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Describing forest canopy gaps efficiently, accurately, and objectively: New prospects through the use of terrestrial laser scanning

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ABSTRACT

Canopy gaps are an important ecological component in forested landscapes. One limitation to investigating gaps is the lack of efficient, accurate, and objective methods to characterize gap size and shape. This study aimed at investigating various methodologies to overcome this limitation. Six man-made canopy gaps were measured in a coniferous and a deciduous Stand (total of twelve) using a terrestrial laser scanner. Using the point clouds from these measurements, gap sizes were manually derived as a baseline to assess the accuracy of using fully automatic delineations of edge-lines for gap size calculations. Furthermore, we compared these results to those obtained from simulated conventional gap measurements that are based on assumptions regarding the gap shape (ellipse) or on a varying number of distance measurements (between gap center and Stand edge). Using the manual gap delineations as a reference, automatic delineations yielded slightly smaller gap sizes with a relative root mean square error between 3.4% and 5.3%, depending on gaps size. All simulated conventional approaches (with various numbers of measurements and shape assumptions) yielded larger errors. However, the gain in accuracy by increasing the sample size declined rapidly when more than 16 measurements were taken to describe the gap shape. To further the discussion about gap shape, we developed an approach to calculate the fractal dimension of the canopy gap edge-line from laser point clouds. Finally, we discuss other approaches to deepen our understanding of gap related processes in forests by means of a more detailed description of the three-dimensional gap shape.

1. Introduction

Canopy gaps are the most dominant type of natural disturbance in many forest ecosystems (Muscolo et al., 2014; Winter et al., 2015). Depending on the severity of the disturbance event (fall of a large branch, canopy tree or a group of canopy trees) and time since gap creation a gap can vary in dimension and shape (Kucbel et al., 2010). Dimension and shape have been shown to have a major effect on a variety of conditions and processes inside gaps (Fahey and Puettmann, 2008; Ye and Comeau, 2009) and adjacent forests (Harper et al., 2005). Different tree species require different minimum resource levels, as influenced by gap sizes, for regeneration (e.g., Nagel and Svoboda, 2008; Nagel et al., 2010; Zhu et al., 2014a,b). Consequently, stands or landscapes diverse in gaps' sizes likely contain higher species diversity in the regeneration (Muscolo et al., 2014). Furthermore, gap size plays an important role in determining the amount and composition of vascular plant species inside the gap (Naaf and Wulf, 2007; Fahey and Puettmann, 2008). The presence of vascular plants, especially tree regeneration, is a major factor influencing future Stand dynamics (e.g., Coates and Burton, 1997; McCarthy, 2001; Kimmins, 2004). These vegetation responses are influenced by different light availability in gaps of different sizes (e.g., Canham et al., 1990), which may also influence the growth (York et al., 2004; Raymond et al., 2006) and architecture of regenerating trees (e.g., Canham, 1988; Poulson and Platt, 1989). Other physical factors depending on gap size and shape are also influencing vegetation patterns and dynamics. These are, among others, patterns of snow interception (Hedstrom and Pomeroy, 1998), snowmelt (Hardy et al., 1997), and biogeochemical processes (Prescott et al., 2003; Lima, 2005; Ritter, 2005), such as availability of nutrients (Schliemann and Bockheim, 2011; Thiel and Perakis, 2009). In addition, crucial ecological processes in gaps, such as germination and early establishment of trees act at small spatial scales (Kuuluvainen, 1994; Baier et al., 2007; Dodson et al., 2014).

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Thus, detailed information about gap dimensions is important for managing these processes (Kenderes et al., 2008).

'Canopy gaps' were first defined as the ground area in a canopy opening extending to the bases of trees surrounding the opening (Runkle, 1981), later labeled 'expanded gaps' (Runkle, 1982). In contrast, Brokaw's (1982) definition of gap size was limited to the vertical projection of the canopy opening. Most studies published since 1982 used one of these definitions and relied on assumptions about gap shape (typically a circle or ellipse) and a few distance measurements (typically less than 16) to determine the projected gap area (Kucbel et al., 2010; Schliemann and Bockheim, 2011). In contrast, Salvador-Van Eysenrode et al. (1998) calculated relative measures of gap size (in pixel numbers) and gap perimeter (in pixel sides) from hemispherical photographs taken in the gap. Absolute gap dimensions (real area size or real perimeter) could yet not be obtained using this method.

Shapes of canopy gaps are typically extremely irregular in forests. However, the assumptions about gap shape were rarely investigated (Nagel and Svoboda, 2008) and existing approaches to describe the shape are mostly subjective (Van der Meer and Bongers, 1996), despite the known influence of gap shape on distribution of sun flecks, general light availability and many other ecological conditions within the gap (Marquis, 1965; Canham et al., 1990; Lertzman and Kerbs, 1991). Gap shapes are classified based on similarities to geometrical forms, including circles (Goldblum, 1997; Cappelli, 1988; Piussi, 1994; Del Favero, 2010), ellipses (Runkle, 1981; Del Favero, 2010; Kucbel et al., 2010), squares (Cappelli, 1988; Del Favero, 2010), or triangles (Salvador-Van Eysenrode et al., 1998). To overcome the error associated with the simplifying geometrical assumptions of gap shape (e.g., Schliemann and Bockheim, 2011), Salvador-Van Eysenrode et al. (1998) calculated 17 different shape indices from the actual gap shape obtained through their image-based approach. Newer measures of shape or edges, such as fractal dimensions (Mandelbrot, 1983), have been used to represent tree crowns (Zeide and Pfeifer, 1991; McGarigal and Marks, 1995; Zhu et al., 2014a,b). Since tree crowns are bordering gaps, fractal dimensions would be an obvious candidate to represent gap edges as well. Fractal dimensions can be of relevance for future gap-related studies as tree crowns, and therefore, canopy gaps as well, differ from the objects we usually measure in forest science, such as tree stems, in that they are not solid objects. Approaching the complex architecture of canopy gaps requires new ideas and understandings of spatial relationships, which may be found in fractal geometry (Zeide, 1998).

Describing the three-dimensional shape and size of gaps has been reflected in the "gap ratio" (gap diameter-to-Stand height) (Spies et al., 1990; Zhu et al., 2003; Schliemann and Bockheim, 2011). Scaling the gap size by the height of the surrounding trees proved useful for investigating e.g., regeneration of tree species with different shade-tolerance (Cappelli, 1988; Piussi, 1994; Malcom et al., 2001; Del Favero, 2010). Other approaches were based on horizontal gap size measurements at multiple heights (Yamamoto, 2000; Hu and Zhu, 2009). A key shortcoming of such methods is the subjective choice of heights at which the measurements are taken, which will define the three-dimensional gap shape. This shape controls the amount of direct sunlight available for vegetation, pattern of rain throughfall, nutrient deposition, animal abundance etc. (e.g., Schliemann and Bockheim, 2011).

One challenge of obtaining more detailed spatial information on gaps is the high cost of taking accurate gap size measurements. The need for more efficient and accurate measurement techniques has grown in recent years, as gaps have received more interest from scientists and managers, for example, to assess how closely natural disturbance regimes can be imitated by management practices (Schliemann and Bockheim, 2011) or to verify forest growth models (Robert, 2003).

Airborne remote sensing techniques have been used to help with identifying and measuring canopy gaps (e.g., Foster and Reiners, 1986; Koukoulas and Blackburn, 2004; Kellner et al., 2009; Torimaru et al., 2012), but their use is limited to Brokaw's (1982) definition of gaps as vertical projection of the canopy openings. In contrast, ground based approaches, such as terrestrial laser scanning (TLS) can be used to also determine the expanded gap area and detailed boundary of canopy gaps through delineation (Seidel et al., 2015), small within-crown gaps (e.g., Jupp et al., 2008; Seidel et al., 2012) and between-crown gaps (Hajek et al., 2015), as well as three-dimensional gap volume (Seidel et al., 2015).

In our study, we investigate and compare different approaches of using TLS data for measuring size and shape of forest canopy gaps. First, as a case study we examine the reliability of TLS-based gap measurements by comparing the results from two different laser scanners and different methods of referencing scan positions. Second, we test the accuracy when using TLS data to automatically determine two-dimensional gap area. Third, we evaluate errors immanent in conventional field methods, when only few measurements can be taken. Fourth, based on the notion that crowns of neighboring trees have fractal dimensions we tested an algorithm that calculated the fractal dimension of canopy gap edge-lines. Last, we discuss options to further the measurement technologies, such as methods that allow for detailed three-dimensional assessments of canopy gaps and related ecophysiological, as well as biogeochemical processes.

2. Methods

2.1. Study site

Two forest stands in Germany, in which artificial canopy gaps have been created, were selected for measurements. Stand A was near Wuppertal, North Rhine-Westphalia (51°13′N4.67″N and 7°6′21.31″E) and consists of approximately 500 planted coniferous *Metasequoia glyptostroboides* (Hu.) trees about 22 m in height. The second Stand (B) was near Mühlhausen, Thuringia (51°19′39.89″N and 10°21′48.45″E) and is dominated by the deciduous European beech (*Fagus sylvatica* L.). Artificial gaps of different sizes were created in both stands in 2013 and 2014 by cutting down one (Stand A) or multiple canopy trees (Stand B). For our investigation we scanned six gaps in each stand, resulting in a total of twelve canopy gaps.

2.2. Data acquisition and post-processing

We used a terrestrial laser scanner operating based on the phase-difference technology (Faro Focus 3D 120) that utilizes infrared laser light to scan the forest up to a distance of 120 m. The scan resolution was 0.035° horizontally and vertically. Four scans per gap were made in Stand A in May 2014. In these rather small gaps, a first scan was made in the center, followed by three additional scans in a triangular arrangement around the center scan. The same scanner and identical scan settings were used in August 2014 to scan six gaps in the beech dominated forest (Stand B) from four to seven different perspectives depending on gap size. As these gaps were significantly larger than those in Stand A we performed a first scan in the gap center and up to six additional scans around the center and along the edge of the gap. The number and position of scans was determined subjectively based on the overall site conditions (understory, visibility). To link information obtained by all scans in a gap we distributed artificial targets in the scanned scenes. These were used as reference points for orientation of scans relative to each other via Faro Scene (Faro Technologies Inc., Lake Marry, USA).

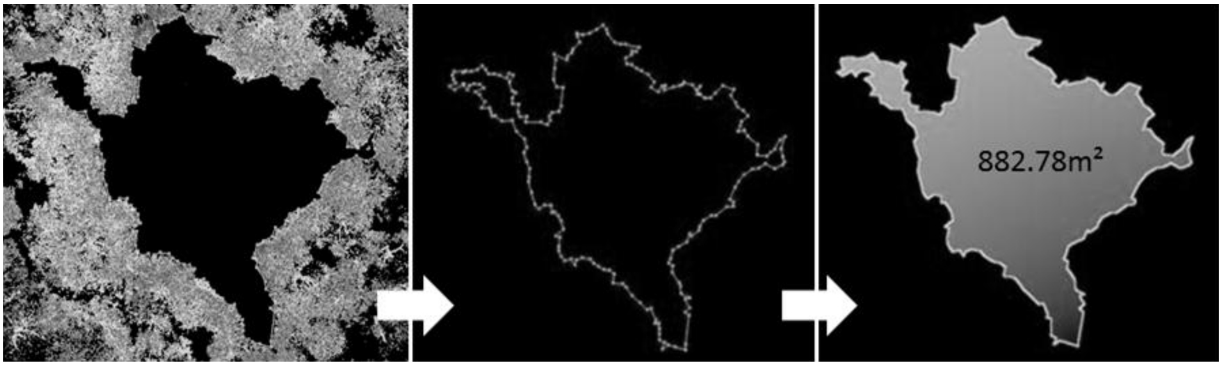

Fig. 1. Orthographic Birds-eye view on a forest canopy gap with all understory and ground returns up to a height of 5 m automatically deleted (Left). Edge-line of the gap after manually performed delineation (Middle). Meshed surface (TIN-method) and automatically calculated 2D-gap area obtained from Cyclone software (Right).

We used a subsample of three gaps in Stand B to test a Z+F Imager 5010C laser scanner (phase-difference technology; resolution 0.036° in both horizontal and vertical direction; maximum distance: 187 m) operating in the traverse measurement program (TMP). TMP procedure allows scan registration to be done by placing the instrument at stations along a path (here circular) in which the position of the previous and the successive scan are captured at each station by the scanner itself, i.e., without the need for artificial targets. These four to five scans per gap were made on the same day and with a delay of approximately 1 h with respect to the measurements made with the Faro instrument. The environmental conditions did not change noteworthy (for all measurements: clear sky, no wind).

All scans were filtered for erroneous points according to standard settings of the specific software provided with the two instruments (Faro Scene and ZF Laser Control software [Zoller and Fröhlich GmbH, Wangen im Allgäu, Germany]).

We exported all filtered scans as pts.-files and imported them to Leica Cyclone 8 (Leica Geosystems AG, Heerbrugg, Switzerland) for visualization as point clouds and quality control. For further processing of the pts.-files we used Mathematica (version 8, Wolfram Research, Champaign, USA). If not explicitly mentioned otherwise, all results refer to scans made with the Faro instrument and standard (target-based) registration.

2.3. Gap measurements

2.3.1. Two-dimensional gap size from manual delineation

Point clouds obtained from TLS were used to manually delineate the edge-line between surrounding tree canopies and the two-dimensional (2D) gap area. The resulting polygons were used to calculate gap area (Brokaw, 1982) and expanded gap area (according to the definition of Runkle, 1982) with high resolution (cf. Seidel et al., 2015). For the purpose of this study we considered the manual delineation of gap edge-line from high resolution laser scanning data (~1–3 cm resolution) the most accurate method currently available. Therefore it was used as a baseline to evaluate the accuracy of the other approaches tested.

We used Cyclone's point cloud visualization in orthographic mode as "base map" for the manual delineation of the gap edge-line (Fig. 1, Left). All understory and ground returns were removed by showing only returns from 5 m above ground level at scanner position. This height was considered suitable, as only ferns and small vegetation reaching heights of not more than 5 m were present in the studied gap areas. Delineation of the visible edge-line of the gaps was conducted by the same operator for all gaps and with an estimated measurement unit length of approximately 15 cm. After finishing a complete polygon (Fig. 1, Middle) a triangular irregular network (TIN) was created which measured the gap area using Cyclone built-in tools (Fig. 1, Right).

2.3.2. Two-dimensional gap size from automatic measurements

Algorithms written in Mathematica were used for the automatic delineation of the gap edge-lines based on pts.-files. We used the same maximum height for understory vegetation or ground returns (5 m) as in the manual approach and all points below this height were deleted. The resolution of the original point cloud was set to a fixed value in order to create a homogeneous spacing between all neighboring points throughout the entire data set. The resulting product is a so-called 'point cloud grid' (abbreviation: PCG; see Seidel et al., 2011). We tested PCG spacings between 2 and 20 cm for the small gaps (Stand A) and between 8 and 200 cm for the large gaps (Stand B). A larger resolution in Stand A was unpractical due to the small gap size, and the minimum resolution in Stand B was determined by the processing capacity of the hardware (2.4 GHz, 16 GB RAM). The PCG was limited in extent to ensure that the entire gap area plus at least 10 m of the surrounding Stand were captured. The PCG was then projected to a horizontal plane. Due to overlay, all points with identical x and y coordinates were displayed as only a single point. The z-coordinate (height) was deleted and the remaining two-dimensional PCGs were rescaled into quadratic images that consisted of black or white pixels (a single coordinate) depending on whether a point was present at a specific coordinate or not. The Mathematica built-in function (name: 'MorphologicalComponents', default settings) was used to identify connected morphological components in the image and to calculate the number of pixels for each component. The number of pixels was scaled to actual ground surface as a function of the PCG resolution, e.g., 400 cm^2 per pixel in case of a 20 × 20 cm grid. To identify the centrally located study gaps within the matrix of tiny intra-crown gaps (gaps within a tree crown as part of the tree architecture) and inter-crown gaps (gaps between tree crowns due to mechanical abrasion, Hajek et al., 2015), we also extracted the centroids of all identified morphological components (polygons) using the Mathematica function 'ComponentMeasurements'. Polygons with their center nearest to the center of the image were considered the canopy-gap polygon of interest, i.e., the study gaps (see Birds-eye view in Fig. 2 for visualization).

2.3.3. Two-dimensional gap size from simulated field methods

In most field studies, two-dimensional gap areas were calculated with the assumption of gaps having regular, often elliptical, shapes. Any regular shape is bound to be only an approximation of real forest gaps. Consequently, this assumption results in inaccurate area measurements and has been criticized extensively (e.g., Schliemann and Bockheim, 2011). We tested the performance of the elliptical-assumption (Runkle, 1981) by calculating the best-fit

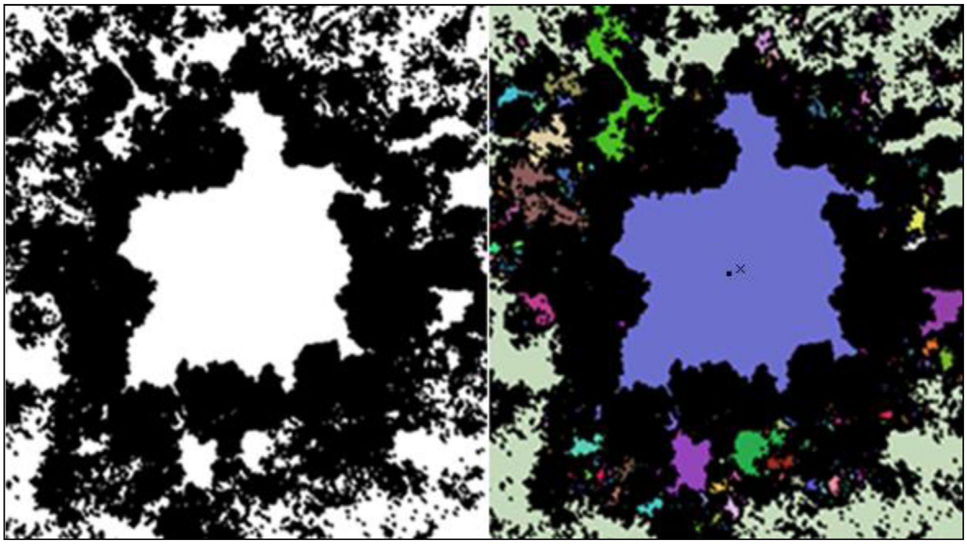

Fig. 2. Graphical visualization of automatic gap size measurement through identification of morphological components in an image-transformed point cloud grid of an exemplary gap (approx. 825 m^2 in size). Left: raw point cloud grid in Birds-eye view. Each pixel in the image represent a ground surface area of 20 by 20 cm (20 cm point cloud grid) that is either covered (black) or not covered (white) with plant material. Right: automatically identified gap areas from morphological-component analysis as available in Mathematica. Different colors indicate different components of the image. The center of mass of the blue polygon (marked with an *x*) was closest to the center of the image (marked by the dot) and the respective polygon was hence considered the study gap of interest. 2D-gap area is then calculated based on the number of pixels (each pixel represents a defined ground surface area). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ellipse for the polygons derived from the manual delineation. Compared to earlier work, our approach avoided additional errors added by manual crown delineations during field measurements. Mathematica software was used again to determine the long and short semi-axes of the best-fit ellipses and to calculate the associated gap areas of each gap (function name: 'ComponentMeasurements', each gap was considered a component).

We also tested the performance of approaches that do not assume regular gap shapes. Instead, these approaches typically rely on distance measurements made from estimated gap centers towards the first evidence of neighboring tree crowns (vertically projected). We used the approximate gap centers as starting point (the position of the first scan) to simulate the approach typically used in field measurements and tested its performance by using different numbers of measurements (i.e., directions) to determine gap sizes. The field measurements were simulated using an algorithm written in Mathematica.

The algorithm searched for all canopy hits (laser returns) from surrounding forests and calculated the smallest Euclidean distance from these edge points to the gap center. The minimum difference between angular directions of measurement was a hundredth of a radian. Finally, polygons were created with the edge-points being its vertices (red line in Fig. 3). Two-centimeter and ten-centimeter PCG resolutions were used for Stand A (small gaps) and B (large gaps), respectively. These PCG resolutions were determined to be fine enough to ensure that sufficient edge-points are detected (Stand A) and are limited by the minimum difference in angle at which measurements are taken (Stand B).

The Gaussian trapezium algorithm was used to calculate the 2D-polygon areas. The calculation based on the maximum number of measurements (629; 100 per radian = 2 × PI × 100 = 629) was considered the best possible estimate of the actual gap areas using an automated angular measurement scheme. Other schemes tested included 8, 10, 12, 16, 32, 64, 128, 264, 512, and 629 measurements (see Fig. 4 for visualization).

To reduce possible effects of directional patterns of gap shapes we repeated angular schemes that used less than 32 measurement directions so that the new measurement directions were halfway between the previous directions, e.g., for eight measurements the angle between measurements was 45°, thus, the point cloud was rotated clockwise by 22.5° around the vertical axis. Logically, the more measurements were taken, the smaller the impacts of the point cloud rotations. Thus, we limited the point cloud rotations to schemes using less than 32 measurements, which include the most sophisticated schemes used in field studies (eight; e.g., Brokaw, 1982; Lima, 2005; Hu and Zhu, 2009 and 16; e.g., Hu and Zhu, 2009). For these, we calculated the mean of the areas of the non-rotated and the rotated schemes.

We compared the relative root mean square error (RMSE%) of the area estimates of approaches using 8, 10, 12, 16, 32, 64, 128, 264, 512, and 629 directions when compared to the manual delin-

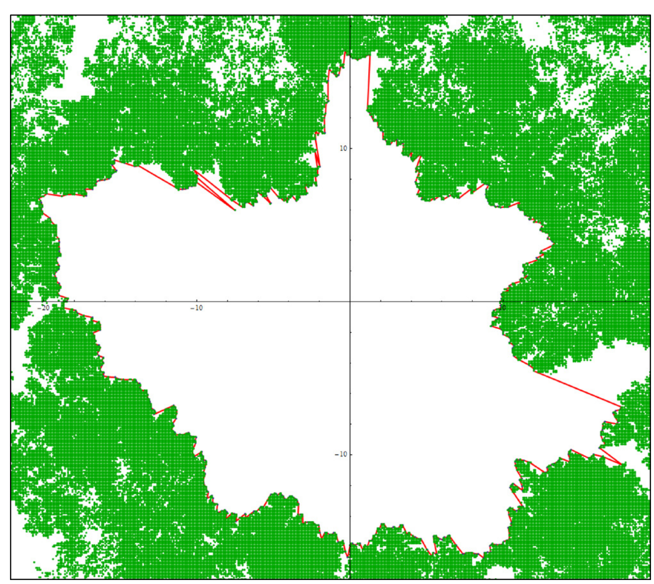

Fig. 3. Automatically identified laser returns on the edge-line of the canopy gap. The minimum difference in angle at which measurements were taken was 0.01 radian. Thus, the positional accuracy was limited to 10 cm by the original 10 cm voxel model. Scale is in meters. Axes origin is the estimated position of gap center from the field. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

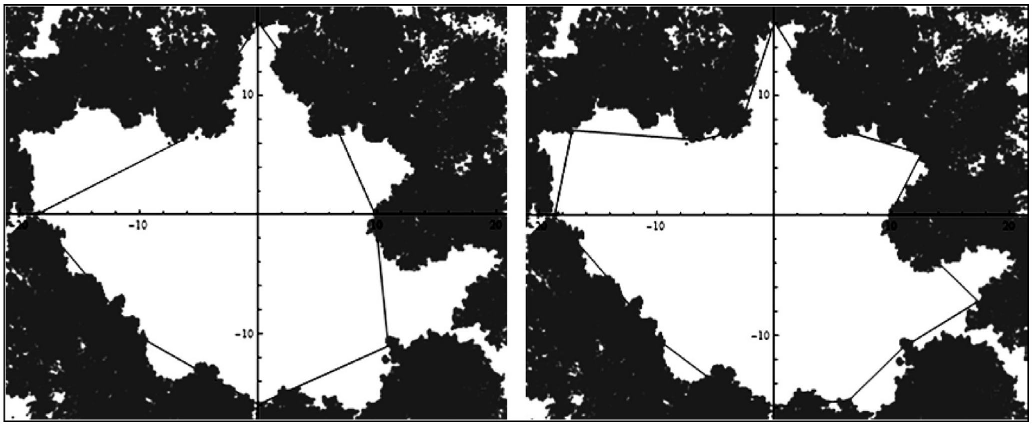

Fig. 4. Polygons describing the canopy gap edge-line resulting from measurements using different angular schemes based on eight (left) and 16 (right) measurements. Scale is in meter. Axes origin is the estimated position of gap center from the field.

eation (baseline). For this analysis we combined all twelve gaps to cover the full extent of natural variation in gaps size and shape available in our dataset. We fit the best power function regression (least-squares method) and determined its parameters to quantify the relationship between RMSE (compared to the baseline) and the number of measurements.

2.3.4. Two-dimensional gap shape

The automatic delineation of gaps accommodates polygons of a variety of shapes, as reflected in the number of variables used to describe such shapes, including compactness, circularity, convexity or elongation of the polygon, as well as the center of gravity, polygon breadth, or polygon length. As an example, we calculated the circularity of our gaps, as the ratio of the area-equivalent disk perimeters and the actual perimeter of the polygons. We chose circularity because it is related to several ecological variables, e.g., light (Hu and Zhu, 2009) and Mathematica contains a built-in function 'circularity' within the function 'ComponentMeasurements'. As an example of a possible application we compared the circularity of the single tree gaps with that of the multiple tree gaps based on a Welch *t*-test using R Development Core Team (2008).

2.3.5. Fractal dimension of canopy gap edge-lines

The fractal dimensions of gap edges (lines that border the vertically projected gap area) reflects the irregularity of neighboring tree crowns, but has never been calculated before, likely due to the fact that the box-counting method to calculate fractal dimensions (Mandelbrot, 1983; Zeide, 1998) is extremely impracticable to apply to canopy gaps. Laser scanning data can overcome this limitation and we applied the box-counting method to the tiff-images of edge-line polygons obtained from the point cloud data. We used the tiff-images of the automatically delineated gaps (smallest possible resolution) and tiled the images in consecutively smaller sub-images (Fig. 5). At each step we counted the number of sub-image tiles that contained a part of the canopy gap edge-line. Fractal dimensions were calculated as the exponents of power functions that described the relationships between the measurement unit size (here: pixels) and the number of units needed to measure the entire edge-line (here tiles) best (best = least-square fit).

It is important to note that fractal dimensions change with the resolution of the underlying point cloud grid as it is scale-dependent for real-world objects (e.g., Halley et al., 2004). Hence, our two study sites cannot be directly compared.

3. Results

3.1. Comparison of different equipment

For our case study (using only three gaps) the ZF Imager in traverse registration mode yielded results that differed marginally from those obtained with the Faro scanner. On average the values obtained from manual delineations of gap areas using the ZF Imager in traverse registration mode were 2.2% smaller than those of the baseline data (Faro Focus with conventional target-based registration). The average difference was 3.6% (Faro Focus 3D > Z + F Imager) when comparing automatically delineated gap areas (Table 1).

3.2. Comparison of 2D-gap sizes obtained through different approaches

Automatic delineations that were based on the smallest possible PCG resolution resulted in the lowest RMSE% for area estimates, compared to the baseline, with the areas of the automatic delineation always being smaller than the reference. The best results were obtained from the smallest PCG resolutions in both stands (2-cm in Stand A; Fig. 6, left and 20-cm in Stand B; Fig. 6, right). Finer resolution yielded no successful delineations. Using the PCG resolution that could be calculated for both gap size types (20-cm) we found the RMSE% to be 45% and 5.2%, for the small and large gaps, respectively.

Based on these results, we will refer to the finest possible resolution when mentioning the automatic delineation in the following. The automatic delineation based on TLS data performed always better than the simulated conventional field approach (Table 2), including the best-fit ellipse, eight-direction angular measurements and sixteen-direction angular measurement schemes. As expected, the 629-direction angular measurement scheme resulted in similar levels of accuracy as automatic delineations, but only for the large gaps (RMSE%: automatic 5.3% vs. 5.2% for 629 angles). The differences were larger for the small gaps, with an average RMSE% of 3.4% and 12.3% for the automatic delineation and the 629-direction angular measurement schemes, respectively.

3.3. Accuracy assessment as influenced by the number of angular measurements

As expected, more measurements resulted in a lower RMSE% for the estimated 2D-gap area (Fig. 7). For our study gaps the minimum RMSE% was 7.2% (when compared to the reference) if the angular measurement scheme was used. Even using the maximum angular resolution (629-direction measurements, 0.01 radian) several

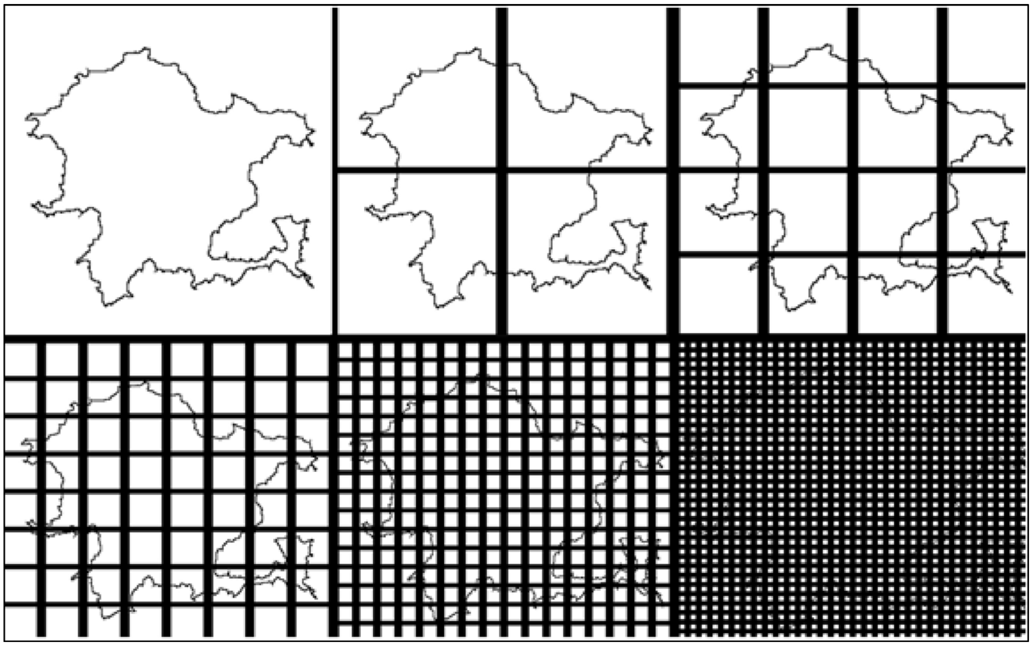

Fig. 5. Canopy gap area edge-line of an exemplary gap represented in a tiff-image created from the automatic delineation. For the calculation of the fractal dimension of the gap edge-line we split the image in tiles (from top left to lower right: 1, 4, 16, 64, 256, and 1024 tiles) and counted the number of tiles containing a part of the line (box-counting method). We used a maximum of 256 × 256 tiles as finest resolution (image not shown).

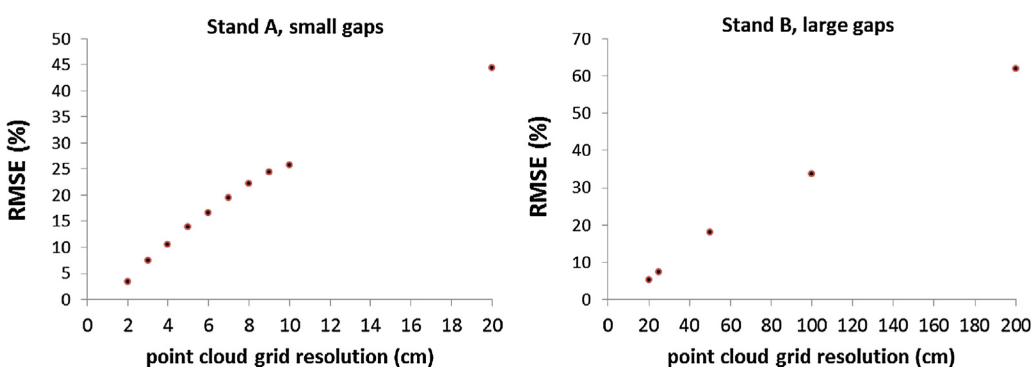

Fig. 6. Relative root mean square error (RMSE%) of area estimates (manual delineation as reference) of all point cloud grids that could be used to automatically delineate the gap edge-lines (Stand A: left; Stand B: right). Smallest possible grids performed best in both study sites.

"dents" in the gap edge-line (see Fig. 3) remained undetected and hence the error did not drop to zero. As a consequence, the reference areas were always larger than those obtained from the angular schemes.

The relative increase in accuracy decreases with increasing number of angular measurements (Fig. 7). The negative exponential shape of a line connecting the data points in the figure suggests marginal gain if more than 32 measurements are taken. Also, the variation in area due to the rotation of the azimuth, ranged up to 10% of the actual area (note, that these were only calculated for 8, 10, 12, or 16 measurements).

3.4. Two-dimensional gap shape

The circularity of the twelve gaps averaged 0.49 (range from 0.32 to 0.72; standard deviation of 0.15). For the gaps in the two

Table 1
Summary of some characteristics of the two different scanning approaches and the obtained gap areas for the three gaps assessed with both instruments.

Scanner	Angular scan resolution (°)	No. of scans per gap	Gap number	Registration mode	Gap area manual delineation (in m^2)[a]	Gap area automatic delineation (in m^2)
Faro Focus 3D 120	0.035	4–7	B2	Target based	1174.18	1124.40
			B3	Target based	882.78	871.36
			B6	Target based	981.43	931.24
Z + F Imager 5010	0.036	4–5	B2	Traverse	1136.54	1099.04
			B3	Traverse	857.41	814.88
			B6	Traverse	975.93	910.32

[a] 20-cm point cloud gird resolution was used for all data.

Table 2
Canopy gap areas as derived from the different measurement approaches and corresponding relative root mean square errors when compared to reference areas.

Gap number	Area in m²					
	Manual delineation (reference)	Automatic delineation[b]	Best-fit ellipse[b]	Eight angular measurements[c]	Sixteen angular measurements[c]	629 angular measurements[c]
A1	20.11	19.81	23.01	17.87	19.21	19.14
A2	19.37	19.68	23.88	15.17	17.86	18.15
A3	19.73	19.63	21.29	15.61	18.11	18.99
A4	15.74	14.93	15.94	14.79	15.57	14.87
A5	17.21	15.95	18.33	13.63	15.28	16.00
A6	27.13	26.60	37.47	19.83	21.18	21.61
	RMSE%[a]	3.40	24.25	21.19	13.75	12.25
B1	649.14	612.88	721.23	513.60	606.33	638.27
B2	1174.18	1124.40	1361.98	896.58	1081.81	1116.22
B3	882.78	871.36	995.47	910.17	839.04	876.28
B4	501.11	459.84	545.79	392.76	458.87	477.85
B5	522.86	477.56	612.45	425.10	469.90	490.92
B6	981.43	931.24	1095.18	730.04	929.89	910.93
	RMSE%[a]	5.25	14.34	22.10	7.26	5.21

[a] Root mean square error with the manual delineation used as reference.
[b] A1–A6: 2-cm point cloud grid resolution; B1–B6: 20-cm point cloud grid resolution.
[c] A1–A6: 2-cm point cloud grid resolution; 0.01 radian angular resolution and B1–B6: 10-cm point cloud grid resolution; 0.01 radian angular resolution.

stands mean circularity values differed significantly (Welch t-test $p < 0.001$; two-sided; $n = 12$). Fig. 8 shows the Box-and-Whisker plots for circularity, separated by site.

3.5. Fractal dimension of canopy gap edge-lines

The fractal dimension of all gaps was successfully calculated with the box-counting method as described above. All power functions describing the relationships between the measurement unit size and the number of units needed to measure the entire edge-line fit extremely well (all $R^2 > 0.95$). Table 3 provides information about the fractal dimensions for both stands separately, as due to the different resolutions of the point cloud grids, calculations could not be combined.

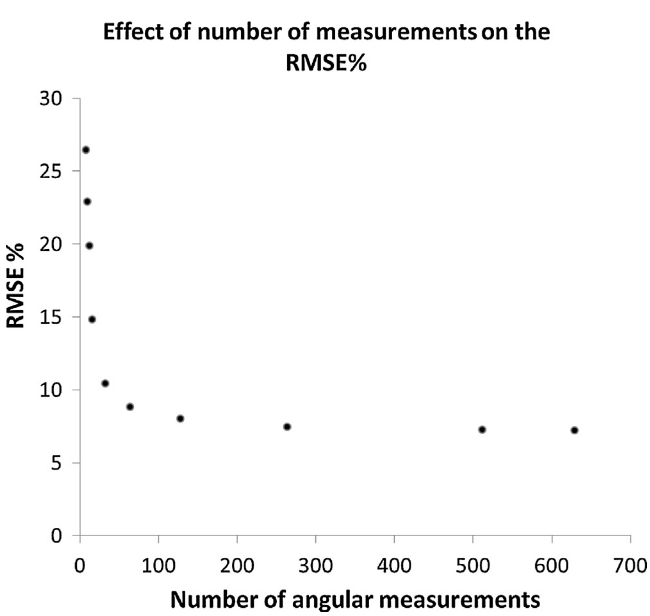

Fig. 7. Effect of the number of measurements (directions; determined by various fixed angular step widths) on the RMSE% of 2D-canopy gap area estimates when compared to the manually delineated 2D-areas.

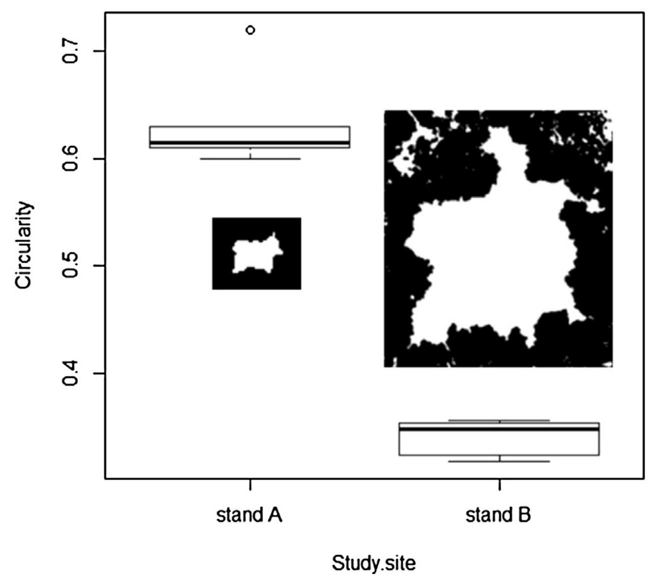

Fig. 8. Box-and-Whisker plot of circularity of gap polygons. An image of a gap from each Stand is also included (in scale; single tree gap: Stand A; multiple tree gap: Stand B).

4. Discussion and outlook

Both scan procedures (standard target-based registration with the Faro Focus 3D and traverse registration mode with the Imager 5010) produced comparable results. Our data indicated that the target-based registration process had a negligible benefit for data quality and our results suggest using the less-laborious approach (traverse registration mode). Surprisingly, the slightly lower scan resolution and the fact that fewer scans were taken with the Imager

Table 3
Arithmetic mean, standard deviation, minimum, and maximum of fractal dimensions of gap edge-lines as derived from the box-counting method. N is sample size (number of gaps) per stand.

Site	PCG resolution	Fractal dimension				N
		MEAN	STDW	MIN	MAX	
Stand A	2 cm	1.20	0.03	1.16	1.23	6
Stand B	20 cm	1.13	0.08	1.05	1.22	6

5010 did not result in larger gap areas, even though one would expect the point cloud to be slightly less detailed. It is also to be expected that a larger number of scans should result in more complete point clouds and hence smaller gap areas. At the same time the amount of new information added to the point cloud will tend to decrease with each scan added, which may be an explanation for the situation in our study. As the gaps in our study were relatively open areas with good visibility it may not have made a large difference whether five or six scans were made. Our knowledge on these effects is still very limited and therefore element of ongoing research.

Another factor to consider is wind. As we avoided windy conditions during all scans it is unlikely that wind-induced crown movements during the scans with the Imager 5010 are the leading cause for the smaller gap areas derived from the scans, especially since they were made with very little time delay to the measurements made with the Faro instrument. However, wind effects can cause a bias towards smaller gap areas. Moving crown elements will be captured in various positions through the course of the scanning procedure and chances for being captured at a different position increase with the number of scans made at a site.

Finally, an important factor to consider when comparing independent point clouds is the actual position of the scans. Scanner positioning determines the degree of shadowing in the data but it is complicated to account for in a systematic manner during the field work. Hence, it is common practice to decide subjectively which scan positions provide the best view on the object of interest (e.g., Seidel et al., 2012, 2013). So far, despite first attempts to provide guidance (e.g., Van der Zande et al., 2008), no universal and practical solution is available for scanning complex natural environments with predefined scanner setups.

Concluding, we assume the differences in scan resolution, scan number and scan positioning were minimized through the use of the PCGs in our study, hence the unexpected result of the comparison of the two different scan procedures and instruments. Furthermore, after visual inspection of the point clouds, we hypothesize that differences in the standard filtering algorithms yielded a slightly higher amount of noise near the crown edges in the data obtained from the Imager 5010 when compared to the Faro equipment, resulting in smaller gap areas. However, for practical purposes these differences are marginal, especially considering that different instruments, different scan positions and different numbers of scans were used in this comparison.

The automatic delineation of canopy gap areas from point clouds obtained through TLS proved to be highly accurate for small and large canopy gaps, when compared to the manual delineation of gap edge-lines from the same data source. It is important to note, that differences in estimated gap sizes are influenced by the relationship between data resolution and gap sizes. For example, using a PCG of 20 cm for both stands resulted in RMSE%s that were larger for the small gaps than for the large gaps. Relative to their absolute size, the 20-cm approximation of neighboring canopies has a much larger effect in small than in large gaps (size effect).

Obviously, best-fitted ellipses, or approaches using eight to 16 directional measurements provide questionable estimates of gap sizes, especially for small gaps. For our study gaps, neither angular schemes with relatively low number of measurements nor best-fit ellipses provided better gap size estimates compared to using the maximum of 629 angular measurements. On the other hand, there was very little difference between gap size estimates from the 629 measurements and any measurement scheme that had 32 or more measurements, suggesting that increasing the number of field measurements beyond 32 would be hard to justify in terms of the accuracy of gap size estimates. As a cautionary note, the accuracy of all angular-measurement schemes is dependent on the actual shape of the gap and hence our recommendation should be used with caution in gaps with extremely high irregularities, such as bulges (more than shown in the examples in Figs. 2 and 3). We hypothesize that such irregularities are responsible for the minimum RMSE% of ~7.2% in our study. Our mixed sample of small gaps in a coniferous Stand and large gaps (on average about 40 times larger) in a deciduous Stand suggest that for a wide range of typical gap shapes, using eight or sixteen angular measurements (Brokaw, 1982; Lima, 2005; Hu and Zhu, 2009) to determine canopy gap areas would result in RMSE%s of about 26%, and 16%, respectively. Using 32 or more measurements results in gap area estimates with a RMSE% of approximately 10% for a range of gap shapes. Using the best-fit ellipse approach consistently results in overestimations of gap area in our study. In contrast to our LIDAR data, distances to canopy edges measured in the field (e.g., with range finders) using vertical projection of crown edges (e.g., with canopy mirrors) have additional measurement errors, suggesting that our RSME%s are conservative for studies with such field measurements. Also, the accuracy of both LIDAR and field based approaches will be influenced by subjectively determined locations of gap centers, especially in irregular shaped gaps, which can be difficult to be done (e.g., Schnitzer et al., 2000).

The assumption of gap shapes in area calculations benefits from an understanding of the gap creating mechanisms. For example, our finding about gap circularity (gaps in Stand A with small single tree gaps had significantly higher circularity than gaps in Stand B with large multiple tree gaps), is reflecting that the single trees removed in Stand A had likely a more circular shape than the cumulative crown areas of the multiple trees removed in Stand B. Accounting for such shape differences may have important consequences for calculation of light regimes on forest floors within gaps (e.g., Hu and Zhu, 2009). In contrast, the ecological meaning of other shape information, such as fractal dimensions of canopy gap edge-lines, is not fully understood. By developing and highlighting the results of a new method to calculate fractal dimensions, we provide an efficient tool for investigating ecological patterns in more detail that hold promise for new insights into gap ecology (Halley et al., 2004).

For example, given the ecological importance of light regimes in stands (e.g., Wagner et al., 2009; Vockenhuber et al., 2011) and that they are altered through gap creation, future research would benefit from more detailed assessment of the 3D-crown dimensions, which directly influence light availability on the forest floor and thus tree regeneration (Brown, 1996; York et al., 2004) and other understory vegetation (Fahey and Puettmann, 2007, 2008). Several studies have shown that not only the distance to gap edges (or centers) are influential, but also the cardinal direction (e.g., Wayne and Bazzaz, 1993; Fahey and Puettmann, 2008; Schliemann and Bockheim, 2011), further suggesting benefits of more detailed 3D-descriptions of gaps. Height of the surrounding trees has been shown to be another important factor influencing light conditions in gaps (e.g., Kneeshaw and Bergeron, 1998). We propose that an accurate description of the 3D-shape will perform better than the often used gap diameter-to-Stand height ratio in estimating the amount of light that reaches the forest floor. As height of the edge trees is also related to maximum root distance from tree trunk, 3D-gap information may also be used to better underStand root dynamics after gap creation (Müller and Wagner, 2003).

Furthermore, the crown radius of adjacent trees can be used to estimate the amount of overhanging plant material in the expanded gap (e.g., Spies et al., 1990; see Fig. 9). Along with information about crown base height of adjacent trees and understory density, such data may provide an indicator for potential (physical) growing space available for regeneration. TLS data can be used to efficiently represent space-occupation (e.g., Seidel et al., 2013), including density profiles (e.g., Ashcroft et al., 2014).

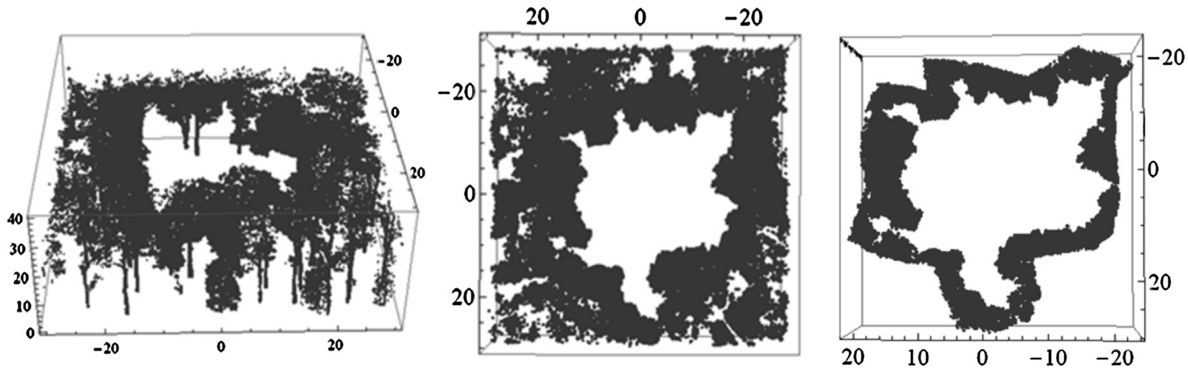

Fig. 9. left: 3D-point cloud of a canopy gap and the surrounding Stand (understory and ground-returns deleted). Middle: Birds-eye view on the same gap. Right: Birds-eye view on the plant material located in the expanded gap area.

A detailed 3D-description of gap shape would also allow the calculation of light availability for any point inside the gap. TLS data can thus replace the need to take hemispherical photographs in points of interest, such as above seedlings in gaps (Woodgate et al., 2015). Hemispherical photographs simulated from the scan data as presented by several earlier studies (Danson et al., 2007; Seidel et al., 2012; Cifuentes et al., 2014; Hancock et al., 2014) could easily be applied to canopy gaps. This would allow determining the light regime in the gap area in dependence of the 3D-shape of the gap, compass directions and geographical position. Also, first successful attempts to perform ray-tracing approaches that simulate light-penetration through the canopy based on TLS-data have already been presented (e.g., Bittner et al., 2012). While one may treat canopy elements as solid blocks based on non-opaque voxels or point cloud grids as presented here, there are also TLS-based approaches that accounted for light penetration through canopy elements including leaf reflectance and transmittance (e.g., Van der Zande et al., 2010). Hence, the application of TLS can range from evaluations of errors immanent in existing field methods, to providing new means to describe canopy structure including gaps (e.g., fractal dimension) or even complete simulations of the radiation regime in a stand.

5. Conclusion

Using single tree gaps in a coniferous and multiple tree gaps in deciduous forests, our study provided insights about the direction and magnitude of error in canopy gap area estimations when using different measurement approaches. Our results suggested that measurement protocols need to be considered as a potential complicating factor when comparing results from different studies and provide guidance about how to account for such differences. Also, our results showed that automatic delineation of gap edges using LIDAR data can lead to efficient, objective, and accurate gap size estimates and provided guidance about the tradeoffs between adding more measurements and gains in accuracy of gap size estimates. Furthermore, we provided insights about the role of gap shapes in determining gap area estimates and presented an approach to determine the fractal dimension of the gap edge-line, which can lead to interesting future applications.

Despite great opportunities, TLS data have not been utilized widely to calculate detailed 3D-descriptions of canopy gaps. For example, parameters, such as 3D-gap volumes that represent spatial patterns of gaps in single values, proved useful, e.g., as surrogate for available growing space or growth performance of the fallen tree (Seidel et al., 2015). Our investigations into the 2D-shape of gaps suggest that descriptions of the 3D-shapes of gaps may also be very useful to underStand gap dynamics and deepening our understanding of gap ecology.

We conclude that the application of TLS in analyzing forest canopy gaps can provide data urgently needed by ecologists and foresters. Apart from the findings presented here the full potential of 3D-data from TLS as a tool to achieve detailed descriptions of canopy gaps in all three dimensions remains to be exploited in future research.

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