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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).