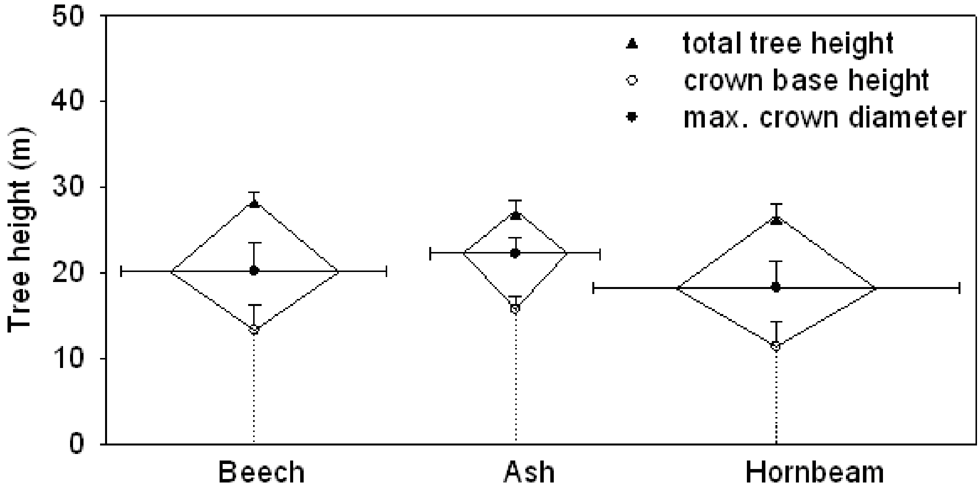


Fig. 4: Average crown dimensions of the beech, ash and hornbeam focal trees (n= 5 per species) based on the parameters total tree height, crown base height, height of maximum crown projection area (HCPA) and crown diameter at the height of maximum crown projection area (calculated from CPA with the assumption of a circular crown shape, mean ± 1 SD). Y- and x-axis have the same scale.

2.3.3. Relating crown deformation to competitive pressure

Crown asymmetry (ASYM) was defined as the horizontal distance between the centre of the crown at the height of maximum crown projection area (CCC), which serves as a proxy of the tree`s crown centre of mass, and the stem-location on the ground-level (CCG). ASYM was calculated for each of the 15 target trees as a measure of relative crown deformation at the height of maximum horizontal crown extension (Fig. 5). In a second step, for each neighbor tree surrounding a target tree, we calculated a vector from the neighbor`s crown centre at the height of the maximum crown projection of the focal tree (CCatCPAcomp) to the target tree`s crown centre (CCC) as an expression of the competitive pressure exerted on the target tree. The vector`s direction was defined by the axis CCatCPAcomp-CCC, its length by a measure of the neighbor`s importance, which is similar to what has been done in other studies (Franco 1986; Brisson and Reynolds 1994; Rouvinen and Kuuluvainen 1997; Umeki 1995a, 1995b, 1997; Brisson 2001). Structural parameters used for quantifying a neighbor tree`s importance in competition with the target tree were crown distance

(HD, more specifically the distance CCatCPAcomp-CCC), DBH, tree height, crown height (CH) and others more.

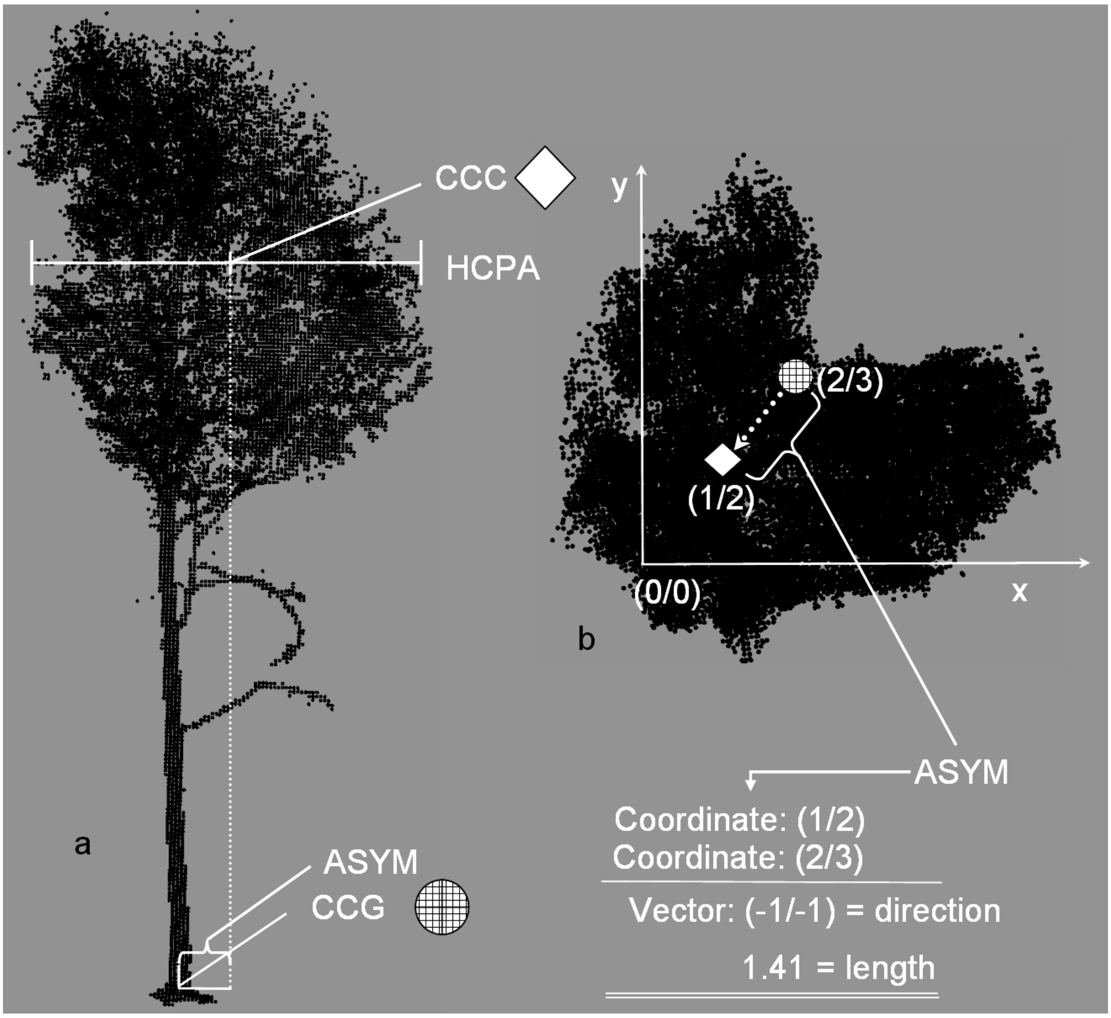


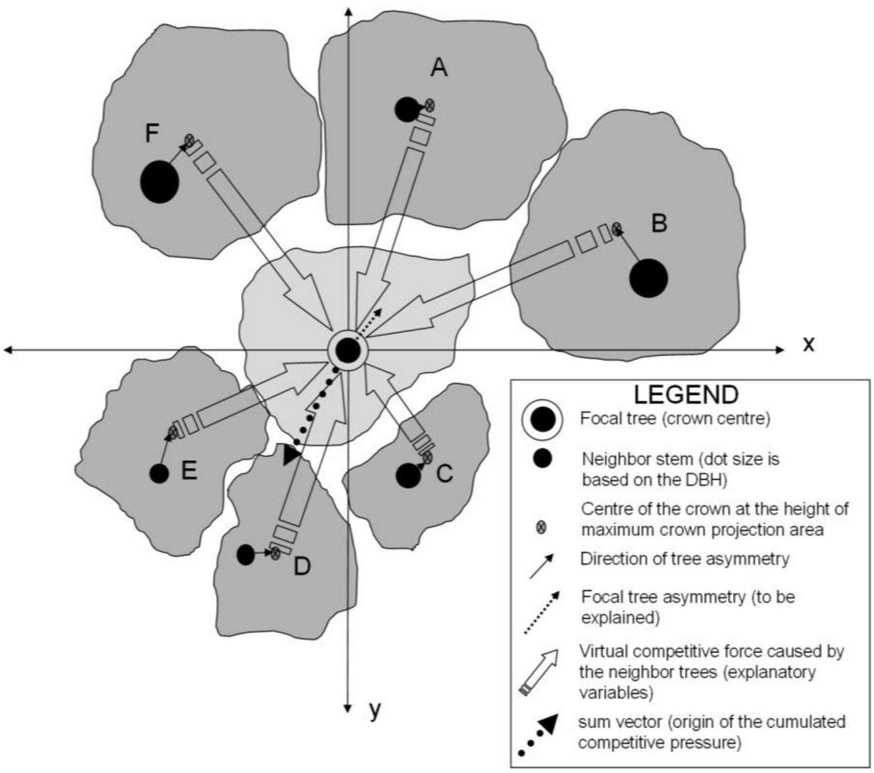
Fig. 5: Graphical presentation of structural parameters used to quantify the degree and direction of the asymmetry of a canopy. a) Side view on a tree with the asymmetry (ASYM) being equalled with the horizontal distance between CCG and CCC. b) Top view on the same tree with CCC and CCG marked including their coordinates. The difference between the x- and y-values can be expressed as a vector, with the length of the vector being the measure for the degree of asymmetry.

According to an assessment of these parameters, which were tested in their suitability as indicators of importance against the measured asymmetry of the target tree (see below), we selected DBH and the inverse of the square-rooted distance (HD) as most appropriate importance parameters (Fig. 6, Tab. 4). We then added all neighbor vectors to obtain a vector of virtual competitive pressure of all neighbors on the target tree. Accordingly, neighbors that are close and large (high DBH) exert a larger pressure than more distant and smaller neighbors. To test for the accuracy of this model of competitive pressure in a target tree`s neighborhood, we compared the direction of the competitive pressure vector with the direction of the measured crown asymmetry of the target tree. According to results presented in the literature (e.g.

Young and Hubbell 1991; Holmes 1995; Umeki 1995b; Brisson 2001; Muth and Bazzaz 2002), we assumed that the competitive pressure results in canopy expansion preferentially away from the direction of the main neighbor pressure causing canopy asymmetry in the opposite direction. The correspondence between modelled and measured canopy asymmetry direction was measured as the difference in degrees between the two vectors. The models were run with different combinations of neighbor importance variables (see above), resulting in the preference of distance (HD) and DBH as model parameters. Besides the direction of crown deformation, we also investigated the degree of deformation by comparing the length of the competitive pressure vector with the measured crown asymmetry (in m) for the 15 target trees. Finally, we investigated whether the identity of the target tree species (beech, ash or hornbeam) and its position in forest succession (mid-successional light demanding vs. late-successional shade-tolerating species) had an influence on the direction and degree of canopy deformation in this mixed forest.

2.3.4. Statistical analyses

All statistical analyses were done with the software 'R' (Vers.2.8.0, The R Foundation for Statistical Computing). In order to detect possible differences in the predictability of the asymmetry among the three investigated deciduous tree species (ash, beech and hornbeam), we performed an analysis of variance (ANOVA). A Shapiro-Wilk-test was used to test the normality of data distribution prior to the ANOVA runs. With a multiple regression analysis we aimed to identify possible crown structure parameter combinations that had a significant impact on the success of the model prediction on crown asymmetry. Finally, we conducted an ANOVA with Tukey´s post-hoc test to test for a significant difference in the structure and size of the three tree species under the 15 investigated focal trees. Significance level was $p < 0.05$ in all tests.



Focal tree: (x_0/x_0)

Neighbor A: (x_1/y_1) $\quad \overrightarrow{a}\begin{pmatrix} x1 \\ y1 \end{pmatrix}$ *DBH*(1/ Sqrt(Distance))

Neighbor B: (x_2/y_2) $\quad \overrightarrow{b}\begin{pmatrix} x2 \\ y2 \end{pmatrix}$ *DBH*(1/ Sqrt(Distance))

Neighbor C: (x_3/y_3) $\quad \overrightarrow{c}\begin{pmatrix} x3 \\ y3 \end{pmatrix}$ *DBH*(1/ Sqrt(Distance))

Neighbor D: (x_4/y_4) $\quad \overrightarrow{d}\begin{pmatrix} x4 \\ y4 \end{pmatrix}$ *DBH*(1/ Sqrt(Distance))

Neighbor E: (x_5/y_5) $\quad \overrightarrow{e}\begin{pmatrix} x5 \\ y5 \end{pmatrix}$ *DBH*(1/ Sqrt(Distance))

Neighbor F: (x_6/y_6) $\quad \overrightarrow{f}\begin{pmatrix} x6 \\ y6 \end{pmatrix}$ *DBH*(1/ Sqrt(Distance))

$$\text{sum}\,(\overrightarrow{\text{a-f}}) = \mathbf{af}\begin{pmatrix} x \\ y \end{pmatrix}$$

The vector af is the sum of all competitive pressure vectors based on the importance measures diameter at breast height (DBH) and distance (between the centre of the crown of the neighbor trees and the centre of the crown of the focal tree, both at the height of maximum crown projection area of the focal tree). The vector af is hypothesized to point exactly in the opposite direction of the direction of asymmetry of the focal tree.

Fig. 6: Graphical presentation of the competitive pressure exerted by 6 neighbors on a focal tree. Given are the x/y- coordinates of the centre of the polygon representing the tree crowns of all trees in a neighborhood cluster at the height of the maximum crown projection area of the focal tree. The corresponding vectors describing the assumed virtual competitive pressure of the neighbors on the focal tree are indicated as arrows.

3. Results

The validation of total height, DBH and CBH calculated from the laser scanning approach against optical data yielded high correlation coefficients and thus was successful (Table 2).

Table 2: Pearson correlation coefficients, significance level and root mean square error between laser-scan derived data and optical determination of DBH and total tree height (TTH) for trees used in the study. DBH was measured with a dendrometer tape with a resolution of 1 mm, total tree height with a Vertex height meter (0.5 -1.0 m accuracy). Crown base height CBH was estimated from the scanner data in two ways: by hand (operator) and automatically (computer). Field data on crown base height was not available.

Parameter	n / df	r	p	RMSE
DBH	109 / 107	0.99	<0.001	3.93 cm
TTH	19 / 17	0.91	<0.001	1.20 m
CBH	109 / 107	0.94	<0.001	1.93 m

With this confidence in structural data obtained by laser-scanning of the crowns and stems, we compared the each five focal trees of the three species with respect to the vertical and horizontal extensions of the crowns. The ash trees differed significantly from the beech and hornbeam trees with respect to crown base height, crown projection area and stem diameter (DBH), despite similar tree heights (22-27 m). The ash trees had significantly thinner stems than the beech trees ($p < 0.05$) and a significantly smaller crown projection area when compared to the hornbeam trees ($p < 0.05$). Comparing the latter two species we further found a significantly higher crown base height for ash than for hornbeam ($p < 0.01$). Furthermore, the vertical extension of the ash crowns (crown height, CH) was tended to be smaller than in the other two species (Fig. 4, $p < 0.1$). Thus, the crown of the ash focal trees in this mixed stand was usually rather small in its vertical and horizontal extension, was concentrated in the upper part of the canopy and rested upon a rather thin stem when compared to the beech and hornbeam trees. Despite a tendency toward a rather large canopy projection area and low crown base height in hornbeam, *Fagus* and *Carpinus* differed not significantly in their crown dimensions in our restricted sample.

Table 3: Deviation in degrees between the direction of stem and crown growth asymmetry obtained from a laser-scan based model of crown structure as compared to an asymmetry prediction derived from 'competitive pressure vectors' of the neighbor trees on the focal tree (see Fig. 6). For a definition of the distance ASYM see Fig. 5.

Focal tree	Deviation in degrees [d][1]	Prediction error in degrees [2d][2]	Length of ASYM (m)
Beech 1	11	22	2.90
Beech 2	70	140	2.02
Beech 3	9	18	1.93
Beech 4	51	102	2.70
Beech 5	73	146	1.55
Hornbeam 1	3	6	2.78
Hornbeam 2	31	62	0.78
Hornbeam 3	64	128	1.61
Hornbeam 4	31	62	2.01
Hornbeam 5	8	16	0.91
Ash 1	54	108	1.50
Ash 2	46	92	3.06
Ash 3	144	288	0.56
Ash 4	93	186	0.58
Ash 5	38	76	0.54
Mean ± SD	48 ± 38	96 ± 76	1.70 ± 0.89

[1] Deviation between the measured and modelled direction of asymmetry.
[2] As the deviation between the directions is not defined in terms of 'to the left' or 'to the right', the values deviation is doubled to cover both possible directions.

Based on the various structural parameters measured in the crowns by laser-scanning we were able to predict the direction of crown asymmetry of the 15 focal trees as response to the calculated competitive pressure of the neighbors with a mean error of 96 ±76 degrees (Table 3).

This angle prediction is significantly different from a random angle and allows to exclude a sector of more than 260 degrees in the possible crown growth direction on a circle when applying our model of neighbor competitive pressure. We run the model with combinations of different canopy structural parameters in order to identify those parameters that would characterize the competitive pressure of a neighbor best (see Table 4).

Of the twelve variables used to characterize crown dimensions and distance to the focal tree, we identified the distance between the crown centres of neighbor and focal tree (HD) and DBH as leading to the best prediction of crown asymmetry direction in the 15 test trees. All other factor combinations, including the distance between the stems (DCCG) instead of the crown centres, and measures of canopy size and the contact sphere between the neighbors (CONT) resulted in a higher prediction error of the asymmetry angle (Table 4). The model test runs also allowed to evaluate the quality of several crown size or crown shape and distance parameters that have been used in earlier studies for assessing the importance of a neighbor in competitive interactions, among them tree height, canopy depth (vertical canopy extension), and stem distance. According to our laser-scan data, which gave these parameters with a high accuracy, the use of these proxies of neighbor importance should lead to less reliable predictions of competitive pressure than crown centre distance and DBH.

A comparison of three tested tree species with respect to the predictability of the direction of crown asymmetry using ANOVA showed no significant species differences (Table 5); however, a non-significant trend to higher errors in ash is visible from Table 4. This indicates that our model based on crown distance and DBH is rather insensitive to the tree species, at least in our small species sample.

Table 4: Quality of the model for predicting the asymmetry of the focal trees when using crown structural different parameters and distance measures to quantify the neighbors` importance

Tested model parameters	Prediction error[1] in degrees ± SD
CPV * 1/ (HD^0.5) * DBH	96 ± 75
CPV * 1/ (HD^0.5) * TTH	127 ± 100
CPV * 1/ (HD^0.5) * CH	126 ± 110
CPV * 1/ (HD^0.5) * (TTHneighbor/TTHfocal)	128 ± 100
CPV * 1/ (HD^0.5) * CBH	128 ± 99
CPV * 1/ (HD^0.5) * CPA	122 ± 144
CPV * 1/ (HD^0.5) * common crown height	121 ± 102
CPV * 1/ (DCCG^0.5) * DBH	98 ± 79
CPV * 1/ (DCCG^0.5) * TTH	125 ± 109
CPV * 1/ (HD^0.5) * CONT (3m)	148 ± 188
CPV * 1/ (HD^0.5) * CONT (2m)	160 ± 204
CPV * 1/ (HD^0.5) * CONT (1m)	202 ± 245

CPV = competitive pressure vector of each neighbor tree.
Common crown height = Vertical extension (in m) of the possible contact zone of both crowns (neighbor and focal tree).
CONT = Number of voxels of the focal tree being less than 3/2/1 m apart from the neighbor tree.
[1]**Prediction error** = Deviation*2 between the measured and modelled direction of asymmetry. As the deviation between the directions is not defined in terms of 'to the left' or 'to the right', the deviation is doubled to cover both possible directions.
DCCG = Distance between the stem locations of the competitor and the focal tree.

Table 5: Analysis of variance of the model quality for the three tested tree species (beech, ash and hornbeam).

	Df	Sum of squares	F	P>F
Deviation in degrees (model error)				
Species	2	23351	2.4935	0.1234
Residuals	12	56188		

The multiple regression analysis with backward variable selection did not allow us to identify structural variables or combinations of them characterizing the neighbors` crown that have a significant impact on the error in the prediction of the asymmetry angle, even though HD and DBH resulted in the best prediction (Table 6).

Table 6: Coefficient of determination (R^2) for the dependency of the model prediction quality on tree structural parameters calculated based on multiple regression analysis with backward variable selection. No parameter is significant.

Variable	R^2	p-value
CPA	-0.27	0.33
HCPA	0.39	0.15
BHD	-0.19	0.50
TTH	0.21	0.45
CBH	0.18	0.52
Length of ASYM	-0.44	0.10

The same was true for the structural characteristics of the focal trees themselves: we found no significant dependency of the model quality on the size or shape of the tree that was to be modelled in its asymmetry. A further result is, that the used competitive pressure model does not allow to predict the degree of crown asymmetry of the focal tree as expressed in the length of the deformation vector ASYM (R = 0.34, n.s.), but only the direction of asymmetry.

4. Discussion

4.1. Crown structural analysis: a parcour for the application of laser-scanning

The quality of the high-resolution canopy structure data derived from terrestrial laser-scanning is mainly determined by the completeness of the point cloud, in particular in remote parts of the upper sun canopy. Evaluating the quality of this data is difficult in a protected forest as only a destructive harvest of the biomass might allow to obtain suitable validation data. We computed with volume-related pixels (voxels) which is a promising approach to minimize the related inaccuracies in the determination of structural parameters in canopies (e.g. Henning and Radtke 2006). Further, the strong relationships found between traditionally measured and laser-scan derived total tree height data and DBH (r^2> 0.81) indicated an excellent data quality in our study. The confidence in the quality of laser-scan data is in accordance with the results for structural parameters obtained from laser scanner data in other studies on forests, (e.g.

Hopkinson et al. 2004: $r^2 \sim 0.85$ for DBH and total tree height measured with two independent methods). It should be stated here that traditional tree height measurements (e.g. with a Vertex height meter), as needed for the determination of the crown base height or total tree height, are believed to be of an accuracy of about 0.5 to 1.0 m in large canopies (e.g. Hollaus et al. 2006). In contrast, the ZF Imager 5006 measures distances with an accuracy of less than 1 mm within a range of 50 m (ZF Imager 5006, Datasheet). Due to the fact that all trees were scanned from eight angles (on average) in the stand, it is very likely that a laser beam emitted from any of these scanner positions reached indeed the uppermost top of the canopy. Nevertheless, it is still possible that the laser beam has missed the uppermost branches of the canopy in certain trees. The fact that we conducted the canopy analysis in the more transparent leafless period and scanned the trees from a multitude of positions, should have resulted in a markedly higher quality of the canopy structure data than has been obtained in earlier studies (e.g. Hopkinson et al. 2004). In addition, the ever increasing spatial resolution of laser scanners will further increase the quality of laser-based canopy analyses in the future. A problem is that validation data obtained by independent methods most often suffer from a lower resolution in space than the laser-scan data. Further studies should focus on this topic and on the development of suitable methods for evaluating the quality of the overall representation of a tree crown in laser scanner data.

4.2. Crown deformation and competition

A variety of genetic and environmental factors determine the morphology of a tree and its crown (e.g. Muth and Bazzaz 2003; Schneider and Sagen 2005; Valladares 2007). Competition is undoubtedly an important factor that leads to a reduction in crown size and in crown asymmetry if the competitive pressure from the surrounding trees is not uniform in space. Crown deformation is not an indicator of competitive inferiority of the focal tree but an expression of inhomogeneous competitive pressure from different directions. The competitive pressure vector of our study sums up the competitive force of all neighbors and expresses the asymmetric distribution of important and less-important neighbors surrounding the focal tree.

Three factors are most important for determining the competitive pressure a tree canopy is exerting on its neighbors: (i) canopy size, which is related to tree height, but also to canopy depth and maximum crown projection area, because it controls the size of the shadow a tree is casting on its neighbors, (ii) the distance between the canopies, because light competition decreases with growing distance, and (iii) canopy transmittance for photosynthetically active radiation, which depends not only on canopy size (see i), but also on species-specific traits, such as leaf area density, leaf angles, leaf transmittance properties, and the spatial distribution of leaf area in the crown. In many tree species, DBH is closely related to tree height and thus to canopy size; this relationship may be weaker in old trees (e.g. Niklas 1995). It appears that other variables used as a surrogate of canopy size, such as tree height, canopy depth or crown projection area, do correlate less with the shading potential of a canopy than does DBH. As a distance measure we used the more accurate distance between crown centres (HD) instead of the distance between the stem bases. By this approach, the canopy asymmetries of the focal tree and the neighbors are also considered in the calculation. However, the model results obtained when calculating with stem-to-stem distance, as a widely used measure for tree distances (Bella 1971; Hegyi 1974; Lorimer 1983; Biging and Dobbertin 1995; Wimberly and Bare 1996; Vettenranta 1999), were only slightly less accurate (Tab. 4).

Even though we found no significant differences among the three investigated tree species with respect to the model accuracy of predicted canopy asymmetry direction, this result does not allow the conclusion that species differences in canopy structure and light transmittance properties are irrelevant for the process of asymmetric canopy growth. Species-specific traits could influence the direction and degree of canopy deformation through both an alteration of the effect component and the response component of competitive interactions (e.g. Goldberg and Landa 1991). Late-successional trees with a low canopy transmissivity such as beech and hornbeam will exert, in general, a greater effect as neighboring early-to-mid-successional trees including ash. On the other hand, ash has developed strategies to reduce its responsiveness to a neighbor`s pressure by fast height growth. In fact, we found tendency toward a weaker model accuracy with respect to the predicted direction of crown asymmetry in case of ash trees when compared to the other two species, which might partly be explained by the characteristic growth patterns of this tree species. As visualized in Table 3, ash trees tend to escape competitive pressure by investing more resources into height growth than for capturing horizontal direction.

In many mixed stands, *Fraxinus excelsior* has a more rapid height growth than other co-occurring broad-leaved species such as beech (Petritan et al. 2009) which can reduce the competitive pressure of the neighbors and may lead to a smaller degree of canopy deformation in ash, but to a vertical stratification of the canopies. Such a phenomenon has frequently been observed in mixed stands of beech and ash with *Fagus* expanding its shade-tolerant lower crown (Petritan et al. 2009). In the literature, there are controversial reports as to whether light-demanding pioneer or shade-tolerant late-successional trees are more plastic in their canopy growth and thus will more easily respond with canopy deformation (Canham 1988; Chen et al. 1996; Messier and Nikinmaa 2000; Paquette et al. 2007). Most studies on canopy plasticity were conducted with juvenile trees anyway (e.g. Petritan et al. 2007). From our small sample it appears that late-successional trees with extended shade-crowns are particularly flexible in the spatial arrangement of their foliage in response to heterogeneous light regimes.

However, it is not only the availability of light and shading by neighbors that can induce crown deformation. Mechanical interactions between neighboring crowns can lead to the continuous abrasion of leaves and twigs of sensitive tree species, resulting in the loss of canopy volume in contact zones with mechanically more robust canopies (e.g. Frech 2006).

Our model of neighbor competitive pressure was found to be suitable for predicting the direction of canopy deformation of a target tree, but it cannot be used to draw conclusions on the expected degree, or intensity, of crown asymmetry, as symbolised by the length of the vector ASYM. This finding is not surprising because the absolute amount of canopy deformation is not only influenced by the present constellation of superior and inferior competitors in the neighborhood, but depends largely on the time factor and thus on historic neighborhood constellations, and also plasticity of crown growth.

With our study design it was also not possible to identify species-specific effects of certain neighbors on a focal tree because of the near-natural structure of the studied mixed forest. The non-experimental design does not allow to compare define competition situations due to variable inter-tree distances and unknown competitive pressures on the neighbor trees themselves caused by their neighbors in the second row. These two uncertainties and the lack of true repetition in the neighborhood constellations hinder the analysis of species-specific competition effects in near-natural stands. While the obtained data allow to quantify the effect of each tree individual on the focal tree, it is not possible to draw conclusions on the species level. Variation in distance, size, age and competitive situation of the neighbor tree most likely are overlaying and masking any species-specific competition effects. Future studies on crown deformation and on effect and response in tree competition in mixed stands with defined inter-tree distances and defined neighborhood constellations in terms of the neighbor trees at least up to the second row of trees when measured from the focal tree.

5. Conclusions

In contrast to several earlier unsuccessful attempts to predict crown deformation from information on the spatial structure of the stand (e.g. Getzin and Wiegand 2007), we present a model of competitive pressure from the neighboring trees that is able to quantify the expected direction of asymmetry with remarkable accuracy. We assume that this success is enabled by the comprehensiveness of the spatial data on crown position and crown dimensions available in our study. A successful model predicting crown asymmetry, which based on traditionally measured crown structural parameters, was presented by Muth and Bazzaz (2003).

Unlike conventional competition indices (see for example Pretzsch 2002) the model of Muth and Bazzaz (2003) calculates with the 'centre of canopy mass' and thus includes a measure of canopy shape, even though the authors derived their mass centre from a conventional 8-point canopy projection which mostly ignores the 3-dimensional crown structure.

Our approach of a precise laser-scan-based canopy analysis and the derivation of competitive pressure vectors using crown centre distance and DBH as importance values offers a considerable potential for competition research in mixed forests. Multiple-aspect laser scanning of tree canopies can help to achieve a better understanding of the dynamics of canopy space exploration and may lead to an optimization of silvicultural management activities in mixed stands. A higher accuracy of canopy shape analysis is also needed to test the suitability of conventional crown measures (such as crown depth or crown projection area) as estimates for crown volume and importance in competitive interactions.

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Chapter 5

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

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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 a portable 3D-laser scanner system 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 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 calibration of the laser scan data against the biomass harvest gave a good correlation for total above-ground biomass, leaf biomass, leaf area, and the mass of stems and twigs (R^2 0.61-0.88). Biomass estimates using allometric regressions between total plant height or total leaf number and above-ground biomass as an alternative non-destructive method gave no better results than laser scanning 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. Additionally, this technique can also provide valuable data on canopy structure.

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 & Leverenz 1989, 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. However, investigations on the use of the laser technique for measuring the total biomass and for monitoring the growth of trees are missing so far.

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 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 and elevated nitrogen availability as is expected to occur under climate change in parts of Central Europe. 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 May and ending with the last harvest in September (see Table 1), when the sapling trees were about five 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) that uses the phase difference technology. The Imager 5006 is battery powered and can be used as a stand-alone unit in the field. The scanning resolution was set to 10000 pixels for the 360° view (vertical and horizontal), whereby the scanning itself took 3 min and 22 s. The angular step width was 0.036°, which equals a point distance of 0.6 mm on a surface perpendicular to the beam in 1 m distance in both horizontal and vertical direction. The emitted laser beam is circular with a diameter of three millimetres and a divergence of 0.22 mrad (Zoller and Froehlich 2007).

The scanner positions were not fixed at the different scan sessions during the growth monitoring to allow a fast and flexible instrument setup. 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. 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 to 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 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, that had 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 Tab.1). With these two repeated scans of the same objects, we tested the reproducibility of the laser scan results.

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

Date	Monitoring event	No. of scanned trees With leaves	Without leaves	No. of harvested trees
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

After scanning the ensemble of 23 to 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 and exported to 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 to screen for erroneous points (dust, insects, measurement errors) and for twigs and leaves from neighboring 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 neighboring 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). Figure 1 shows three images of an exemplary tree based on the original point cloud (Figure 1a), a 0.5-cm point cloud grid (Figure 1b) and a 1-cm point cloud grid (Figure1c).

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.

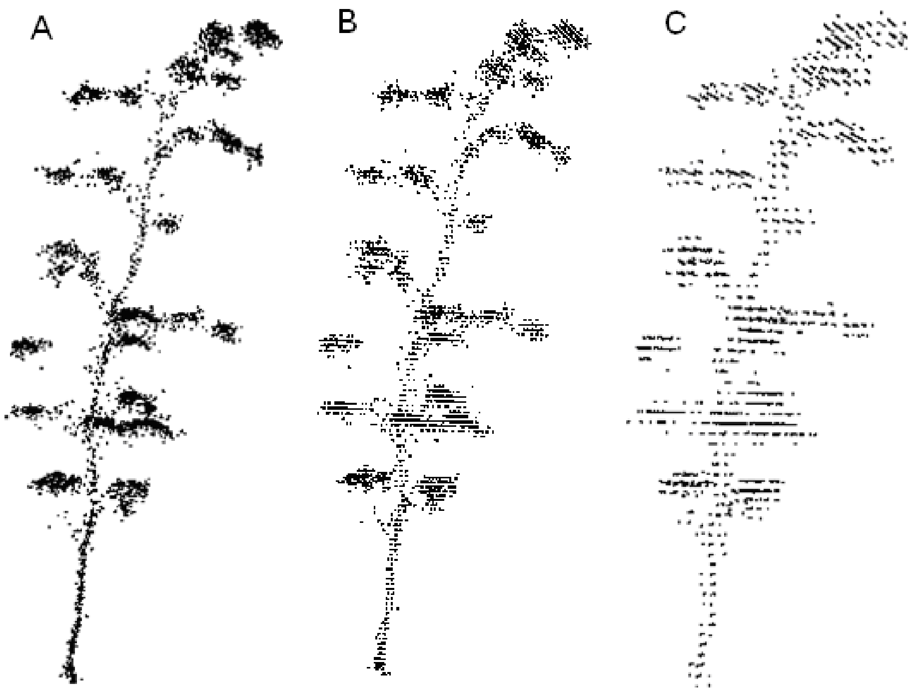

Fig. 1: Tree point clouds of an exemplary juvenile beech tree. With increasing grid space the resolution of the tree model decreases and finer contours disappear. Tree height was about 41 cm.
A) Point cloud as created from the original scanner data (3411 points). B) 0.5-cm point cloud grid computed with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

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 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 to estimate 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).

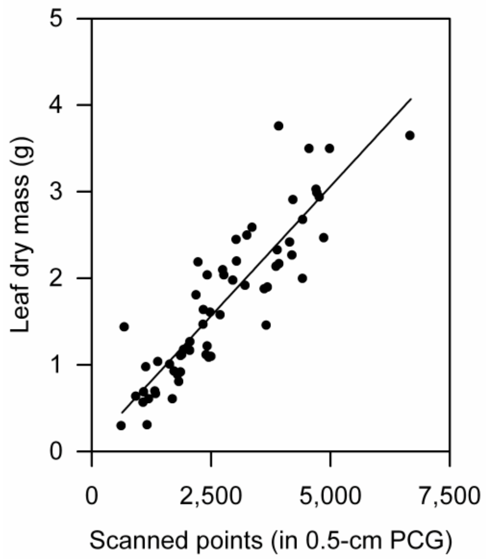

Fig. 2: Relationship between leaf dry mass per tree measured by harvesting and the number of points in a 0.5-cm point cloud grid created by laser scanning (p< 0.001; R^2= 0.81; n= 60).

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).

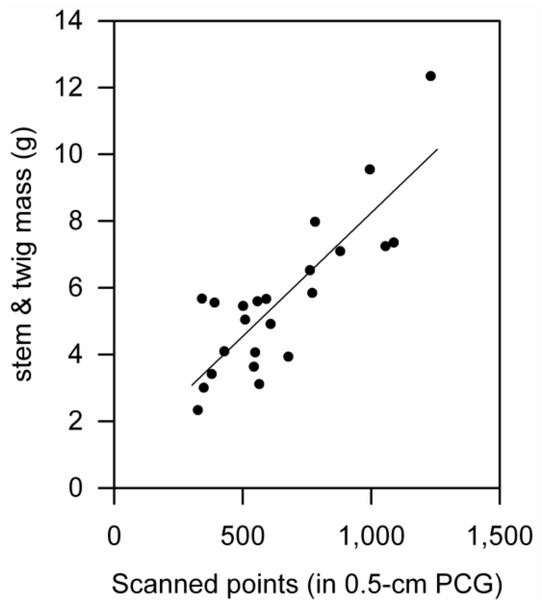

Fig. 3: Relationship between the total stem and twig biomass of a tree measured by harvesting and the number of points in a 0.5-cm point cloud grid created by laser scanning ($p < 0.001$; $R^2 = 0.70$; $n = 60$).

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).

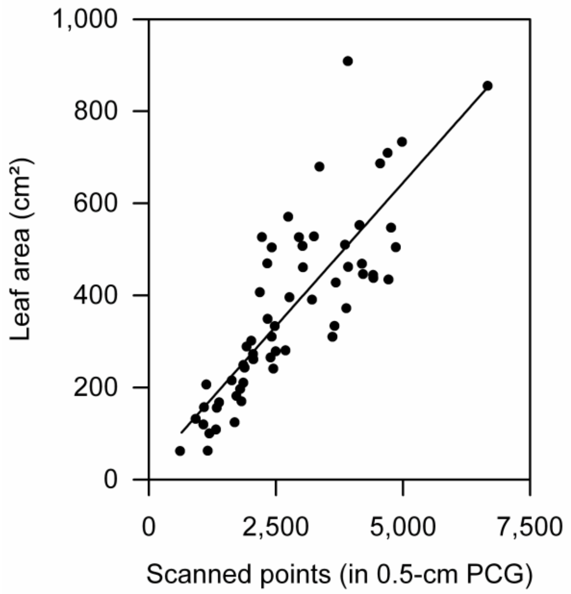

Fig. 4: Relationship between the total leaf area of a tree measured by harvesting and the number of points in a 0.5-cm point cloud grid created by laser scanning ($p < 0.001$; $R^2 = 0.83$; $n = 60$).

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 (Figure 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 2cm-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. Figure 5 gives the biomass increase of 36 investigated beech saplings over a period of 77 days as derived from four consecutive laser scan campaigns (2-cm PCG), showing the biomass increment in percent of the existing biomass during three time intervals.

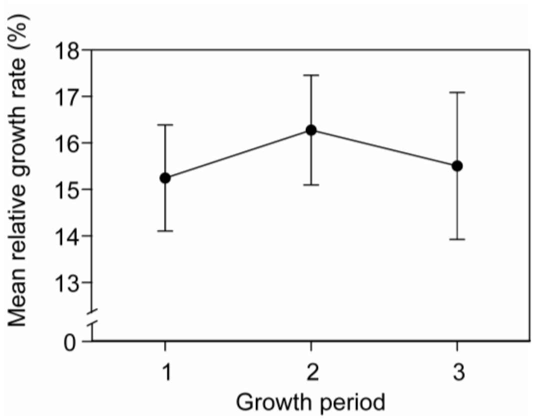

Fig. 5: Mean relative growth rate (%) of 36 experimental trees that were measured on four occasions during 77 days. Error bars show the standard error (n= 36). Growth was measured as the relative biomass increase during three periods: *Period 1*: July 13, 2009 - July 27, 2009; *Period 2*: July 27, 2009 - September 9, 2009; *Period 3*: September 9, 2009 - September 28, 2009.

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 (Table 2).

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). 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.

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**	**0.5-cm PCG**	**R^2** **2-cm PCG**	**3-cm PCG**	**n**
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

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). 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 two 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 is evident from the coefficient of determination in Table 2 and the coefficient of variation in Table 3.

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[1]	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

[1] Trees scanned during the monitoring events M2 and M3

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 two hours 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 form 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 & 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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Chapter 6

Synopsis

Terrestrial laser scanning in forest ecological research: measuring structural characteristics, competition and growth of trees

1. Structural parameters and distribution of biomass

A single tree is already a complex structured organism with an individual shape determined by the form of the stem, branches, twigs, and a large number of leaves or needles. A forest, especially if naturally grown, comprises trees that are not independent from each other, but interwoven into one of the most complex ecosystems on the planet (e.g. Schulze et al. 2002). Its spatial structure is the result of environmental factors that modified the genetically determined phenotype of the present plant individuals, as well as the consequence of interactions between the individuals themselves, such as competition (e.g. Kikuzawa and Umeki 1996; Frech et al. 2003; Schneider and Sagan 2005) or facilitation. In order to understand the biogeochemical processes and biotic interactions within a forest ecosystem a detailed knowledge on the spatial distribution of the biomass is essential (Lowman 2004). In this thesis I show that there is an urgent need for new methods allowing for a fast, objective and comprehensive measurement of the distribution of the above-ground biomass in forest stands (Chapter 2, 3, 4). The 3-D terrestrial laser scanning approach was evaluated as a new method to fulfil this task and the main conclusions are presented here.

We found the used instrument, the Z+F Imager 5006, to be suitable to create comprehensive three-dimensional representations of the real forest structure when a multiple-scan approach was used.

The superposition of different perspectives on the same scene is one crucial step if a complex-structured object is to be scanned. We found the used number of scans (5-13, mean: 8) to be sufficient to capture groups of three or more trees in the studied mixed type of forest. The number of scans required is subjective and depends on the overall structure of the investigated scene, which makes it impossible to derive any universal scan protocol. In a dense forest with plenty of understorey vegetation a larger number of scans is needed when compared to a rather open, hall-like forests characterized by mainly stems in the lower height levels. The same was found to be true for different times of the year: in summer, foliated trees cause more obstruction-effects in the uppermost part of the canopy and hence require more scans than leaf-less trees in winter time. However, even a single-scan design can produce a wealth of information, depending on the study goals, and this design has the big surplus that the registration of the tree individuals is not necassary.

Whatever the number of scans is, there will always be a problem of reduced data density in the remote areas of the scans scene, including the top of the canopy. This problem is caused by the measurement scheme of the scanners and should be corrected by applying a voxelization to the combined point clouds of a forest patch. Due to our results, we strongly recommend the use of a voxel-model (Chapters 3, 4, 5) in order to optimize the quality of the obtained data on the tree structure. The voxel size depends on the aim of the study and should not be too small. We found voxels of three centimetres edge length to be most suitable for a fine-scaled analysis, as is needed in the representation of photo-like views through the forest (Chapter 3). Smaller voxel sizes will strongly reduce the homogeneity of the data, which should be avoided. In Chapter 4 we presented an approach to investigate the influence of competition on the asymmetry of tree crowns, in which 10-cm voxels were used successfully. It is also possible to overcome the spatial trends in the laser scanner data with a 'point-cloud grid', which was one important finding of the study presented in Chapter 5. This approach is computationally less intensive than a voxel-model.

The conducted studies (Chapter 3, 4) enabled us to evaluate the quality of the comprehensiveness of the scanner-derived spatial information on the forest structure. While the stems of trees can be modelled with a high data quality (see Chapter 5) it is to be expected that tree crowns are more difficult to access. The simulation of hemispherical views through the canopy was possible based on the scanner data (Chapter 3), allowing for the characterization of canopies based on a gap distribution analysis. However, we found some essential requirements that could certainly improve the results of studies focusing on the biomass distribution of a stand or certain structural parameters of the trees:

Firstly, we recommend to use high resolution scanners with a scanning-range exceeding the maximum visibility within a forest (at least 100 m), which became available recently (e.g. Z+F Imager 5010: 187 metres). The quality of simulated views throughout the virtual equivalent of the investigated forest scene will profit from this technical improvement. This in turn will enable for a better usage of the voxel-model of a study site in order to describe the availability of light and space at certain positions in a studied forest patch. Secondly, laser scanning in forests is prone to distortions in the data caused by wind-induced movements of the canopy. Shaking leaves and twigs, as well as swinging stems result in blurring effects and fuzzy edges visible in the scan data. Hence, we recommend not to perform scans if the wind speeds exceed 5 $m*s^{-1}$. Only a faster scanning procedure could minimize this problem and it should be stated here, that recent laser scanning devices are able to achieve more than 1,000,000 points per second, which is more than twice the data acquisition rate of the used Imager 5006. A large but only temporary problem when working with laser scanning data are the extensive hard- and software resources required for handling and processing the data (e.g. >12GB RAM, expensive software etc.). Anyway, it can be expected that the above mentioned hindrances will be solved in a few more years of computer development.

2. Competition

We found strong relationships between traditionally measured and laser scanner-derived tree structural parameters (Chapter 4). Hence, we gained confidence that investigations on competition for light and space within the canopy of a near-natural mixed stand become possible based on the high-resolution canopy structure data derived from terrestrial laser scanning in combination with the use of a voxel-model.

In our approach, the canopy asymmetry of a focal tree was related to the virtual competitive pressure exerted by its neighbor trees. The determination of a competitive pressure vector, defined by the sum of the competitive pressures exerted by every neighbor tree, allowed to quantify crown deformation successfully as consequence of interspecific competition.

Our model of neighbor competitive pressure was found to be suitable for predicting the direction of canopy deformation of a target tree, but it cannot be used to draw conclusions on the expected degree, or intensity, of crown asymmetry. As the degree of asymmetry largely depends on the time factor and thus on historic neighborhood constellations, but also on the plasticity of crown growth, this results comes not unexpected. The absolute amount of canopy deformation is not only influenced by the present constellation of superior and inferior competitors in the neighborhood, but also on historic neighbor effects and is therefore much more difficult to predict without knowledge on former spatial configurations of the standing biomass.

Species-specific effects of certain neighbors on a focal tree could also not be evaluated with on our model because of the near-natural structure of the studied mixed forest. Variation in distance, size, and age of the focal trees in our mixed stand site, as well as the unknown competitive situation of the neighbor trees itself, most likely are overlaying and masking any species-specific competition effects. An experimental design with fixed inter-tree distances and known competitive pressure on the neighbor trees themselves, caused by their neighbors in the second row, would clearly support further studies focusing on species-specific competition effects.

Crown deformation analysis is not only of academic interest but economically important in planted stands as well, because competition can reduce the yield and vigor of target species, and may eventually lead to their suppression and death. Multiple-aspect laser scanning of tree canopies can help to achieve a better understanding of the dynamics of canopy space exploration and may lead to an optimization of silvicultural management activities in mixed stands. Additionally, the suitability of traditional crown measures, such as crown depth or crown projection area as estimates for crown volume and their importance in competitive interactions can be evaluated based on the higher accuracy and resolution in canopy shape information obtained from laser data.

3. Tree biomass and growth

Experiments with potted juvenile trees conducted to examine their growth response to altered environmental factors require accurate estimates of plant biomass (e.g. Spinnler et al. 2002). Large numbers of replicate trees, consecutively over the time of the experiment, were used in conventional approaches to quantify the biomass increase of tree saplings (e.g. Pregitzer et al. 1990). The precise structural analysis of tree canopies offered by the terrestrial laser scanning approach was tested to provide accurate non-destructive estimations of the standing biomass of juvenile trees. We used a multiple scan approach in order to create high resolution three-dimensional representations of the trees, based on structural information obtained from laser scans taken from a variety of perspectives. By using point-cloud-grids we invented a simple method to generate spatially homogeneous models of the study trees that could be used to estimate the biomass of the trees from the number of data points that represented a tree. Successful estimations of the total above-ground biomass (stems, twigs, leaves), the biomass of axes (stems and twigs), of leaf biomass and leaf area were possible based on the point-cloud-grids. A traditional biomass harvest was used for calibration of the laser scan data and good correlations were found (R^2: 0.6- 0.88). In addition, biomass estimates using allometric regressions between total plant height or total leaf number and above-ground biomass were used as an alternative non-destructive method for comparison of the results obtained from the laser scanning approach. 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). Thus, allometric relations gave no better results than laser scanning and required a similar calibration effort.

We conclude that 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), which is also needed in case of allometric relationships. Furthermore, laser scanning enables for repeated scanning of the same plant which can be used to monitor biomass increase over time. Another advantage of the new method is that it 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 & Fleck 2009).

Conclusion and future perspectives

For research in the field of woody plant ecology, probably the most challenging part in the use of laser scanners is not on the hardware site, even though the price of the laser scanners might be a general hindrance for their use. The real duty is the development of algorithms that reliably extract desired parameters from the created point-clouds, voxel-models or point-cloud-grids (depending on the aim of the study). These problems will remain even if faster laser scanning instruments and computers are available in the future. Studies dealing with biological, physical or chemical processes in forests, require ready-made algorithms for the calculation of stand structural parameters as the simple modelling of the biomass distribution alone is of little use as long as there is no objective way of parameter extraction, e.g. leaf area index, above-ground biomass or canopy openness.

The present thesis aimed to develop new algorithms that can be used to extract structural parameters widely used in forest biometrics and canopy analysis, from laser scanning data. In addition we tested the potential of laser scanning for applications, such as competition analysis in forests or non-destructive biomass estimation of juvenile trees. A variety of parameters were successfully extracted based on newly developed algorithms, which were all based on xyz-file input data, a simple format for laser scanner data exchange (Table 1).

Table 1: Parameters shown to be extractable from multi-aspect terrestrial laser scanning data in the present thesis. Coefficients of determination (R^2) for the correlation between laser-scan and traditional measuring approaches.

Structural parameter	Range of objects	Measure of accuracy
Total tree height	for all sizes	0.83; $p < 0.001$ (Chapter 4)
Diameter at breast height	not for juvenile trees	0.98; $p < 0.001$ (Chapter 4)
Crown centre	at variable heights	n.a. (see Chapter 4)
Crown height (depth)	for large trees	n.a. (see Chapter 4)
Crown projection area	at variable heights	n.a. (see Chapter 4)
Crown base height	for large trees	0.88; $p < 0.001$ (Chapter 4)
Crown asymmetry	for large trees	see Chapter 4
Total tree biomass	for juvenile trees only (non-destructive)	0.61-0.83; $p < 0.001$ (Chapt. 5)
Leaf area	for juvenile trees only (needs harvest)	0.83; $p < 0.001$ (Chapt. 5)
Leaf biomass	for juvenile trees only (needs harvest)	0.81; $p < 0.001$ (Chapt. 5)
Canopy openness	for forest patches	0.76; $p < 0.001$ (Chapt. 3)

In addition to the parameters presented in Table 1 we showed the potential of terrestrial laser scanning for the monitoring of growth of juvenile trees (Chapter 5) as well as successful applications in the field of crown competition analysis in mixed forests (Chapter 4).

All studies presented above profited from the high accuracy and resolution of the structural information obtained with the laser scanning technology. We tested and evaluated the quality of the data produced with an exemplary scanning system and showed a small selection of possible applications in the field of forest ecological research. The future use of terrestrial laser scanning now depends on further simplifications in the field of data processing and automatic parameter extraction via standardized calculation protocols, respective algorithms. The automated separation of tree individuals from point clouds would be such an useful and long-needed algorithm future work should focus on.

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Coloured cover images by Göttingen Centre for Biodiversity and Ecology
(legend top to bottom)

1 Mixed deciduous forest in the Hainich region (Central Germany)
2 Different insect taxa on the flowers of a thistle (*Cirsium* sp.)
3 *Glomeris* sp., a member of the decomposing soil fauna in forest ecosystems
4 *Pleodorina californica* (Chlorophyceae), colony-forming freshwater phytoplankton species
5 Grasshopper *Tettigonia cantans*, distributed from the Pyrenees to Northeastern China
6 *Microcebus berthae* (Cheirogaleidae), the smallest extant Primate species (Madagascar)
7 Tropical rain forest (Greater Daintree, Australia)
8 *Lethocolea glossophylla* (Acrobolbaceae), a liverwort of alpine mountain ranges in South America
9 Part of a coral reef in the Red Sea

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