Acquisition and Characterization of Canopy Gap Patterns of Beech Forests

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submitted by
Robert S. Nuske
born in San Diego, California

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1. Referee: **Prof. Dr. Joachim Saborowski**

2. Referee: **Prof. Dr. Kerstin Wiegand**

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Contents

1 Introduction

Canopy gap research in European beech-dominated forests has experienced a remarkable upswing in the last decades. Its contribution to forest ecology and forest management in Europe is discussed in the first section. In the subsequent section a review of canopy gap definitions is given. These are followed by an overview of the state of the art regarding acquisition and characterization of canopy gap patterns. This chapter concludes with an outline of the aims and structure of the present thesis.

1.1 Silvicultural motivations

The concept of close-to-nature forest management has become widely accepted and has gained popularity in practice in Central Europe (von Oheimb et al. 2005, Ciancio et al. 2006, Ligot et al. 2014, Schütz et al. 2016). Close-to-nature forest management is also known by several other terms which emphasize different aspects of the concept, such as "nature-based forestry" (Diaci 2006, Larsen and Nielsen 2007), "ecosystem-oriented forest management" (Ammer et al. 2018), "emulation of natural disturbances" (Long 2009, Kuuluvainen and Grenfell 2012), "uneven-aged forest management" (Boncina 2011, Diaci et al. 2011) or "continuous-cover forestry" (Pommerening and Murphy 2004, Schütz et al. 2012). The various descriptions have in common that they use natural forests as a model and attempt to mimic natural processes, which are regarded a useful source of inspiration for optimizing silvicultural interventions. Although close-to-nature forest management is in high demand, the degree to which on-the-ground-management actually conforms to natural patterns varies greatly. This is partly due to a lack of specific quantitative guidelines for mimicking natural patterns and processes (Seymour et al. 2002). Close-to-nature forest management, thus, needs reference values from natural forests growing under similar conditions (geographical area, altitude, nutrient and water supply).

Forests in Central Europe are on a wide range of site conditions dominated by European beech (*Fagus sylvatica* L., Bohn et al. 2000, Giesecke et al. 2007, Caudullo et al. 2017, Leuschner and Ellenberg 2017). Beech is able to thrive in a wide range of soil and climate conditions from the lowlands to the tree lines. It is a vigorous, long-lived, shade-tolerant tree species that has a strong ability to compete with other tree species. Therefore, it is present in various mixed forests as well as in pure stands throughout Central Europe (Jahn 1991, Peters 1997, Mölder et al. 2014, Leuschner and Ellenberg 2017). These characteristics make European beech a dominant tree species in Central Europe whose range extends from the north of Spain and the south of England and Sweden to the east of Poland, the Carpathian Arc and down to the south of the Balkans and Italy (Bohn et al. 2000, Caudullo et al. 2017).

Furthermore, the dominance of European beech is fostered by the disturbance regime prevailing in Central Europe. Strong winds are the most common natural disturbance type, while hurricanes and typhoons, known from North American and Southeast Asian temperate forests, as well as major fires, as in boreal forests, are absent (Fischer et al. 2013, Brázdil et al. 2018). Together with less frequent small-scale disturbances such as snow breakage, pathogen and insect infestations or breakdown due to tree senescence (Peterken 1996, Zeibig et al. 2005, Fischer et al. 2013), this results in a disturbance regime defined by frequent small and rare intermediate scale disturbances (Drößler and von Lüpke 2005, Splechtna et al. 2005, Nagel and Diaci 2006, Šamonil et al. 2013, Feldmann et al. 2018, Wohlgemuth et al. 2019).

Pickett and White (1985) defined disturbance as “any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment”. Most generally speaking, a disturbance is any discrete event that removes organisms and frees up both space and resources to be used by new individuals (Fischer et al. 2013). In temperate forests, this usually means the death of one to a few canopy trees and the formation of gaps in the otherwise closed forest canopy. The resulting fine-scale gap-phase dynamics are a characteristic feature of natural beech-dominated forests of Central Europe (Peterken 1996, Bengtsson et al. 2000, Emborg et al. 2000, Splechtna et al. 2005).

The formation of canopy gaps is recognized as a crucial disturbance process in many forest ecosystems (Runkle 1990, Lertzman and Krebs 1991, McCarthy 2001, Nagel and Svoboda 2008). It is a vital component of forest dynamics, since canopy gaps "drive the forest cycle" (Whitmore 1989) by creating growing space and favorable environmental conditions, especially in terms of light availability (Mountford 2001). The light conditions at ground level increase strongly after gap formation (Emborg 1998, Ritter et al. 2005, Drössler and von Lüpke 2007, Diaci et al. 2012) with the largest increase in the northern part of the gap and below the canopy just north of the gap (in the northern hemisphere, Wright 1998, Gray et al. 2002, Ritter et al. 2005, Madsen and Hahn 2008). Compared to the surrounding forest, soil moisture and nutrient availability also strongly increase after gap formation (Bauhus and Bartsch 1995, Coates and Burton 1997, Ritter et al. 2005, Gálhidy et al. 2006). The microclimatic conditions in gaps influence nutrient release through decomposition and mineralization processes (Prescott 2002) and, together with water fluxes, the loss of nutrients from the forest system (Vitousek et al. 1979, Bartsch et al. 1999). Thus, the microclimate within the gap is distinctly different from sub-canopy conditions (Ritter et al. 2005, Latif and Blackburn 2010). Among other factors, it determines whether and how well natural regeneration establishes after a disturbance provided space for a new tree generation (Watt 1947, Madsen 1994, Madsen and Larsen 1997, Wagner et al. 2011).

Small or fast-closing gaps provide pulses of light that may only favor the recruitment of shade-tolerant species, as they are able to withstand intermittent periods of low light. Shade intolerant species can only establish if light levels remain high for a sufficient period of time allowing them to reach the canopy (e.g. Runkle 1982, Busing and White 1997, Webster and Lorimer 2005, Kneeshaw and

Prévost 2007, Wagner et al. 2011). For example, small gaps in mixed stands of oak and beech frequently lead to beech-dominated mixed regeneration. Young oaks are outcompeted by beech, since the light requirements of young oaks are not met (von Lüpke 1998, Ligot et al. 2013, 2015, Mölder et al. 2019). If light-demanding species are desired, gaps should be of substantial size and stay relatively open for several years (Diaci et al. 2008, Madsen and Hahn 2008). Gap size drives the species composition of the regeneration. Varying gap sizes favor different tree species, which may contribute to enhanced tree biodiversity.

Gap formation also often leads to a significant increase in herbaceous cover, especially in the center of gaps (Mountford et al. 2006, Falk et al. 2008, Kelemen et al. 2012), that may, however, result in high competitive pressure on tree regeneration (Wagner et al. 2011). Additionally, a number of studies found that the herbaceous species richness increases within gaps as compared to beneath closed canopy (e.g. Busing and White 1997, Schumann et al. 2003, Naaf and Wulf 2007, Kelemen et al. 2012). In most temperate deciduous forests, the gap size affects also the species composition of the herbaceous vegetation (Degen et al. 2005, Naaf and Wulf 2007). Gaps are not only positively affecting plant species diversity, but may also provide important habitats for woodland animal species (Coates and Burton 1997, Sebek et al. 2015, Lachat et al. 2016). It has been observed, that anthropogenic small-scale disturbance increased the abundance of forest birds (Forsman et al. 2010).

Especially in beech-dominated forests, rapid lateral crown expansion of neighboring trees closes small gaps within a few years after gap formation (Madsen and Hahn 2008, Collet et al. 2011). In larger gaps, however, vertical gap filling through ingrowth of lower canopy layers and (advanced) regeneration is the dominant process (Kucbel et al. 2010). Larger gaps usually remain open longer while smaller ones close quickly (Frelich and Reich 1995). The distinction between the different gap closure processes is crucial, since only the vertical ingrowth leads to a generational turnover.

Hobi et al. (2015b) reported that more than two-thirds of the ingrowing trees needed two or more release events in order to access the canopy in a primeval beech forest. Nagel et al. (2014) found that an even higher number of 81% of the beech trees experienced a period of suppressed growth prior to canopy accession in a mixed fir-beech primeval forest. Advance regeneration is common in beech forests since the seedlings are capable of surviving several years at very low light levels ("Oskar syndrome", Silvertown 1995, Emborg 1998, Nagel et al. 2006, Wagner et al. 2010) and are able to respond quickly to increased light availability (Newbold and Goldsmith 1981, Peltier et al. 1997, Collet et al. 2001).

It is an ongoing debate whether gap-bordering trees are more likely to die than trees in the forest matrix. Some authors describe considerable gap expansions (Drößler and von Lüpke 2005, Nagel and Svoboda 2008, Bottero et al. 2011, Rugani et al. 2013) caused by destabilized bordering trees through mechanical damage, exposure to wind, or direct sunlight overheating the bark (Peterken 1996, Schelhaas et al. 2003, Westphal et al. 2006, Firm et al. 2009). Other authors found gaps to be formed exclusively by single disturbance events (Tabaku and Meyer 1999) and the mortality of trees neighboring a gap not to be higher than in the canopy trees in the closed stand (Runkle 2013).

Besides the changes of the proportion of forest area in gaps and the distribution of gap sizes, the question of where in the canopy changes occur is also of interest in order to determine the rate of gap formation and closure as well as gap shrinkage and expansion. Such data on spatially explicit temporal changes of gaps can be gained by repeated terrestrial inventories (e.g. Feldmann et al. 2018), Dendrochronology (e.g. Piovesan et al. 2005, Petritan et al. 2013) or series of aerial images (e.g. Nuske 2003, Meyer and Ackermann 2004, Nuske 2006a, Kenderes et al. 2008, Kathke and Bruelheide 2010, Rugani et al. 2013).

Many studies of natural disturbances describe a static picture. There is still limited information on the dynamics of canopy gaps based on repeated observations of the individual stands, especially in beech forests. A longer period of tree canopy structural data and the inclusion of dendrochronological information is needed to better understand the disturbance regime and dynamics of natural forests (Kenderes et al. 2008, Feldmann et al. 2018).

For designing silvicultural interventions that resemble natural disturbances, knowledge of the characteristics of natural disturbances (frequency, extent, severity, Frelich 2002) is of utmost importance (Brang 2005). Close-to-nature forestry emphasizes the importance of mimicking processes recognized in natural forests growing in similar site conditions. A major obstacle in Central Europe, however, is the lack of reference conditions. Although beech forests are among the most widespread forest types in Europe (Bohn et al. 2000, Packham et al. 2012), little is known about the dynamics of primeval beech forests since man began changing European forests thousands of years ago (Parviainen 2005). Forests gave way to settlements and were considerably reduced by the Middle Ages. Because of human activities such as mining, glass fabrication, livestock herding, fuelwood or litter collection and hunting, forested areas adjacent to settlements and agricultural land were particularly under pressure due to human activity (Bücking et al. 1994, Rackham 1995, Romane 1997). Only scattered remnants of natural beech forests have survived. Most of them can be found in remote and mountainous areas of the Carpathians, the Balkans and the Alps, where management or even exploitation is difficult and often not profitable (Commarmot and Brang 2011, Sabatini et al. 2018).

An incomplete substitute for the missing primeval forest in Central Europe can be set-aside areas such as unmanaged strict forest reserves (Meyer 2005, Ammer et al. 2018). As early as the 20th century, individual forest stands in Central Europe were dedicated to free development, with single examples dating back until 1838 (Sip 2002, Bücking 2003, Schmidt and Rapp 2006, Welzholz and Johann 2007, Vrška and Hort 2008, Mölder et al. 2017). The idea of strict forest reserves in the modern sense was developed in the 1930s (Hesmer 1934a, b). However, strict forest reserves were not implemented on a larger scale and systematically investigated until the 1960s in East Germany (Bauer and Niemann 1965, Bauer 1968, Niemann 1968) and the 1970s in West Germany (Trautmann 1976). Currently, less than 2% of European (ForestEurope 2015) and in the year 2019 2.8% of German forestland (Engel et al. 2019) are dedicated to free development.

Strict forest reserves will initially continue to show the effects of past management, e.g. absence of old-growth structures and lack of senescence phases (Peterken 1996, Winter et al. 2010, Meyer and Schmidt 2011) and probably will do so for centuries (e.g. Tabaku 2000, Rademacher et al. 2001). However, they are, if selected well, of similar species composition and spatially close to the managed forests, thus, growing under similar conditions. In the absence of better sources, they will provide essential reference data for close-to-nature forest management. Strict forest reserves facilitate the assessment of the impact of management on forest ecosystems (Parviainen et al. 2000).

The extent to which the type and intensity of silvicultural interventions lead to near-natural patterns can be evaluated by comparing them with patterns and processes in unmanaged forests (Tabaku and Meyer 1999). A number of studies comparing managed and unmanaged forests have been published in recent years (e.g. Boncina 2000, Commarmot et al. 2005, Winter et al. 2005, Begehold et al. 2016, Horvat et al. 2018). Two meta-analyses aggregate the literature with regard to the effect of managed and unmanaged forest on biodiversity indices (Paillet et al. 2010, Dieler et al. 2017). Dieler et al. (2017) found no clear relationship between compositional diversity (species richness, diversity) and forest stand management. Paillet et al. (2010) concluded that the literature does not systematically support the hypothesis that unmanaged forests are more species-rich than managed forests. However, tree size, its diversity, the number of microhabitats and the amount of deadwood are considerably lower in managed forests. Anyhow, the differences between managed and unmanaged forests are vague. According to the authors, this is mainly due to the fact that unmanaged stands are still in the process of developing old-growth attributes because management was abandoned too recently for significant changes in forest structure to have occurred. They tend to become more homogeneous for at least some decades unless disturbances create substantial structural heterogeneity. Additionally, modern forest management already emulates natural disturbances by femel or group selection creating heterogeneous structures and habitats. The differences become blurred, since unmanaged forests are hardly primeval and lack old-growth structures, and forest management tends towards close-to-nature approaches (Dieler et al. 2017, Meyer and Ammer 2019).

The most prominent and visible silvicultural intervention is the removal of trees, which immediately changes horizontal and vertical stand structure and usually creates a canopy gap. Puettmann et al. (2008) stated that the size distribution and spatial arrangement of gaps tends to be more uniform in selectively logged stands and Hessburg et al. (1999) conjectured that forest management regimes might be detectable in the canopy gap patterns. A quantitative description of the canopy gap patterns, thus, could be a good addition to commonly used indices of forest structure. It could also help to formulate quantitative guidelines for mimicking natural patterns and processes as requested by Seymour et al. (2002). A larger number of canopy gap patterns acquired preferably for remnants of natural beech forests and differently managed forest stands would be expedient in order to gain reference values. To study processes, such as canopy gap dynamics, long time series are needed, which could be acquired from archived aerial imagery (e.g. Meyer and Ackermann 2004, Nuske 2006a, Kenderes et al. 2008).

1.2 Canopy gap definitions

Canopy gaps are openings in the canopy layer. They were defined by Runkle (1981) as “the ground area under a canopy opening extending to the bases of canopy trees surrounding the canopy opening” and by Brokaw (1982) as “a ‘hole’ in the forest extending through all levels”. The second definition is convenient, as it is straightforward and easy to apply in the field (Schliemann and Bockheim 2011). In contrast to the first, it can easily be adapted to remote sensing purposes as the gap according to this definition can be observed from above, since the gap is delimited by the canopy drip-line, i.e., the vertical projection of the edge of the surrounding tree crowns. Gaps recorded according to the first definition are called “extended gaps” (Runkle 1982). This definition is still in use since it accounts for the fact that changes in microclimate associated with gap formation are not limited to the area directly under the opening in the canopy (Runkle 1982, Ritter et al. 2005, Madsen and Hahn 2008). Field surveys sometimes capture both the extended and the canopy gap (e.g. Drößler and von Lüpke 2005, Nagel and Svoboda 2008, Diaci et al. 2012). The second definition, however, prevails and is the only one in use in remote sensing.

There are different reasons for the formation of a gap (i.e. "birth" of a gap). Lertzman et al. (1996) distinguished between ephemeral developmental gaps caused by tree mortality (loss or removal) and branch fall, and persistent gaps, which result from edaphic or topographic conditions, such as small lakes, bogs or rocks. Some studies, mostly based on field surveys, try to ensure to exclusively map developmental gaps by checking for remnants of gapmakers, preferably trees from the main canopy layer (Kucbel et al. 2010, Nagel et al. 2010, Bottero et al. 2011, Danková and Saniga 2013, Petritan et al. 2013). This is done rarely in gap mapping by remote sensing, but Kathke and Bruelheide (2010) excluded gaps that did not change in their time series.

Since the beginning of canopy gap research, there was disagreement on the definition of gap closure (i.e. "death" of a gap). Runkle (1982) stated that regeneration in the gap had to reach a height of 10 m to 20 m for a gap to be considered closed, while Brokaw (1982) argued that a regeneration height of 2 m was sufficient. The disagreement still continues. Studies apply regeneration height thresholds from 2 m (Kenderes et al. 2008), 3 m (Bonnet et al. 2015), 4 m (Blackburn et al. 2014), 10 m (Gaulton and Malthus 2010), half of the stand height (Meyer and Ackermann 2004, Zeibig et al. 2005, Nagel and Svoboda 2008, Kucbel et al. 2010, Nagel et al. 2010, Bottero et al. 2011, Petritan et al. 2013, Rugani et al. 2013) and two-thirds of the stand height (Münch 1995, Hoffmann 2001, Drößler and von Lüpke 2005, Nuske and Nieschulze 2005, von Oheimb et al. 2005, Gaulton and Malthus 2010, Feldmann et al. 2018, White et al. 2018). The last height threshold seems to predominate since it is often argued that the regeneration has to reach the main canopy for the gap to be closed. Following a definition by IUFRO (Leibundgut 1956), this is often regarded as two-thirds of the top height. Two studies (Gaulton and Malthus 2010, White et al. 2018) even measured the height of the average drip-line and arrived at the same relative height.

Already Brokaw (1982) recognized that the minimum gap size varies among forest types and asked for it to be reported in canopy gap studies since the definition of the minimum gap size influences statistical parameters. Today, minimum canopy gap sizes from 1 m^2 up to 50 m^2 (Getzin et al. 2014, Bonnet et al. 2015) can be found. The most common minimum sizes are 20 m^2 (e.g. Brokaw 1982, Meyer and Ackermann 2004, Drößler and von Lüpke 2005, Nuske and Nieschulze 2005, Garbarino et al. 2012, Rugani et al. 2013, Blackburn et al. 2014) and 5 m^2 (e.g. Zeibig et al. 2005, Vepakomma et al. 2008, Gaulton and Malthus 2010, Kucbel et al. 2010, Nagel et al. 2010, Danková and Saniga 2013). Reasons for the chosen minimum sizes are the studied topics, which range from herb-layer diversity to natural disturbances on the landscape scale, and sometimes methodical restrictions, such as workload in field surveys or spatial resolution of remote sensing data. Schliemann and Bockheim (2011) suggest to also set a maximum gap size at 1000 m^2 since larger openings are usually created by other disturbance agents (fires, tornados, downdrafts or hurricanes). Those openings exhibit largely differing characteristics compared to gaps caused by the fall of one or a few canopy trees. They have less shading from surrounding trees and therefore higher light levels and soil temperatures. They also tend to have higher soil moisture due to a reduction in transpiration (Gray et al. 2002, Muscolo et al. 2007).

Since the definitions in use are so manifold, it is widely accepted practice in literature to explicitly state one's own definition. The gap mapping technique employed has, besides the objective of the study, a strong influence on the definition. The mapping techniques differ in the following chapters, which are separately published studies. The approaches range from field surveys over manual delineation of gaps based on very high resolution remote sensing data to automatic mapping based on canopy height models and data fusion products. Thus, there is no unified gap definition in this thesis, but each chapter states its own.

1.3 Mapping canopy gaps

Disturbances in forests have been studied using a wide range of methods. In Central European temperate forests, disturbances manifest themselves usually in small to intermediate canopy gaps ranging from the loss of one to a few canopy trees up to about 1000 m^2. Larger, stand replacing disturbances are usually not in the focus of canopy gap studies. Mapping canopy gaps – whatever the method – is a classification task. Every bit of a forest stand or landscape is assigned to one of two classes: gap or canopy. Gaps are assumed to be easily distinguishable from the surrounding high canopy (Vepakomma et al. 2008, Ke and Quackenbush 2011).

1.3.1 Terrestrial surveys

Canopy gaps have been mapped terrestrially (e.g. Koop and Hilgen 1987, Drößler and von Lüpke 2005, Zeibig et al. 2005, Kucbel et al. 2010, Petritan et al. 2013, Feldmann et al. 2018) and based on various remote sensing data originating from different types of sensors and carriers, such as satellite data (e.g. Garbarino et al. 2012, Hobi et al. 2015a, Rehush and Waser 2017), aerial images (e.g. Brunig 1973, Fox et al. 2000, Fujita et al. 2003a, Nuske 2003, Betts et al. 2005, Kenderes et al. 2008, Rugani et al. 2013), airborne laser scanning (e.g. Koukoulas and Blackburn 2004, Vepakomma et al. 2008, Gaulton and Malthus 2010, Bonnet et al. 2015, White et al. 2018) or unmanned aerial vehicles (UAV, e.g. Getzin et al. 2014, Bagaram et al. 2018).

A traditional and still frequently adopted approach to map gaps is based on field survey methods. Terrestrial mapping, in contrast to remote sensing, offers on the one hand the possibility to collect a rich set of additional tree and stand parameters, such as information on the species, diameter at breast height and time of fall of the gapmaker and the species composition and density of the regeneration (e.g. Petritan et al. 2013). But is on the other hand quite time and labor-intensive and often leads to small plots or sampling approaches obstructing the analysis of the spatial distribution of canopy gaps (e.g. Hobi et al. 2015b).

The line intersect sampling is one of the first approaches, where all gaps are measured that cross transects running a certain distance apart across a forest stand (e.g. Runkle 1981, Drößler and von Lüpke 2005, Nagel et al. 2010, Feldmann et al. 2018). The total gap area is estimated based on the line intersect sample. A similar but somewhat less accurate method, which uses stripes instead of lines, is the belt transect method (Yamamoto 1989, Bottero et al. 2011). A point sampling approach to estimate the gap fraction of the 100 km² large primeval beech forest Uholka-Shyrokyi Luh in the Carpathians was employed by Hobi, Commarmot, and Bugmann (2015b).

Complete recordings of canopy gaps of entire forests are extremely time-consuming. Therefore, field surveys of canopy gaps are often carried out in smaller areas. Mostly, the area confined by the vertical projection of the crowns of the surrounding trees is recorded as gap (e.g. Kucbel et al. 2010, Petritan et al. 2013). Only few studies still resorted to the method originally proposed by Runkle (1981) to measure the length and perpendicular width of a gap and to calculate the area using the ellipse formula (e.g. Zeibig et al. 2005, Sefidi et al. 2011). A more labor-intensive method rarely applied is the "canopy height profile method" where the height of the vegetation is measured in a regular grid with a measuring pole. Fujita et al. (2003a) measured a 4 ha plot with a spatial resolution of 2.5 m as ground truth for gaps mapped from canopy height models constructed from aerial images.

Although canopy gap definitions aim at objectifying the mapping, the subjective influence of the observer remains relevant especially for terrestrial mapping techniques. Many methods involve some judgment such as the ocular evaluation of the exact limits of the gap, the height of regeneration or the size of the gapmaker.

1.3.2 Remote sensing

Canopy gaps which, in contrast to extended gaps, form a hole through all levels of the canopy can be observed from above and are detectable and delineateable by suitable remote sensing data. Remote sensing generally offers the possibility to map entire landscapes and, if archived data is available, describe changes based on time series. A variety of different remote sensing carriers and sensors have been investigated for mapping canopy gaps, including satellite images (e.g. WorldView-2, Hobi et al. 2015a), unmanned aerial vehicles (e.g. Getzin et al. 2014), true color and color infrared stereo aerial images (e.g. Brunig 1973, Nuske 2006a), airborne laser scanning (e.g. Koukoulas and Blackburn 2004, Vepakomma et al. 2008) and terrestrial laser scanning data (e.g. Seidel et al. 2015). Although remote sensing allows an automation based on the assumption that gaps are distinguishable from the surrounding canopy, Vepakomma et al. (2008) concluded that detecting canopy gaps and delineating their boundaries using any technique is a complex task.

Historically, canopy gaps were mapped by interpretation of aerial images by skilled and experienced human analysts. Brunig (1973) used a scanning stereoscope to map gaps in a stereoscopic or 3D view. Later, more sophisticated equipment for mapping in 3D view were employed such as analytical stereoplotters (e.g. Meyer and Ackermann 2004) or nowadays digital stereoplotters (e.g. Rugani et al. 2013). Manual delineation of canopy gaps is very tedious and involves some judgment of the analyst. Depending on the position of the sun, shadows can be good indicators for canopy gaps but also hinder the exact delineation of the canopy drip-line. Correctly mapping larger illuminated gaps or deciding whether the regeneration in a specific gap reached the main canopy and closed the gap is only possible with a 3D impression of the scene. Therefore, analysis of stereopairs with devices conveying a 3D view is preferred to orthorectified aerial images (e.g. Zeibig et al. 2005). Manual delineation of canopy gaps based on remote sensing data is today mostly done for small areas (e.g. Getzin et al. 2014), for obtaining a reference or training dataset (e.g. Hobi et al. 2015a, Rehush and Waser 2017) or because of heterogeneous image quality (e.g. Kenderes et al. 2008).

Automatic classification of gaps based on spectral information is often criticized for the same reasons as the manual delineation. The classifier cannot clearly distinguish between regeneration in gaps and tree crowns of the upper canopy. They are spectrally inseparable. Trees in small gaps can be shaded or obscured by adjacent canopy trees. The lighting conditions in smaller gaps complicate the delineation of canopy gaps (Vepakomma et al. 2008, Rugani et al. 2013). An additional challenge is to get enough suitable training data for automatic classification.

High resolution satellite image data offer the possibility to map larger areas. Garbarino et al. (2012) used unsupervised pixel-based classification based on spectral and textural features from Kompsat-2 images but were only able to detect about 10% of the gaps a parallel field survey mapped (cf. Bottero et al. 2011). Rehush and Waser (2017) classified canopy gaps by thresholding the lightness value after a color space transformation of the bands red edge, yellow and blue of a WorldView-2 image. A similar approach was chosen by Bagaram et al. (2018) who used an unmanned aerial vehicle (UAV) equipped with a commercial camera. They employed the contrast split algorithm based on the red band to differentiate dark objects, usually shaded canopy gaps, from bright objects, which, in most cases, corresponded to forest canopy.

Seamless height information for an entire forest can be a good basis to detect and delineate openings in the forest canopy. Currently, there are mainly two sources for comprehensive height information: airborne laser scanning (ALS) and digital aerial photogrammetry (DAP, White et al. 2018). The data is typically acquired either from an airplane or an UAV. Satellite data does currently not provide the precision needed for mapping the usually small canopy gaps (Hobi et al. 2015a).

The height of vegetation across space is commonly expressed as a surface of vegetation heights above ground and is known as canopy height model (CHM). It is the difference between a digital terrain model (DTM), which represents the height of the terrain above sea level, and a digital surface model (DSM), which represents the height of the uppermost surface above sea level. The height models are usually in the form of raster datasets.

Airborne laser scanning (also known as airborne LiDAR) is an active remote sensing technology that measures the three-dimensional distribution of vegetation. ALS data enable the detailed representation of the terrain, even under forest canopy, as well as the accurate estimation of stand heights on a large scale. A high-density ALS dataset, thus, allows the derivation of a digital terrain model and a digital surface model and thus a canopy height model from one data source. ALS is still a young technology, so that only short time series are available. So far only few studies have dealt with gap dynamics based on ALS (e.g. Vepakomma et al. 2008, 2012, Blackburn et al. 2014, Choi et al. 2019). However, ALS demonstrated its capacity to systematically and accurately map canopy gaps (White et al. 2018).

Digital aerial photogrammetry generates digital surface models from stereoscopic aerial imagery utilizing principles of stereophotogrammetry or multiview photogrammetry (Baltsavias et al. 2008). Nowadays, height models are derived automatically from aerial images using image matching or structure from motion algorithms (Surovy and Kuzelka 2019). Additional information about the terrain is needed to construct a canopy height model. This information can often but not always be acquired from official surveying office or an independent ALS campaign (Nuske 2006a, Kenderes et al. 2009, Hobi et al. 2015a, Zielewska-Büttner et al. 2016). In contrast to ALS, archived aerial imagery may be used to establish long time series since aerial images were often acquired for other purposes in the past. Photogrammetric data are typically cheaper and commonly provide also spectral information (White et al. 2013).

The two most common methods for delineating canopy gaps based on digital height models, as reported in the literature, are fixed and relative height thresholds (White et al. 2018). The choice of method is often guided by the available data, its quality or the gap definition. If no usable DTM is available, a relative height threshold might be the only option (Betts et al. 2005). Furthermore, a relative height threshold might be advisable if the growing conditions and thus the canopy height varies considerably within the stand. The height thresholds are usually applied to raster datasets. Gaulton and Malthus (2010) compared the use of a relative height threshold to both a raster canopy height model and the 3D point cloud and found that gap detection using the point cloud directly resulted in a slight increase in gap detection accuracy of 3.7%. However, the authors also noted that the use of the point cloud was “considerably more computationally demanding" and may not be justified over large areas given the relatively low gain in recognition accuracy.

White et al. (2018) compared airborne laser scanning to digital aerial photogrammetry in the scope of mapping canopy gaps. They concluded that DAP does not provide equivalent results to ALS for the detection and mapping of canopy gaps and that ALS data provide considerably higher accuracy and more detailed gap characterization. Gap detection rate of DAP varied markedly across stand ages whereas ALS was fairly unimpaired. They attributed the low quality of DAP in old stands to the confounding effects of canopy complexity and related occlusions and shadows on image matching algorithms. This is in accordance with Zielewska-Büttner et al. (2016) who reported that gap mapping accuracy decreased with forest height and associated shadow occurrence. Betts et al. (2005) stated that areas lacking sufficient texture to allow a successful match, such as within shadows, are usually poorly represented in height models generated by image matching. This is a problem for gap studies in particular because canopy gaps are usually shaded by the surrounding canopy.

However, the virtually ubiquitous availability of aerial images and frequent existence of long time series suggests exploiting this data source as much as possible. This is currently the only way to study the dynamics of canopy gaps of large areas, since the other remote sensing data sources do not cover sufficiently long periods of time. Mapping of canopy gaps exclusively based on color or DAP height information does not provide completely satisfying results (Nuske 2006b). Nonetheless, a promising approach is to use a combination of multiple data sources (Nuske et al. 2007, Bonnet et al. 2015). The fusion of multiple sources of information allows to exploit different aspects of canopy gaps for mapping. Besides the fact that many gaps are darker than the surrounding canopy, the vegetation height will be considerably lower and the image texture usually differs. Image matching algorithms often fail due to no texture in hard shadows or the corresponding point being covered in the other image of the stereopair. Depending on the algorithm this can lead to missing values or low quality measures, which itself can be valuable information (cf. Nuske et al. 2007).

Machine learning techniques are particularly suitable for data fusion tasks. Compared to traditional linear regression models, they can handle nonlinear datasets, learn from limited training data, and successfully solve difficult to distinguish classification problems (Cooner et al. 2016). Machine learning algorithms, such as *k*-nearest neighbor, classification and regression tree, random forest, support vector machine and artificial neural network, have been widely adopted for land-cover classification (e.g. Shao and Lunetta 2012, Rodriguez-Galiano et al. 2015).

Support vector machine classifiers (Vapnik 1995) were used for mapping burn scars, forest disease monitoring, illegal logging and forest fire fuel classes (Liu et al. 2006, Cao et al. 2009, Kuemmerle et al. 2009, García et al. 2011). Mountrakis et al. (2011) found support vector machines to be a fairly reliable method for processing remote sensing data and superior to most of the alternative algorithms. The current success of artificial neural networks was brought about by the tremendous increase of computing power, especially distributed and GPU systems, large amounts of good quality training data, and algorithmic advances allowing for lots of hidden layers (e.g. Raina et al. 2009, Rawat and Wang 2017). In particular, convolutional neural networks such as the U-Net were increasingly used for image recognition and segmentation tasks (Ronneberger et al. 2015, Gu et al. 2018).

The classification of remote sensing data, especially in the scope of canopy gap mapping, is particularly difficult because most of the supervised learning schemes require large amounts of training data, but the definition and collection of reference data is often a critical problem (Chi et al. 2008). One way to deal with the demand for lots of training data are self or adaptive learning approaches, where the training dataset grows from a small seed to a sufficient size (e.g. Nuske et al. 2007, Tuia et al. 2011).

The subjective influence of the observer on the delineation of canopy gaps can be reduced and canopy gap maps of continuous large areas can be obtained by automated canopy gap mapping based on remote sensing data. This thesis contributes to the methodology of automatic canopy gap mapping. Three different approaches to automate canopy gap mapping based on remote sensing are presented in the Chapters 2 to 4. Chapter 2 uses exclusively a photogrammetric height model, Chapter 3 employs a data fusion technique and Chapter 4 explores the possibilities of airborne laser scanning data.

1.4 Characterizing canopy gaps

Canopy gaps are the most prominent feature of forest structure and influence the forest ecosystem in many ways. The regeneration and thus the further development of the stand depends substantially on the size, shape and distribution of gaps in the canopy of forests (Coates and Burton 1997).

Canopy gap patterns are formed both by the past disturbance agents, such as strong winds, snow, pathogens, tree senescence or silvicultural interventions, as well as the developmental stage and constitution of the forest. Wu et al. (2016) conjectured that canopy gap patterns with different characteristics may have been generated by different processes and may experience different regeneration dynamics.

Many measures were suggested in order to characterize canopy gap patterns. They range from simple parameters such as gap area to more complex ones, such as spatial distribution of gaps.

Nearly all studies on canopy gaps report size related gap properties. Common are the proportion of forest area in gaps, the number of gaps per hectare and the distribution of gaps sizes (e.g. Runkle 1982, Tabaku and Meyer 1999, Zeibig et al. 2005, Kenderes et al. 2009, Kucbel et al. 2010, Feldmann et al. 2018). Historically, those were estimated from line intersect samples with gap areas approximated by an ellipse (e.g. Runkle 1981, Kucbel et al. 2010). If the gap boundary is captured as a polygon, the area can be calculated precisely (e.g. Kenderes et al. 2009, Petritan et al. 2013); nowadays usually in a geographic information system (GIS). Gap boundary polygons can be gained in field surveys by measuring locations along the canopy drip-line wherever significant changes in the orientation of the gap boundary occur or based on remote sensing data. The size of the canopy gaps influences markedly the species composition of the regeneration (Runkle 1982, Kneeshaw and Prévost 2007). The gap size distribution on the other hand is a strong indicator of the primary disturbance agents (Turner 2010).

The shape or shape complexity of gaps can be characterized in many different ways. This is of interest, since the shape affects the light levels as narrow gaps will receive less light at the ground level than circular gaps of the same size (Canham 1988). The complexity is also associated with the composition and development of the understorey (Bagaram et al. 2018). One of the first measures in use was the ratio of the major axis to the minor axis of the approximated ellipse, which is a simple measure of eccentricity or elongation (Tabaku and Meyer 1999, Sefidi et al. 2011). Common measures are the ratio of the perimeter to the area, often called circularity (Lertzman and Krebs 1991, Petritan et al. 2013), and the ratio of the gap perimeter to the perimeter of a circle of equal area, also known as compactness (Bonnet et al. 2015, Bagaram et al. 2018). Since measures involving the perimeter are susceptible to scale effects, the fractal dimension is often suggested but so far without ecological interpretation (McGarigal and Marks 1995, Seidel et al. 2015, Bagaram et al. 2018).

The orientation or main direction of the gap influences, along with the size and shape of the gap, the amount of light reaching the ground. Long, narrow gaps receive more light with a north-south orientation than with an east-west orientation (Diaci et al. 2008, Schliemann and Bockheim 2011). Systematic orientation of non-circular gaps could be an indication of a disturbance agent, e.g. windthrow (van Wagner 1968). However, the orientation of gaps is seldomly reported (Eysenrode et al. 1998, Diaci et al. 2008, Garbarino et al. 2012, Bonnet et al. 2015).

Temporal distribution of canopy gaps is often described by gap age, the turnover rate or gap closure and formation rate. These parameters provide information about the dynamics of canopy gaps (Kucbel et al. 2010, Vepakomma et al. 2012). Gap age is mostly assessed in field surveys by dendrochronology of gapfillers, counts of whorls or annual bud scars and decay stages of gapmakers (Schliemann and Bockheim 2011). Canopy gap studies using remote sensing data usually focus on gap formation and closure rates (Fujita et al. 2003b, Kenderes et al. 2009, Kathke and Bruelheide 2010). Vepakomma et al. (2012) also distinguished appearance and expansion, disappearance and shrinkage as well as displacement of canopy gaps.

The spatial distribution is the only parameter needing comprehensive mapping of canopy gaps. Such complete maps of canopy gaps of an area of interest, a sufficiently large core area, forest stand or forest landscape, are seldomly available from field surveys with the notable exception of Petritan et al. (2013) and Zeibig et al. (2005). Most seamless canopy gap maps are acquired by remote sensing (e.g. Brunig 1973, Kenderes et al. 2009, Wu et al. 2016). Canopy gap patterns differ by forest composition, developmental stage and stand history (e.g. Petritan et al. 2013). Hessburg et al. (1999) conjectured that the forest management regimes might be detectable in the canopy gap patterns.

A variety of methods has been proposed for characterizing the spatial pattern of canopy gaps, such as hemispheric images (e.g. Trichon et al. 1998), landscape indices (e.g. Hessburg et al. 1999, Wu et al. 2016), spatial autocorrelation (e.g. Frelich and Lorimer 1991), nearest neighbor distances (e.g. Poorter et al. 1994, van der Meer and Bongers 1996, Salvador-Van Eysenrode et al. 2000) and point processes (e.g. Garbarino et al. 2012, Silva et al. 2019). In contrast to most methods, point pattern analysis allows the spatial distribution of objects to be investigated on several scales. Second order statistics, such as Ripley's K function, the associated L function or the pair-correlation function, have proven useful in ecological research (e.g. Perry et al. 2006, Picard et al. 2009) and a rich set of reliable and mature tools is available (e.g. Ripley 1981, Stoyan and Stoyan 1994, Baddeley and Turner 2005, Illian et al. 2008). The only drawback is that objects of interest are assumed to be points in classical point pattern analysis. Thus, canopy gaps are represented by points, e.g. the center of mass, which may obscure the real spatial relationships if the sizes of the gaps are in the same range as the investigated spatial scales (Simberloff 1979, Prentice and Werger 1985, Nuske et al. 2009).

Representing objects by their boundary polygon instead of center points and measuring distances between the boundaries of the objects is the main idea of the adapted pair-correlation function (Nuske et al. 2009). This approach avoids pseudo hard- and soft-core effects and is able to describe the real interaction effect at small scales and allows the analysis of patterns of objects of finite size and irregular shape.

The adapted pair-correlation function is introduced in Chapter 5 and example applications are presented in the Chapters 6, 7 and 8. The method was first implemented in the geospatial database PostGIS and later as an R package. The second implementation, directly interfacing with the GEOS library, has yielded a considerable improvement in performance. This re-implementation is presented in Chapter 8.

1.5 Structure and aims of this thesis

Canopy gap patterns of unmanaged beech forests are still scarce. This is even more true for the analysis of the spatial distribution of the gaps, as the patterns must be sufficiently large. Since canopy gaps are objects of finite size and irregular shape and the relevant interactions are at the scales of the gap sizes, the description of the spatial distribution of gaps is a complex task. This thesis wants to contribute to the methodology of automatic mapping of canopy gaps based on remote sensing data to help collect more and larger canopy gap patterns. Moreover, it proposes a method for analyzing the spatial distribution of the gaps respecting their finite size and irregular shape.

Chapters 2 and 3 were published in conference proceedings, with Chapter 3 selected as a talk based on a peer review of the full manuscript prior to the conference. The later Chapters 5, 6 and 7 were published in peer reviewed journals. These already published studies are supplemented by the Chapters 4 and 8 covering an investigation of canopy gaps in all Hessian strict forest reserves dominated by European beech.

Chapters 2 to 4 look at mapping canopy gaps based on remote sensing data. The first two focus on time series of archived aerial imagery and explore photogrammetric height models and a data fusion approach to automatically map canopy gaps. Chapter 4 explores the possibilities of airborne laser scanning and focuses on the analysis of a large number of areas instead of multiple time steps. The second topic, the description of the spatial distribution of canopy gaps, is presented in the Chapters 5 to 8. An adaptation of the classical pair-correlation function to areas of finite size and irregular shape is introduced in Chapter 5. Chapters 6, 7 and 8 contain example applications of the adapted pair-correlation function in three very different studies. The first study describes an old-growth forest remnant in the Carpathian Mountains, Romania. The characterization of the spatial pattern is part of a comprehensive analysis. The second study focuses on the comparison of three spatial correlation functions for the investigation of canopy gap patterns by the example of the Biodiversity Exploratories "Schwäbische Alb" and "Hainich-Dün". Of the Chapters 6 and 7 only the parts on the adapted pair-correlation function contribute to this thesis. However, the articles are included in total to provide context to the application of the adapted pair-correlation function. The last study applies the adapted pair-correlation function to a large number of sites and presents the necessary performance improvements and the implementation as an R package. All studies are jointly discussed in the closing Chapter 9.

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2 Assessing forest gap dynamics using remotely sensed digital height models and GIS

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Abstract

Canopy gaps play an essential role in continuous cover forests, as they have a strong effect on regeneration dynamics and species composition. However, canopy gaps have been widely neglected in current monitoring and planning practices, which might be caused by the fact that mapping of canopy gaps from the ground is labour-intensive, tedious, and error prone.

An approach to automated canopy gap delineation based solely on canopy height information was developed and evaluated within a Geographic Information System. Remote sensing can provide the required data enabling surveys of canopy gaps over large areas. Digital height models of sufficient resolution can be derived from laser scanning (LiDAR) or softcopy photogrammetry using digitized CIR imagery and digital terrain models. These techniques provide very

accurate height models for large areas with a minimum of human interaction. Based on the digital height models not only the number, size and distribution of gaps were analyzed but also other ecological parameters describing the morphology of the canopy surface. Data taken at four dates facilitate to study the dynamics of canopy gaps and canopy morphology, which has not been possible on a large scale so far.

2.1 Introduction

Canopy gaps play an essential role in continuous cover forests, as they have a strong effect on regeneration dynamics and species composition. They have been investigated in a number of studies, but predominantly mapped terrestrially (cf. Runkle 1982, Barden 1989, Runkle 1992, Leibundgut 1993, Emborg 1998, Tabaku and Meyer 1999). Only a few studies used remotely sensed data to map canopy gaps (cf. Brunig 1973, Tanaka and Nakashizuka 1997, Fox et al. 2000, Fujita et al. 2003, Nuske 2003). Canopy gaps and the canopy surface, especially, have been widely neglected in current monitoring and planning practices. This might be due to the fact that terrestrial as well as analogue photogrammetric measurements are particularly problematic in dense broadleaved stands. Blackburn and Milton (1996) conclude that automatic gap detection and large scale studies of gap dynamics will contribute to an enhanced ecological comprehension.

High resolution Canopy Height Models (CHM) can be used to study the morphology of the canopy layer, including canopy gaps. A CHM is usually given by an array of grid points representing the height of the vegetation, excluding the terrain. These CHMs may come from different sources. At the moment there are two main sources of high resolution CHMs of considerably large areas.

The most precise way to measure heights of forest canopy surfaces is to use an airborne LiDAR system (Baltsavias 1999). Since some of the laser pulses penetrate the vegetation, a Digital Terrain Model (DTM) and a Digital Surface Model (DSM) may be derived from the same dataset through appropriate filtering. The use of LIDAR data for forest applications is documented in a number of studies (Koch and Friedlaender 1999, Diedershagen et al. 2003, Lim et al. 2003). This method has a lot of potential, but is still far from being widely accepted, mainly because of its still high costs.

The derivation of DSM from aerial photographs by means of digital photogrammetry is a less expensive alternative that also offers other advantages. Since the use of aerial imagery is an old and widely used remote sensing technique, most of the German forests are covered as part of the standard forest inventory in a ten year cycle. Aerial imagery, thus, enables retrospective studies of the dynamics of forest canopies, and quantitative analyses of large areas. But, in order to build a CHM from this type of data, a DTM from another source is needed, since digital photogrammetry is only capable of calculating the height of the uppermost surface.

Based on the CHM, not only stand heights (cf. Nuske and Nieschulze 2004), but also number, size, and distribution of canopy gaps can be obtained. Appropriate methods for a highly automated process based on remote sensing and GIS will be developed. Gap delineations of four points in time are then used to study the dynamics of canopy gaps.

2.2 Material and methods

2.2.1 Study site

The study area “Limker Strang” is situated at 51°24′ N and 9°24′ E in southern Lower Saxony, Germany. For comparability reasons, the same boundaries used in previous studies done at the same site (Tabaku and Meyer 1999, Tabaku 2000) were chosen (cf. Figure 2.1).

The study site covers an area of 10 ha and the altitude ranges from 384 to 420 m above sea level. The area has a slight exposition towards the WNW- and ENE-Directions. The area has a suboceanic climate. The stand stocks on a medium to

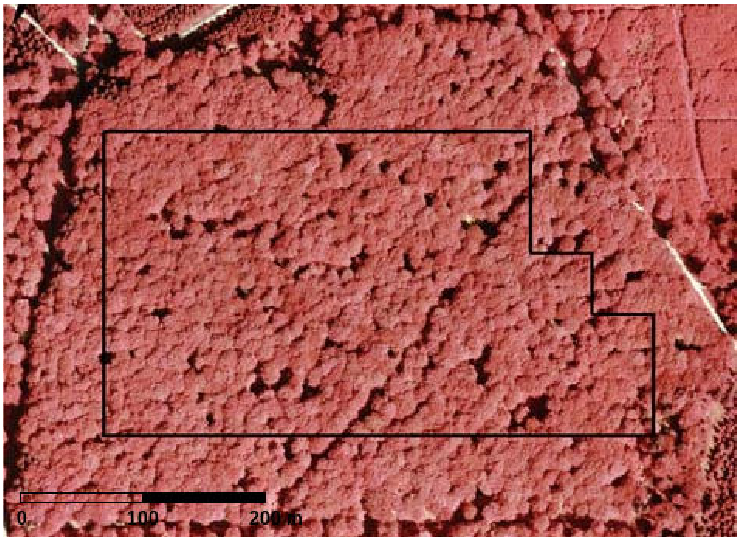

Figure 2.1: CIR-Image with study site boundaries.

deep brown soil with bedrock of New Red Sandstone. This results in a moderate nutrient supply and a moderately moist to moist water supply (Lamprecht et al. 1974, Otto 1991). The considered forest is a 153 year old unmanaged European beech stand (*Fagus sylvatica* L.), with only one main canopy layer. The stand is mainly closed but has gaps in some regions due to windthrow and previous salvage logging.

2.2.2 Aerial imagery

CIR aerial photographs from four dates were used (cf. Table 2.1). The flights were done with sufficient overlap during the vegetation period to provide a stereoscopic view on the canopy surface. For each date, a stereopair covering the study area was chosen for derivation of a DSM. The aerial photographs were provided as diapositives and scanned for further processing. The chosen resolution of 0.40 ± 0.05 m corresponds to the accepted opinion that the spatial resolution for photogrammetric vegetation measurements should be 0.1 to 0.5 m (Hall et al. 1998, Gong et al. 2000, Herwitz et al. 2000). Details of the georectification and the achieved precision are given in Table 2.1.

Table 2.1: Image and georectification details (values in brackets show the resolution after resampling).

Date of Flight	Nominal Scale	Spatial Resolution (m)	Total Number of GCPs	Number of Stereo-GCPs	X-RMSE (m)	Y-RMSE (m)
Aug. 1989	1:10500	0.36	16	4	0.87	0.74
Sept. 1992	1:600	0.22 (0.44)	16	5	1.48	1.23
Aug. 1998	1:13000	0.45	12	3	1.69	1.56
Sept. 2000	1:6000	0.20 (0.40)	15	4	1.24	1.27

2.2.3 Extraction of the canopy height model

The digitized and rectified stereopairs were used to automatically derive DSMs using digital photogrammetry methods. The matching algorithm employed by OrthoEngine (PCIGeomatics 2003) is based on image correlation, where homologous pixels are identified and the elevations are calculated based on their parallaxes. A postprocessing including noise removal and interpolation was carried out to enhance the quality of the DSM. The noise removal is used to discard any outliers or artefacts which may be in the DSM. A bilinear interpolation fills holes in the DSM that result from the matching or noise removal process.

The result is a digital image, which represents a landscape and its components, such as trees and buildings, by height above sea level. The ground elevation level must be subtracted in order to obtain canopy heights. In this study, a DTM provided by the cadastre service of Lower Saxony is employed. The difference in elevation yields a CHM.

2.2.4 Canopy gap delineation

Our gap definition follows Runkle's definition (1992), which defines a canopy gap as an area within a forest where the canopy is noticeably lower than in adjacent areas. The minimum gap area in this study was set to 20 m^2, without an upper limit. The gap dynamic was studied using the gap delineations of four different stereopairs. Superimposing the four gap delineations gives an impression of the change of the gaps over time. This combined gap delineation can be further investigated using a GIS.

Different methods of automatic canopy gap delineation were tested in a previous study (Nuske 2003). The adaptive median threshold was found to be most suitable. This method classifies that area as a canopy gap, which is lower than a reference height minus a certain range given by variability of the neighbourhood.

To create a reference height that is not influenced by the still to be detected gaps, the median of the height values of a moving window is used. The window has to be at least twice as large as the largest expected canopy gap to ensure that the median always represents a height value of the upper canopy. The interquartile distance serves as a fast and easy to calculate measure of dispersion. Hence, the classification threshold is calculated as the median minus the interquartile distance. The classification is based only on the distribution of the height values of the neighbourhood.

2.3 Results

The automatic gap delineation was compared to a manual gap delineation done with an analytic stereoplotter (cf. Figure 2.2). The canopy gap dynamics is shown in Table 2.2 and Figure 2.3.

Table 2.2: Area based canopy gap characteristics.

Year	Gap Density	Gap Area	Gap Size			
	(N/ha)	(%)	$\tilde{x}$ (m^2)	$\bar{x}$ (m^2)	s (m^2)	max (m^2)
1989	12.6	11.8	60.3	93.6	88.3	521.3
1992	10.7	10.9	61.0	101.6	109.4	646.8
1998	10.4	12.3	64.5	118.4	144.5	800.9
2000	10.8	9.8	55.6	91.4	101.6	523.5

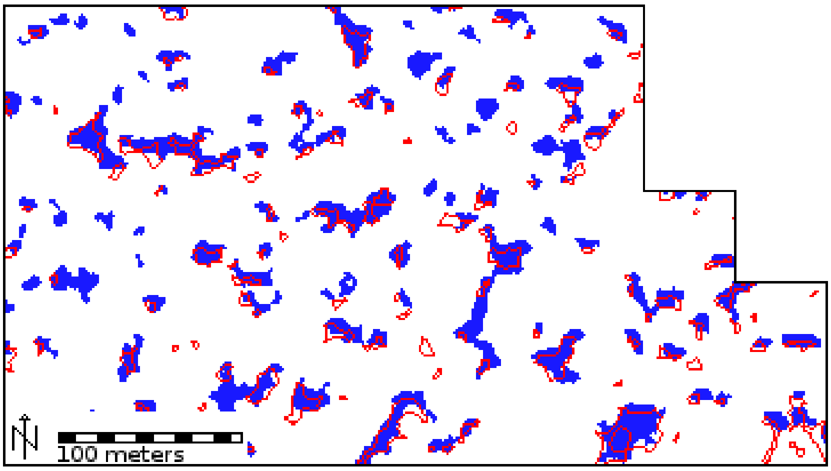

Figure 2.2: Automatic canopy gap delineation (blue area: automatic gap delineation; red polygon: manual gap delineation).

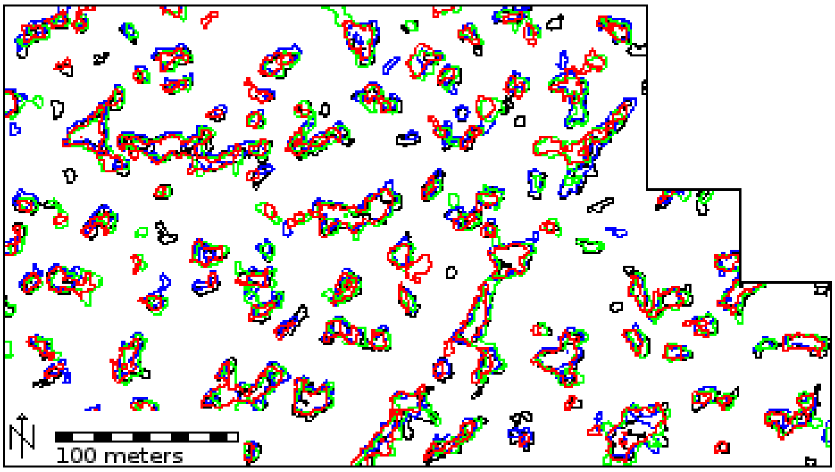

Figure 2.3: Canopy gap dynamics (black: 1989, blue: 1992, green: 1998, red: 2000).

2.4 Discussion

The Analysis of canopy surfaces can be automated using aerial imagery, digital photogrammetry, and a GIS. Because of the automation, this methodology can be applied on a large scale. It is a rather low-cost approach, using the software package OrthoEngine from PCI Geomatics (Brostuen et al. 2001) and the open source software GRASS GIS, which run on a standard PC. Although no high-tech equipment was chosen, we were able to produce results comparable to studies done on analytic stereoplotters.

The gap delineation approaches were assessed by means of a reference gap delineation based on the same stereopair. The manual delineation using an analytical stereoplotter was chosen as reference, because it was the gap delineation with the highest quality available. The comparison of the automatic gap delineation with the reference delineation showed only some differences. The shape of the gaps in both delineations matches approximately. All larger gaps delineated by the human interpreter were also detected by the automatic approach. The two delineations differ as regards the smaller canopy gaps. Some of the small manual delineated gaps were missed, but in general the automatic approach tends to find too many small gaps. This mismatch might be due to the limits of the human interpreter having particular problems judging the existence of very small gaps. On the other side the very simple gap delineation approach applied in this study does not handle small gaps too well. The lower limit of 20 m^2 gap area was chosen to represent a gap created by a large broken off branch. Since small gaps do not have a substantial influence on the forest ecosystem, it might be a good idea to increase the minimum gap size. That would not diminish the ecological relevance but could reduce the discrepancy of the two delineations.

The gap area found in this study is somewhat high (cf. Table 2.2) compared to other studies carried out on the same site, where values range from 3.0 to 11.0% (Spellmann et al. 2003). This might be caused by the different methodologies or by different gap definitions. However, one can see in Figure 2.3 that some of the smaller gaps vanish in the course of time and others appear. At a closer look, it is evident that more gaps vanish than arise. However, the larger gaps also tend to shrink, although this is harder to notice because of their fuzzy boundaries. The total gap area has a clear decreasing trend (cf. Table 2.2). The decline of the number of canopy gaps is reflected in gap density. These results agree with other studies in the same area (Spellmann 1991). These findings also agree with theoretical considerations that mature beech stands tend to close gaps via vertical growth of gap neighbouring trees and height growth of understorey trees (Meyer et al. 2003).

The demonstrated technique ensures reproducible results for large areas and at different points in time. Aerial photographs, which are the basis of this method, are raw information, and therefore independent of different measurement schemes. Thus, this method can be regarded as a very robust monitoring scheme. Aerial photographs of the studied stand taken during the last decades do not only enable studies on gap dynamics but also further ecological studies such as dynamic crown cover and dynamic stand structure, which have not been possible so far.

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3 Self-learning canopy gap mapping for aerial images using photogrammetric height, color and texture information

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Own contributions: Initiation of the study, procurement of aerial photographs, reference delineation of canopy gaps, generation of orthophotos and digital aerial photogrammetric height models, joint implementation of the method and interpretation of results, writing large part of the manuscript and finalization.

Abstract

To study the dynamics of canopy gaps one has to resort to archived aerial imagery, which is in contrast to modern data, such as LiDAR, much more demanding. The color information solely does not permit a reliable canopy gap mapping, since the upper crown has the same gray values as illuminated bushes down in a gap. The photogrammetric heights, derived from stereo images, provide this information but have prevalently failures within canopy gaps. However, the color and texture provides the missing information in these regions. The proposed method is a combination of a model driven identification of small sure canopy/gap spots, a support vector machine, which learns the characteristics of the given image and a graph cut based segmentation that maps finally the canopy gaps. On aerial imagery of three years (1989, 1995, and 2001) the new method was compared to an expert labeling. In all cases the combined usage of photogrammetric height, color and texture information led to better results than a classification based on the color or height information solely.

Keywords: canopy gaps, aerial images, digital photogrammetry, support vector machine, graph cut segmentation

3.1 Introduction

Near-natural forest management is at present the accepted silvicultural approach in most Central European countries, but reference values for forest dynamics are mostly missing (Röhrig 1997). A vital process in broadleaf forests is the formation and closure of canopy gaps. Survival and species composition of the regenerating cohort are determined by the size and shape of the gaps as well as the developmental stage of the forest. Canopy gaps have been investigated in a number of studies, but predominantly mapped terrestrially (cf. Runkle 1982, Tabaku and Meyer 1999, Emborg et al. 2000). Only a few studies used remotely sensed data to map canopy gaps (cf. Tanaka and Nakashizuka 1997, Fox et al. 2000, Fujita et al. 2003). But, canopy gaps have been widely neglected in current monitoring and planning practices. This might be due to the fact that terrestrial and analogue photogrammetric measurements are particularly labor-intensive, tedious, and error prone in dense broadleaved stands.

Our gap definition follows Runkle (1992), who defined a canopy gap as a small area within a forest where the canopy is noticeably lower than in adjacent areas. More precisely, we define all areas lower than 2/3 of the surrounding tree heights to be canopy gaps.

It is straightforward to map canopy gaps using modern data such as LiDAR, providing precise and dense height measurements of the crown layer and the ground (cf. Koukoulas and Blackburn 2004, Mathys 2005). But the development of forests is much slower than the technological progress. Therefore, the only reasonable way to study the dynamics of canopy gaps is to deploy archived aerial images, which are analogue and of varying quality regarding scale and color. The color information does not permit a reliable canopy gap mapping, since the upper crown has the same gray values as illuminated bushes down in a gap. Though digital height models of the forest canopy can be derived using digital photogrammetry, they do not supply the needed accuracy. Height information might be even missing due to failures of the image matching process, which fails prevalently within canopy gaps. However, the color and texture can provide the missing information in these regions.

The challenge therefore is to combine the available heterogeneous data (height, color and texture) with their spatially varying ability to predict a canopy gap to an objective and reproducible measure.

3.2 Material

The study was carried out with data from a forest reserve. The 150 years old pure European beech stand is unmanaged for about 30 years. The site is part of the Nationalpark Eifel, which is located in North-Rhine Westphalia 60 km west of Bonn.

To investigate the robustness of the method Color Infrared aerial photographs from three dates were employed (cf. Table 3.1). The flights were done with sufficient overlap during the vegetation period to provide a stereoscopic view on the canopy surface. The images were then scanned on a photogrammetric scanner. The chosen resolution of about 0,20 m corresponds to the accepted opinion that the spatial resolution for photogrammetric vegetation measurements should be 0.1 to 0.5 m (cf. Hall et al. 1998, Gong et al. 2000, Herwitz et al. 2000) and is twice the size of the original pixel size, which is known to provide more reliable height models in Orthoengine (PCIGeomatics 2003). A digital terrain model (DTM) with a resolution of 1 m derived from LiDAR data was available for the site. The LiDAR data were recorded between February and May 2004 before the trees were fully foliated.

Table 3.1: Image and details of the georectification (values in brackets show original resolution of the aerial images).

	1989	**1995**	**2001**
# Images	5	4	4
Pixel Size	0.14 (0.07)	0.18 (0.09)	0.18 (0.09)
# GCPs	18	22	11
X-RMSE	0.20	0.26	0.26
Y-RMSE	0.27	0.23	0.37

3.3 Method

Our proposed method is based on the fact that it is usually possible (even on a complete new image) to automatically identify some small spots that surely belong to canopy or gap respectively. From these regions we learn the desired statistics by training a support vector machine with Platt's probability estimates and use the learned model to predict the canopy/gap-probability for each remaining pixel in the image. The final regions are found with a graphcut algorithm as the global optimum, which satisfies the pixel-wise gap-probabilities and the gap-edge probabilities between neighboring pixels. The detailed steps are described in the following sections.

3.3.1 Preprocessing

The scanned aerial images of the year 1995 were rectified using mainly signaled ground control points, whose positions were accurately measured on the ground. The years 1989 and 2001 were coregistered to those images.

Photogrammetric heights above mean sea level were derived using an image matching procedure in Orthoengine (PCIGeomatics 2003). Canopy height models were constructed subtracting the DTM from the photogrammetric heights. These were then median filtered and scaled to 2/3 to obtain the parting plane of gap and canopy. Differing from common procedure, the orthophotos were orthorectified using a DTM plus the median smoothed surface model at 2/3 of the tree heights. This ensures pixel-wise correspondence of the color of both orthophotos with the height information at gap borders.

A shading correction was carried out for the two orthophotos by normalization with the illumination intensity. The intensity was estimated by dilation with a disk of 15 m radius and subsequent smoothing with the same radius.

3.3.2 Finding training areas

Small spots that are surely located in a gap or are surely located on the canopy for the training of the support vector machine (Vapnik 1995) were found through relative gray value threshold and height threshold relative to the median height.

The gray value threshold for sure gaps is determined by dilation with a square of 4 m × 4 m and global minimum of resulting image (assuming that at least one gap with at least 4 m × 4 m is present in the image). The height thresholds for sure gap and canopy pixels were established significantly above and below the parting plane at 0.5 and 0.8 of median height, respectively. Ranked by the score of the image matching process only the best 15% of the heights values were selected as training pixels.

The gray values within gaps and canopy show much more variation than the subset selected by the thresholds. To find additional sure gap pixels, the spatial arrangement of the already found pixels is used. Gap and canopy training pixels are added, if there is no training pixel of the other class in a radius of 2 m and if in this area in each of 6 “pie slices” is at least one pixel of the same class exists. This procedure is applied 5 times.

3.3.3 Training

The height, score, color, and texture values of the training pixels are used to train a support vector machine to recognize canopy and gap pixels. The texture value is generated by taking the 3×3 neighborhood of each pixel. Thus, the pixel-wise feature vector contains 20 features:

- height relative to median height,
- score from image matching,
- 9 gray values from left orthophoto,
- 9 gray values from right orthophoto.

The relative weight of the different feature types within this feature vector were specified manually.

For a faster training the number of gap training pixels is representatively reduced to a maximum of 5000 samples and the canopy training pixels to a maximum of twice the number of gap training pixels.

A support vector machine with an RBF kernel (radial basis function) is trained with this training set. The two training parameters γ ("width" of radial basis function) and c (cost for outliers in training data set) were adjusted manually such that the number of resulting support vectors was a few hundred. The same training data set is used to learn a mapping of the resulting decision values (ranging from $-\infty$ to $+\infty$) to probabilities (Platt 1999).

3.3.4 Classification of all pixels of the image

The support vector machine is now used to classify all pixels in the image, and to compute for each of them the probability to belong to gap or canopy class.

The resulting pixel-wise probabilities are noisy such that a simple threshold at a probability of 0.5 results in noisy borders. The final smooth borders are found by a graph cut approach (Boykov and Kolmogorov 2004). The input data for the graph cut are the gap/canopy probabilities for each pixel. Additionally, the pair wise probabilities that two neighboring pixels belong to the same class are computed from the derivates of the decision values and are used within the graph cut. Basing on this information the graph cut is able to find the optimal gap mask with the highest overall probability.

3.3.5 Validation of the results

The gap mask found by the proposed methods $M_{computer}$ is compared pixelwisely to a gap mask which was produced independently by an expert using a analytical stereoplotter M_{expert}. The statistical measures for a quantitative description of the results are precision and recall:

$$\text{recall} = \frac{||M_{expert} \cap M_{computer}||}{||M_{expert}||}$$

$$\text{precision} = \frac{||M_{expert} \cap M_{computer}||}{||M_{computer}||}$$

The recall describes the fraction of true gap pixels that are found by the computer. The precision describes which fraction of the gap pixels that are found by the computer are true gap pixels. An ideal system has a recall of 100% and a precision of 100%.

The reached precision/recall of the proposed method is compared to the precision/recall that could be reached if only gray values or only heights are taken into account. For the later the precision/recall for all possible thresholds is computed (0-255 for the gray values, and 0-1 for the normalized height) and shown in the diagram, which results in a curve.

3.4 Results

A typical example for a manually and automatically extracted canopy gap is shown in Figure 3.1. The quality measures for the three years are shown in Table 3.2. In all studied areas the proposed method shows a significant better precision/recall than a classification based on one type of information only (see Fig. 3.2).

Table 3.2: Classification results for the three years.

Year	Precision (%)	Recall (%)
1989	67.7	78.6
1995	77.0	75.2
2001	76.4	57.2

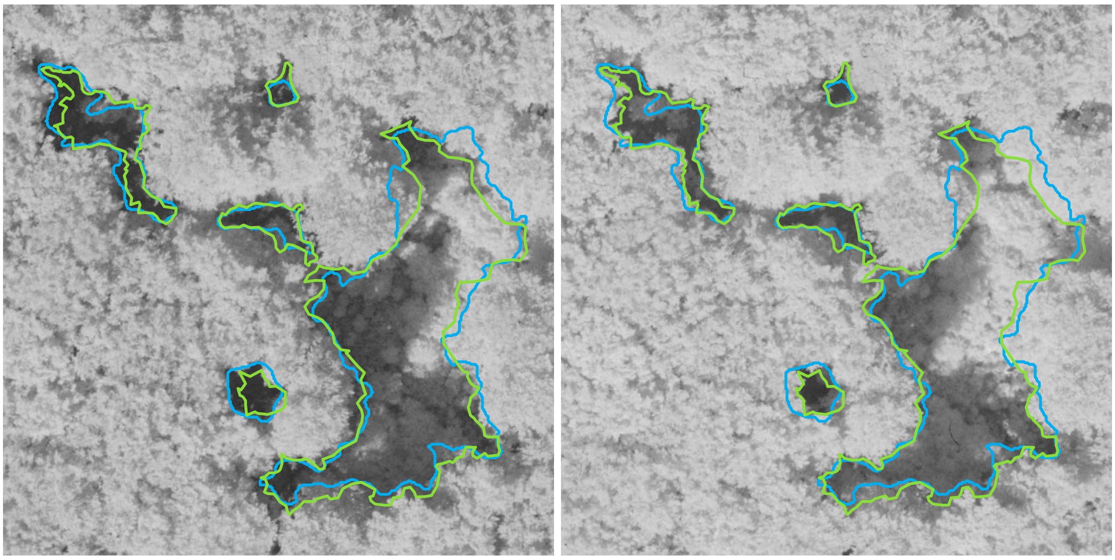

Figure 3.1: Subset of the red channel of left (left panel) and right (right panel) orthophoto (year 1995) overlaid with M_{expert} (green line) and M_{computer} (blue line).

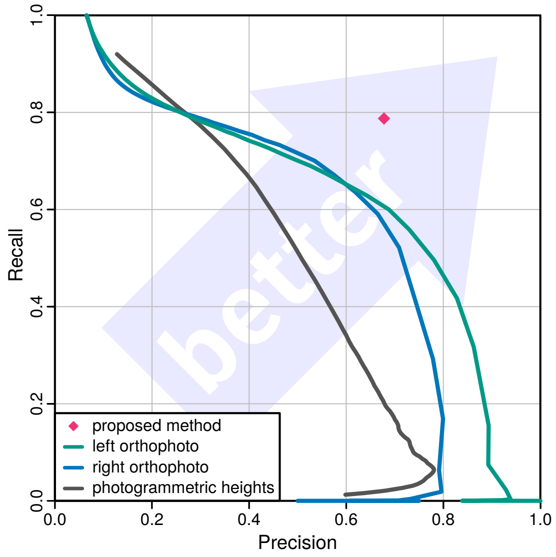

Figure 3.2: Comparison of automatic gap maps with expert mapping on data of the year 1989. The lines show the results of a classification solely based on the respective value. The threshold used for classification changes along the line. The proposed method is symbolized by a cross.

3.5 Conclusion and outlook

The results show that a significant improvement can be obtained by the combination of different data sources. The computed precision and recall are well suited statistical measures to describe relative improvements. For an absolute quality description these measures are somewhat limited in their expressiveness, because already small systematic displacements between the manually and automatically created gap masks result in a significant decrease of precision and recall. Such systematic displacements often appear, because the expert or the computer may put a higher weight on the brighter and therefore more dominant left or on the right stereo image (cf. Fig. 3.1). This is the main reason for the relatively low absolute precision/recall. The shown masks in Figure 3.1 might therefore give a less biased impression of the overall performance of the system.

However, the proposed method seems to be the first viable approach to support the deployment of archived aerial imagery for investigation of canopy dynamics on a larger scale.

The next steps are the analysis of gap dynamics based on the automatically delineated canopy gaps. We assume that the differences between manually and automatically obtained parameters describing gap dynamics will be much lower, because a systematic displacement does not affect the characteristics of the dynamic effects.

Another possibility for further improvements are an automatic determination of those parameters that needed to be fixed manually in the current approach, like the thresholds for “sure” gap or canopy spots or the relative weights for the different data sources.

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4 Mapping canopy gaps in Hessian beech-dominated strict forest reserves using airborne laser scanning data

4.1 Introduction

Strict forest reserves exist in Hesse since 1988. These are formerly managed forests that have been set aside and dedicated to free development. No kind of forest management is practiced anymore in strict forest reserves. Only hunting is continued to prevent excessive growth of the game population, which in turn would impede the natural regeneration of native tree species. The strict forest reserves were selected in such a way that they represent the forest communities typical of Hesse. There are currently 31 strict forest reserves distributed throughout Hesse. They cover a wide range of forest communities, elevations, bedrocks, soils and climatic conditions (NW-FVA and HessenForst 2012).

Without human influence, more than 90% of the Hessian land area would be occupied by beech forests (Bohn et al. 2000). Accordingly, the Hessian strict forest reserves mainly comprise beech forests, but also oak, pine and spruce forests (NW-FVA and HessenForst 2012). In this study, 16 beech-dominated strict forest reserves are investigated (see Figure 4.1).

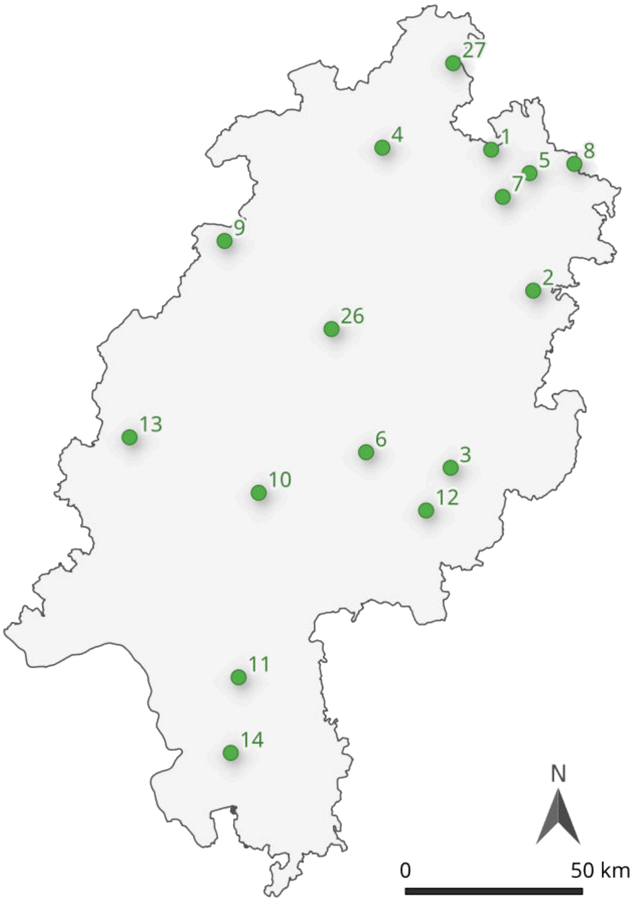

Figure 4.1: Investigated strict forest reserves in Hesse (numbers are the official IDs, see Table 4.1).

The development of the Hessian strict forest reserves is scientifically accompanied by the Nordwestdeutschen Forstlichen Versuchsanstalt and the Senckenberg Institute. The research focuses on forest structure, herbaceous vegetation as well as forest dynamics by means of repeated surveys. An intensive zoological survey is carried out in selected strict forest reserves (NW-FVA and HessenForst 2012). It was already possible to gain insights into the growth dynamics, competitive power and regeneration of native tree species, deadwood dynamics and forest development after disturbances as well as the composition of forest fauna and vegetation (Schmidt et al. 2018). A detailed investigation of canopy gaps has not yet been carried out in Hessian strict forest reserves.

Canopy gaps are openings in the main canopy layer created by the loss of one or a few canopy trees or at least of a strong branch. In the scope of this study, canopy gaps are, according to Brokaw (1982) and Runkle (1992), defined as areas within a forest where there is an opening in the canopy and the vegetation does not reach the main canopy layer. Following the IUFRO definition (Leibundgut 1956), the main canopy layer is described as the upper third of the stand height. The threshold for separating canopy and gap is set at two-thirds of the canopy height. The minimum gap area in this study was set to 5 m^2, without an upper limit.

A good basis for mapping canopy gaps is provided by airborne laser scanning (ALS) carried out for entire Hesse. Numerous studies have verified the capacity of ALS to measure canopy height and canopy vertical structure in a variety of forest ecosystems (e.g. Harding et al. 2001, Parker et al. 2001, Clark et al. 2004). Studies have also shown that retrieval of ground elevations by ALS is superior to that of other means of remote sensing (Clark et al. 2004, Hodgson et al. 2005). Recent studies have demonstrated the potential of ALS for delineating canopy gaps (Koukoulas and Blackburn 2004, Yu et al. 2004, Vepakomma et al. 2008, 2012, White et al. 2018).

According to White et al. (2018), there are two main methods for mapping canopy gaps based on ALS: fixed and relative thresholds. Fixed thresholds characterize all points or pixels below a fixed height as gap. Common thresholds range from 2 m (Brokaw 1982) to 10 m (Hunter et al. 2015). Relative thresholds offer, among other things, the possibility to map canopy gaps, even if no digital terrain model is available (Betts et al. 2005), or to adapt to changing conditions within the stand. The mapping of canopy gaps with the fixed and relative thresholds is mostly done on raster data (White et al. 2018) because of higher processing speed. Gaulton and Malthus (2010) describe a procedure that operates directly on the point cloud. This method offers a slightly higher accuracy although with considerably longer processing times.

This study describes an automated method for mapping canopy gaps in beech-dominated strict forest reserves of various ages based on relative thresholds using airborne laser scanning data provided as a standard data product by a land surveying office.

4.2 Material and methods

4.2.1 Study sites

The study comprises 22 sites in 16 beech-dominated Hessian strict forest reserves (see Figure 4.1 and Table 4.1). Most of the strict forest reserves consist of a number of distinct parts (former compartments), some of which had a high variability in terms of stand age and forest structure at the time of reserve designation. Canopy gaps are only meaningful features of forest structure if the canopy of the stand is more or less closed. Therefore, the natural forest reserves were divided along former compartment boundaries into homogeneous areas excluding roads (see Table 4.2). A description of the considered strict forest reserves with a focus on the selected study sites is given in Table 4.1.

Table 4.1: Description of the investigated strict forest reserves in Hesse. (NWID and Name: official identification and name, Desig.: year of reserve designation, Soil: description of soil and bedrock, Elev.: min-max elevation a.s.l., Precip.: annual precipitation sum, Temp.: annual mean temperature. Climate data according to Gauer and Aldinger (2005)).

NWID	Name	Desig.	Soil	Elev. (m)	Precip. (mm)	Temp. (°C)
1	Niestehänge	1988	red sandstone	480-550	994	7.0
2	Goldbachs- u. Ziebachsrück	1988	loessloam / sandstone	295-370	748	8.1
3	Schönbuche	1988	red sandstone	390-455	886	7.4
4	Wattenberg u. Hundsberg	1988	loess loam / basalt	410-510	798	7.4
5	Meißner	1988	basalt	645-745	997	7.0
6	Niddahänge ö. Rudingshain	1988	loess loam / basalt	540-630	1250	6.5
7	Ruine Reichenbach	1988	shell limestone	450-525	899	7.3
8	Hohestein	1989	limestone / loess	475-555	923	7.0
9	Hasenblick	1988	loess loam / clay slate	385-470	944	7.2
10	Waldgebiet ö. Oppershofen	1988	(calcareous) loess loam	230-245	698	8.6
11	Hegbach	1988	rotliegend formation	135-150	726	9.6
12	Weiherskopf	1989	loess loam / basalt	380-415	967	8.0
13	Kreuzberg	1989	loess loam / basalt	270-360	902	8.1
14	Kniebrecht	1989	loess loam / gneiss	215-310	911	9.1
26	Hundsrück	1993	loess loam	290-305	712	8.0
27	Weserhänge	1997	red sandstone	420-470	836	7.6

4.2.2 Airborne laser scanning data

In this study a standard data product of airborne laser scanning data of the Hessian land surveying office (Hessische Verwaltung für Bodenmanagement und Geoinformation, HVBG) was used. An accuracy of about 15 cm in height and 30 cm in position was aimed at (HVBG 2016a). The data came from two campaigns. The first campaign was carried out in the period 2009 to 2014 and the second started in 2015 and is still ongoing (HVBG 2018). The data is available as 2 km × 2 km tiles. Parts of tiles covering the strict forest reserves were kindly provided by the Hessian state forest enterprise (HessenForst, see Table 4.2).

Table 4.2: Characteristics of the study sites and respective airborne laser scanning data. (ID: identification of the study sites, NWID: identification of the strict forest reserve (see Table 4.1), Area: size of the study site, Stand age: age at ALS acquisition according to taxation, ALS acq.: year of acquisition of ALS data, Pulse density: mean number of laser pulses, Ground pt. density: mean number of points classified as ground, Total pt. density: mean number of all points).

ID	NWID	Area (ha)	Stand age (yrs)	ALS acq. (yr)	Pulse density (m^{-2})	Ground pt. density (m^{-2})	Total pt. density (m^{-2})
1	1	17.2	126-158	2012	11.1	5.9	17.7
2	2	13.2	157	2012	9.9	5.3	14.0
3	2	14.2	159	2012	9.3	4.9	13.2
4	3	23.1	179	2012	6.1	3.8	11.9
5	4	8.9	116-178	2010	6.4	1.8	11.7
6	4	10.1	205	2010	6.2	1.8	12.5
7	5	9.2	183	2017	13.5	10.5	44.1
8	5	19.2	121	2017	17.6	14.4	57.2
9	6	9.8	171	2011	6.1	5.4	9.7
10	6	15.7	149-185	2011	6.2	5.3	10.5
11	7	13.0	81-91	2012	11.9	10.9	32.5
12	8	9.0	156	2017	15.8	16.2	55.0
13	9	40.2	177	2017	16.6	13.7	44.7
14	10	19.7	155	2014	6.5	5.8	10.3
15	11	5.3	65	2016	16.3	13.4	32.2
16	11	9.8	213	2016	13.7	12.7	31.9
17	12	11.6	80	2012	5.8	5.1	11.6
18	13	12.8	193	2014	7.6	5.9	15.3
19	13	13.1	167	2014	7.2	5.2	15.1
20	14	16.8	67-92	2016	20.4	17.6	59.4
21	26	18.4	220	2016	7.2	6.0	17.0
22	27	6.8	69-84	2010	5.9	1.9	11.5

The pulse density (first return point density) was very different for the study sites ranging from 5.8 m^{-2} to 20.4 m^{-2}. The total point density varied even more because the number of returns per pulse increased over the years. Another interesting density is the number of points classified as ground per square meter as they are the basis of the digital terrain model. They ranged from 1.8 m^{-2} up to 17.6 m^{-2}. All laser point densities varied also considerably within the study sites and increased over time (see Table 4.2). Study sites from the same strict forest reserve have usually very similar point densities. Since the tiles are commodity products, no further information about flying heights or laser and navigation instruments was available for the individual tiles. The points of all tiles were already classified in ground and non-ground points. Most tiles were preprocessed according to high quality standards with only few tiles containing spurious points way above the main canopy layer due to clouds or high noise.

4.2.3 Canopy gap delineation

The tiles of airborne laser scanning data were separated in ground and non-ground point clouds using the provided classification. The two point clouds were then transformed into two separate regular raster of 1 m grid spacing. Finer resolutions were tested but were not feasible because of too many and too large areas of missing data in the raster datasets compromising further processing. The digital terrain model (DTM) was constructed from the ground points using a surface interpolation by regularized spline with tension over the entire area. The digital surface model (DSM) describing the top of the vegetation was obtained by taking the highest ALS point within each raster cell while discarding vegetation heights below -5 m and above 50 m (cf. Bonnet et al. 2015). Since the first return point density varied considerably within the investigated study sites, there were usually a few areas with no information. These were filled by local spline interpolations. The canopy height model (CHM) containing the height of the vegetation above ground is generated by subtracting the DTM from the DSM. The strategy of choosing the highest point per cell avoids unrealistic pits and spikes, which often result from triangular irregular network interpolations of first return points (Khosravipour et al. 2016).

Canopy gaps are then mapped based on the CHM by a two-part relative threshold. The first part is the median height of the entire stand. The second part is a local median height calculated for every pixel using a circular moving window with a diameter of 49 m. The stand height was characterized by the median because it is robust against remaining outliers and substantially lower heights of the vegetation within gaps. The size of the circular moving window was chosen so that it never "sinks" into a gap. At least half of the moving window should at every time be filled with pixels of the main canopy. The combined threshold of two-thirds of the local median or the stand median is subsequently applied to every pixel. All pixels below the combined threshold are classified as raw gap pixels according to

$$\mathbf{Gap}(x) = \begin{cases} 1 & \text{if} \quad < \ 2/3\, max(med(X),\ med(L(x))) \\ 0 & \text{else} \end{cases}$$

with X being all pixels of the CHM of the study site, x one pixel and $L(x)$ the pixels of a circular moving window with 49 m diameter centered at the location of the pixel x.

In a subsequent step, all gap pixel groups of less than 5 m^2 were removed. The ragged boundaries of the remaining gap areas were smoothed by mathematical morphology using one pixel dilation followed by one pixel erosion (see Figure 4.2). This fills presumably artificial small fjord like structures and thin channels. The resulting gap areas were then transformed to a vector representation. To get rid of the step-like boundaries of the polygons they were smoothed lightly with an active contour approach (see Figure 4.2). Finally, the gap map was clipped to the study site and remaining gaps smaller than 5 m^2 were excluded. All processing was done in GRASS GIS 7.6.1 (Neteler et al. 2012, GRASS Development Team 2019).

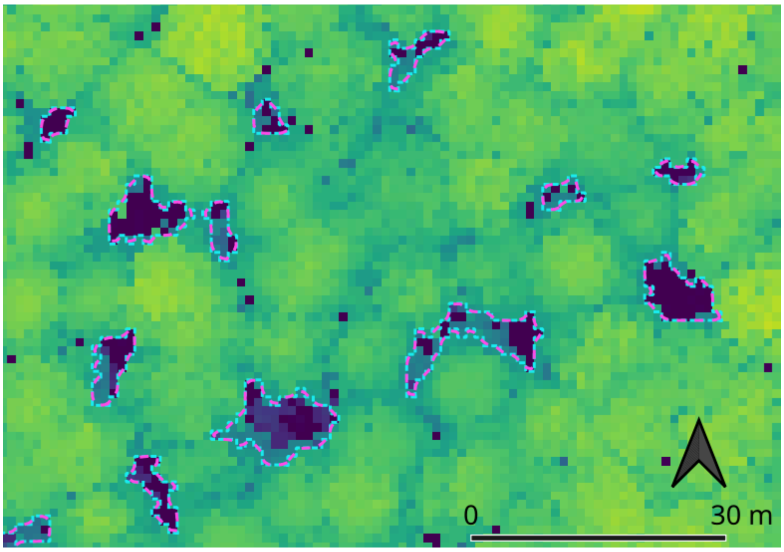

Figure 4.2: Subset of the canopy height model of study site 2 (values from 0 m in dark blue to 41 m in yellow) with raw raster gaps (light blue outline) and final vector gaps (pink outline).

4.3 Results

Gap maps of all study sites are shown in Figure 4.3, 4.4 and 4.5. The canopy gap maps of the studied stands differ substantially. The number of gaps per hectare ranges from 1.1 ha^{-1} to 23.5 ha^{-1} and the gap fraction varies also from 0.2% to 20.6%. The arithmetic mean of the gap size is 17.1-151.2 m^2. The median of the gap sizes is much smaller at 9.0-34.8 m^2. Common parameters describing the gap area, the number of gaps per hectare, the proportion of forest area in gaps within the study area and the gap shape are given in Table 4.3.

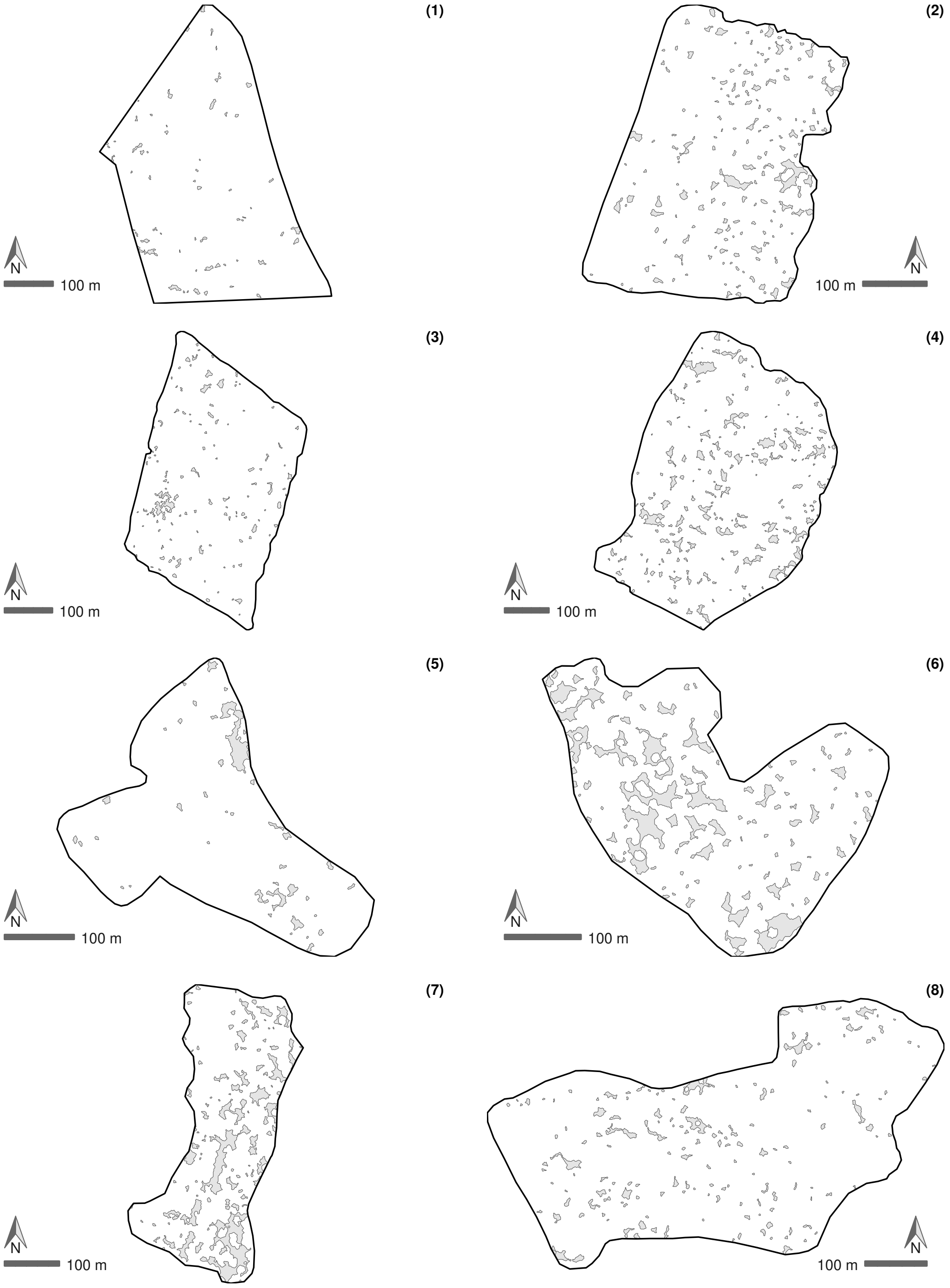

Figure 4.3: Maps of canopy gap patterns (gray) and study areas (black outline) of the sites 1 to 8.

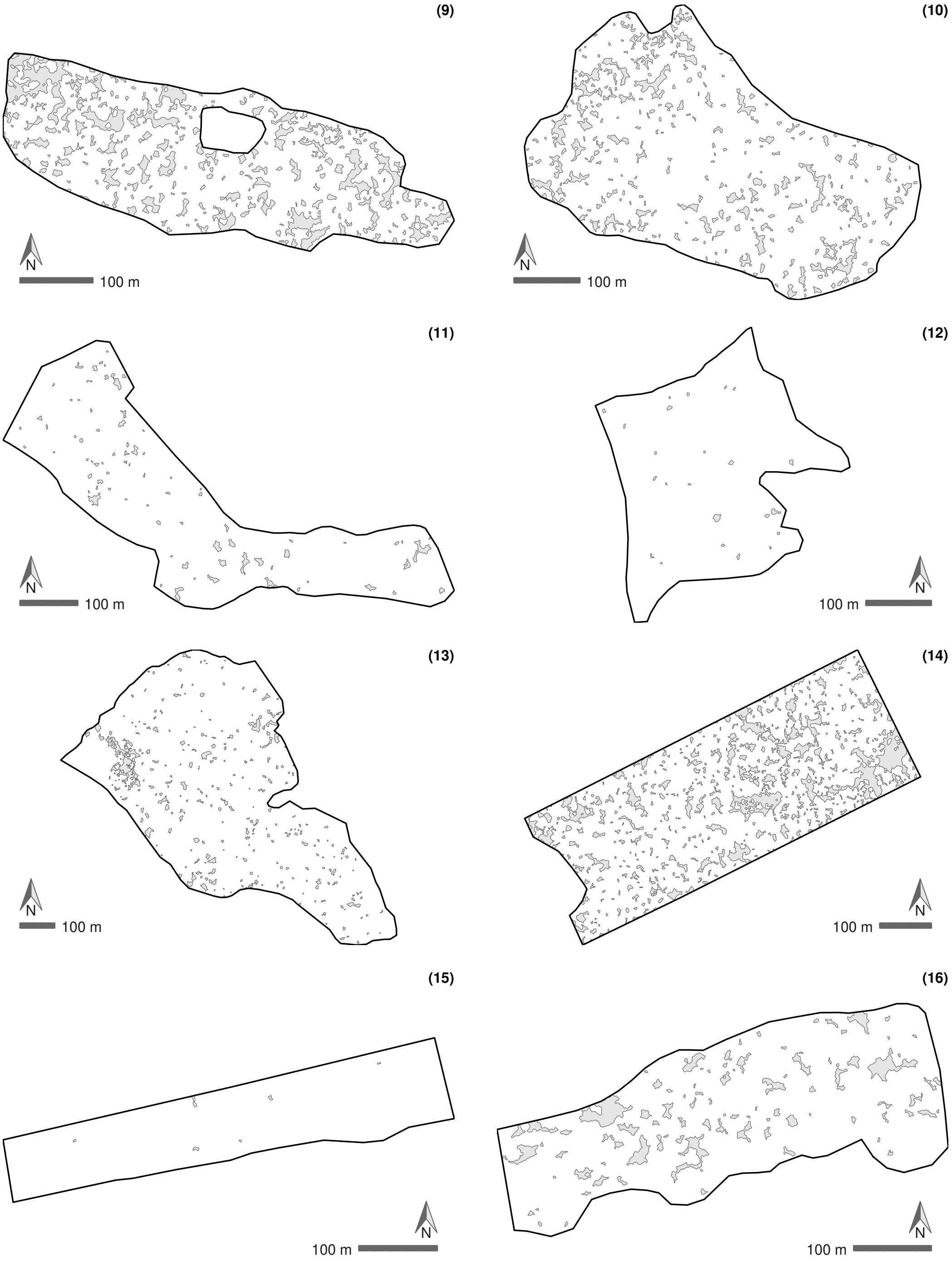

Figure 4.4: Maps of canopy gap patterns (gray) and study areas (black outline) of the sites 9 to 16.

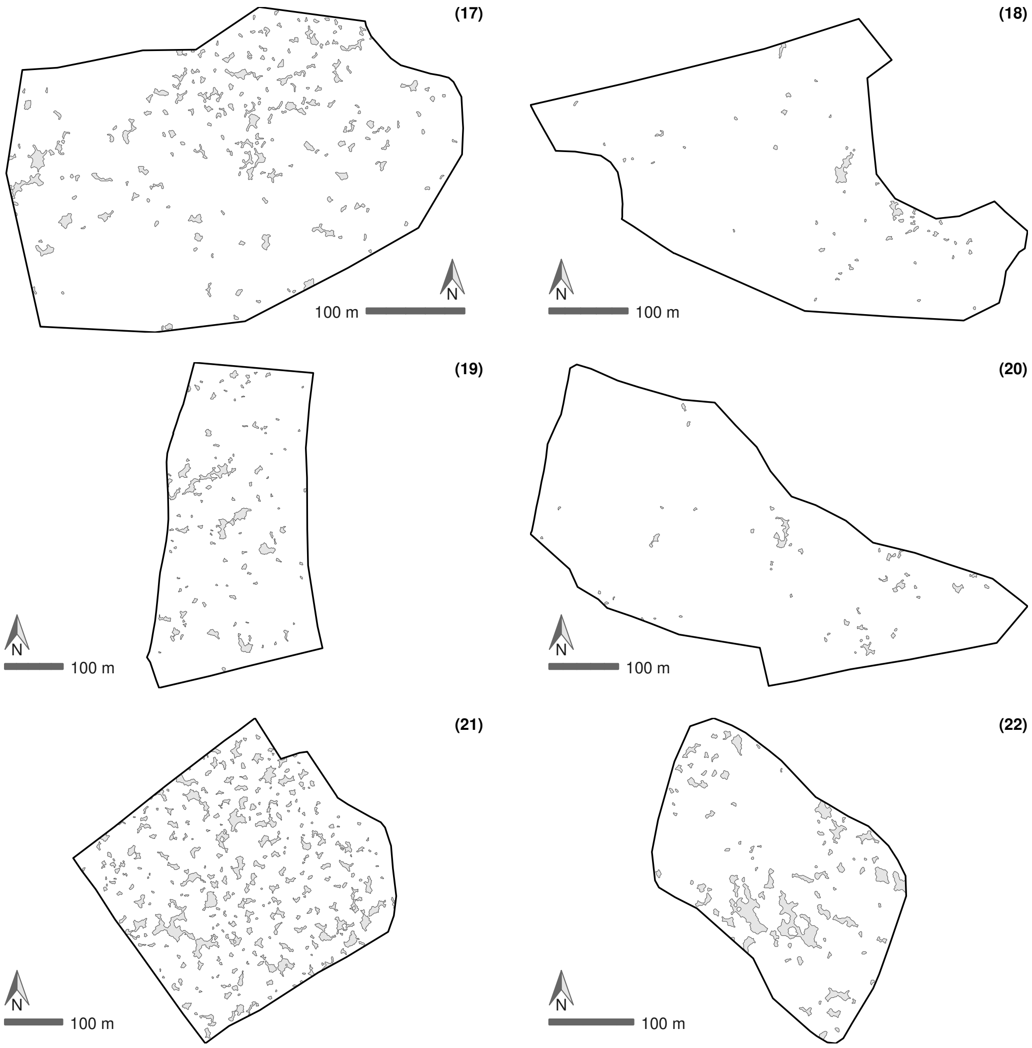

Figure 4.5: Maps of canopy gap patterns (gray) and study areas (black outline) of the sites 17 to 22.

Table 4.3: Overview of the most important gap geometry properties of the study sites. (ID: identification of the study site (see Table 4.2), Density: number of gaps per hectare, Fraction: proportion of forest area in gaps, Size: statistical description of gap sizes, Compactness: description of the shape of gaps, $perimeter/sqrt(4\,\pi\,area)$).

ID	Density	Fraction	Size				Compactness	
	(N/ha)	(%)	$\tilde{x}$ (m^2)	$\bar{x}$ (m^2)	s (m^2)	max (m^2)	$\bar{x}$ (m^2)	max (m^2)
1	3.7	1.3	20.9	36.0	41.8	225.1	1.4	2.8
2	13.3	5.2	17.8	39.2	78.3	829.0	1.3	2.8
3	8.5	2.6	13.9	30.5	71.1	738.3	1.3	3.7
4	8.5	7.1	30.9	83.9	146.0	1251.4	1.4	2.8
5	4.4	3.7	26.9	84.8	250.2	1575.6	1.4	2.8
6	10.7	14.0	31.9	130.1	277.5	1751.3	1.4	3.2
7	10.7	16.2	34.8	151.2	434.6	3644.3	1.5	4.1
8	8.8	3.8	17.9	42.7	69.4	451.5	1.3	2.8
9	22.7	20.6	25.9	90.9	249.0	3077.5	1.5	3.7
10	18.5	9.9	18.0	53.1	93.9	773.9	1.5	3.9
11	6.2	2.5	14.4	40.6	57.6	341.5	1.3	2.3
12	2.6	0.5	13.9	20.8	20.8	91.8	1.2	1.6
13	6.8	3.9	22.4	57.7	195.4	3069.8	1.3	4.4
14	23.5	17.1	15.9	73.1	240.7	2881.3	1.5	3.9
15	1.1	0.2	13.9	17.1	13.2	39.8	1.3	1.8
16	10.1	8.8	28.9	87.3	173.6	1258.5	1.5	3.5
17	17.8	4.3	12.9	24.1	29.9	223.1	1.4	2.5
18	3.8	0.9	9.0	23.7	54.3	351.0	1.3	2.0
19	7.6	3.8	17.9	50.4	103.2	735.0	1.4	3.2
20	2.7	0.9	13.9	32.4	54.2	334.7	1.3	2.9
21	14.9	11.3	34.8	75.5	124.2	1381.3	1.4	3.4
22	12.2	8.8	24.9	72.0	154.6	1068.8	1.4	2.8

4.4 Discussion

Automated mapping of canopy gaps using a two-part relative threshold provided good results. The quality of the canopy gap map was assessed visually by overlaying the automatic mapping into the original point cloud. A comparison with a terrestrial canopy gap survey or an expert mapping using other remote sensing sources did not seem reasonable, as airborne laser scanning is currently the most precise measurement of vegetation heights (White et al. 2016). The resulting maps of entire stands with areas from 5.3 ha up to 40.2 ha enables a detailed description of the canopy gap patterns including the analysis of the spatial distribution of gaps. Using raster canopy height models, derived from the original point clouds, allowed a simpler formulation of the algorithm and a very fast processing. This is in accordance with recent studies (Vepakomma et al. 2008, White et al. 2018). Only very few studies used the point cloud directly (e.g. Gaulton and Malthus 2010). Gaulton and Malthus (2010) found a very small increase in gap detection accuracy of 3.7% compared to processing of a raster canopy height model. The authors noted that the use of the point cloud was "considerably more computationally demanding" and may not be justified over large areas given the relatively low gain in recognition accuracy.

The combination of a local and a stand-wide component in the two-part relative threshold enabled local growth differences to be taken into account and ensured to not miss overly large canopy gaps. Some of the study sites had regions of slightly higher canopy, which might be due to better growing conditions. The moving window part of the two-part threshold will provide a local canopy height so that the relative threshold still separates between the main canopy layer and gaps, even in regions of higher canopy. The stand-wide median warrants that the reference height never falls below a sensible canopy height, which might be the case for the moving window median in extremely large canopy gaps or if too many gaps are very close together.

The standard airborne laser scanning data product offered by the Hessian land surveying office proved to be a good data source for canopy gap mapping. The first return point density varied considerably. However, none of the study sites had a first return point density below 5 m^{-2}. About halve of the study sites had densities between 5 m^{-2} and 10 m^{-2} which is comparable to the densities reported by Vepakomma et al. (2012). Only one of the study sites had a first return density as high as reported by Bonnet et al. (2015). All point densities were sufficient for generating a raster of 1 m resolution, which is also the resolution of the main product "DGM1" derived from these ALS data by the official land surveying office. The generation of a finer spatial resolution and more realistic digital surface model could be feasible by using the spike-free algorithm for generating height models from ALS point clouds, which was specially developed for forest applications (Khosravipour et al. 2016). A spatial resolution of 0.5 m might have captured more details along the border of the canopy gaps, but would also increase the processing time by a factor of four. Nevertheless, 1 m is a common spatial resolution for canopy gap studies based on airborne laser scanning data (e.g. Gaulton and Malthus 2010, Blackburn et al. 2014, White et al. 2018). Most tiles have received a very good preprocessing and showed only a negligible number of outliers. Very few tiles contained noteworthy outliers, which would have resulted in vegetation height well above 100 m. They were filtered out during the construction of the digital surface model. The remaining less distinct outliers did not influence the DSM or gap mapping due to the usage of the median for determining local and stand-wide canopy heights.

Compared to other remote sensing data, ALS is still a young technology, so that only very short time series are available. So far, only very few studies have dealt with gap dynamics based on ALS (e.g. Vepakomma et al. 2008, 2012, Blackburn et al. 2014, Choi et al. 2019). At the moment for most areas of Hesse there is only one ALS recording. The "Laserscan 2" campaign doing a second recording just started a few years ago and is expected to last until 2021. By then, there will be two ALS recordings with a time interval of approximately 6 years (HVBG 2018). It is not clear whether there will be further ALS campaigns in the future. The HVBG indicated its intention to carry out future updates of the digital terrain and surface models using digital photogrammetry based on stereoscopic aerial imagery (HVBG 2016b). So it remains open whether there will be ALS data in the future covering a meaningful period of time for investigating canopy gap dynamics for entire Hesse. The tiles provided by the Hessian land surveying office contained only the most recent data. If the dynamics of canopy gaps are the main objective, archived aerial images, which extend over longer periods of time, have to be used. Although gap mapping is much more labor-intensive when performed by a human interpreter or much more complex to do well automatically on the basis of stereopairs of aerial images, it offers the ability to examine past canopy gap dynamics (e.g. Meyer and Ackermann 2004, Nuske 2006, Nuske et al. 2007).

The canopy gap patterns of the studied sites differed substantially. The number of gaps per hectare ranged from 1.1 ha^{-1} to 23.5 ha^{-1} and the gap fraction varied from 0.2% to 20.6%. Half of the study sites had a gap fraction of less than 5% and a quarter of the study sites had more than 10% gaps. Gap densities in old-growth beech forest ranged from 2.7 ha^{-1} to 24 ha^{-1} (Bottero et al. 2011, Rugani et al. 2013) but were commonly between 6 ha^{-1} and 10 ha^{-1} (e.g. Kenderes et al. 2009, Kucbel et al. 2010, Petritan et al. 2013, Feldmann et al. 2018). The gap fractions of the sites in this study are well in the range of gap fractions from old-growth beech forest, although gap fractions below 5% are rare. Zeibig et al. (2005) found a gap fraction of 5.6% in a beech forest in the Dinaric mountains in Slovenia. Petritan et al. (2013) measured 12.8% in Runcu-Grosi National Reserve in Western Romania. Kenderes et al. (2009) found a gap fraction of 9-11% over a 33-year period in a mixed beech virgin forest reserve in Czech Republic. Feldmann et al. (2018), however, reported a change in gap fraction from 13.6% to 8.2% within 10 years for the Kyjov virgin forest in Slovakia. Feldmann et al. (2018) also noted critically that studies of canopy gaps in beech-dominated virgin forests using terrestrial methods reported gap sizes ranging from 3% to 19%, whereas satellite remote sensing approaches found canopy gap percentages of 1% or even less. This might be due to inadequacy of satellite images (e.g. Garbarino et al. 2012), weakness of the methodology or different criteria for the selection of study areas.

The arithmetic mean of the gap sizes in the present study was much smaller than the median which is typical for canopy gap sizes, since gap size distributions are commonly characterized by many small and very few extremely large gaps (e.g. Kenderes et al. 2009, Kucbel et al. 2010, Bottero et al. 2011, Petritan et al. 2013, Rugani et al. 2013, Feldmann et al. 2018). Kenderes (2008) reported median gap sizes of 40, 43, 61 and 93 m^2 for different years from the Őserdő Forest Reserve in Northern Hungary. Kucbel et al. (2010) found a median gap size of 57 m^2 for a fir-beech forest remnant in the western Carpathians in Central Slovakia. Petritan et al. (2013) reported 79.7 m^2 for the Runcu-Grosi National Reserve in western Romania. The arithmetic means of gap sizes in the literature range from 60.6 m^2 in Albanian old-growth forests (Tabaku and Meyer 1999) to 261 m^2 in Kyjov virgin forest in Slovakia in the year 2003 (Drößler and von Lüpke 2005). However, the mean gap size shrunk to 96 m^2 in the next survey of the same stand in 2013 (Feldmann et al. 2018).

The arithmetic mean and median of the gap sizes, found in this study, are considerably lower than values from old-growth forest in Southeast and Central Europe. This might be due to a lower minimum gap size of 5 m^2 in this study compared to common minimum gap sizes in terrestrial surveys of 10 m^2 to 25 m^2 and due to the young age of the stands as well as their comparatively recent abandonment.

With mean compactness of 1.2-1.5 the gap shapes are in accordance with Petritan et al. (2013) and Getzin et al. (2014). However, the maximum compactness of 1.6-4.4 slightly higher in this study compared to Getzin et al. (2014). Which might be due to larger maximum gap sizes and larger total number of gaps.

4.4.1 Conclusions

An automated mapping approach based on ALS data allowed consistent detection and delineation of canopy gaps over large and numerous areas. No expert judgment, which might differ from stand to stand or interpreter to interpreter, was involved in mapping individual gaps. A consistent set of rules was defined and applied strictly and uniformly to all stands. Since mapping canopy gaps based on remote sensing data by a human interpreter is quite time-consuming and terrestrial surveying even slower, automation increases the sample of mapped stands considerably and the large continuous areas allow for analyzing the spatial distribution of canopy gaps.

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5 Adapting the pair-correlation function for analysing the spatial distribution of canopy gaps

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Own contributions: Idea and concept for the adaption of the pair-correlation function, design and supervision of the implementation of the method, creation of the simulated canopy gap patterns, procurement of aerial photographs, delineation of canopy gaps, analysis and interpretation of the canopy gap patterns, conception and preparation of all figures, writing of the manuscript and finalization.

Abstract

Forestry around the world has been experiencing a paradigm shift towards more nature-oriented forest management leading foresters to emulate natural disturbances by their silvicultural treatments. Important characteristics of all disturbances are their size, severity, temporal and spatial distribution. This study focuses on the spatial distribution of gaps in the forest canopy which are typically caused by small-scale, low intensity disturbances.

The considerable spatial extent and irregular shape of canopy gaps are obvious obstacles to the application of classical point pattern analysis. The approximation of objects by their centroids does not lead to reasonable results, since the objects are at the same scale as the expected effects. By dividing the study area in grid cells and analysing all cells covered by an object, the size and the shape of the objects is accounted for. Nevertheless, both methods show undesirable effects. Thus we propose a new approach using the boundary polygons of the objects and construct the adapted pair-correlation function from the shortest distances between polygons.

The adapted pair-correlation function is presented using simulated data and mapped canopy gaps of a near natural forest reserve. The results of our proposed method are compared to the grid-based approach and the classical point pattern analysis. The presented method provides meaningful results and even reveals the relationship of objects at short distances, which is not possible using the classical point pattern analysis or the grid-based approach. With regard to the analysis of the spatial distribution of canopy gaps, the adapted pair-correlation function proves to be a useful analytical tool.

Keywords: Point pattern, Spatial statistics, Pair-correlation function, Canopy gaps, Disturbances

5.1 Introduction

Forestry around the world has been experiencing a paradigm shift towards more nature-oriented forest management (Lähde et al. 1999, Gamborg and Larsen 2003, Fürst et al. 2007, Puettmann and Ammer 2007). Management objectives are changing from the mere timber production to more diverse goals, such as sustaining native biodiversity (Christensen and Emborg 1996, Mitchell et al. 2002), providing recreational value (Nielsen et al. 2007), improving stand stability (Emborg et al. 2000) and utilisation of "biological rationalization" (Gamborg and Larsen 2003, Schütz 2004). Gamborg and Larsen (2003) state that this trend can be found under various terms e.g. "close-to-nature", "nature-based silviculture", and "ecosystem management" in Europe, North America, and in other forest regions of the world. But the new silvicultural approaches have been motivated and developed differently. Puettmann and Ammer (2007) for instance describe the differences between the North American and European approach. However, both have in common that they build on so-called natural forest dynamics and structure (Gamborg and Larsen 2003). While the disparities between natural disturbance and silviculture can never be fully overcome, the more the intensity, frequency, and spatial patterns created by the silvicultural treatments resemble the characteristics of the natural disturbance regime the narrower the gap (Palik et al. 2002). To assess the size of the gap, one needs meaningful parameters to characterise managed forests as well as comparable (near-) natural forests.

This study focuses on small-scale, low intensity disturbance, which is found under two dominant conditions: (i) in climatic zones where large-scale disturbances are rare, such as in tropical or temperate forests and (ii) in dispersed areas that have escaped catastrophic disturbances, for example boreal forests which have gone undisturbed by fires, blowdowns or lethal insect outbreaks for long time periods. Nevertheless, all forests eventually undergo small-scale gap dynamics if they escape large-scale disturbance (Denslow and Gomez Diaz 1990, Runkle 1990, Coates and Burton 1997). Important characteristics of all disturbances are the size, severity, temporal and spatial distribution (Pickett and White 1985, Coates and Burton 1997). The size, severity, and temporal distribution have been investigated extensively (Denslow 1980, Runkle 1982, Canham et al. 1990, Runkle 1990, Pontailler et al. 1997, Tanaka and Nakashizuka 1997, Fujita et al. 2003, Meyer et al. 2003, Drößler and von Lüpke 2005, Mountford et al. 2006, de Lima and de Moura 2008), whereas the spatial distribution of canopy gaps was analysed only in few studies (Runkle and Yetter 1987, Lawton and Putz 1988, Runkle 1990, Frelich and Lorimer 1991, Poorter et al. 1994, van der Meer and Bongers 1996, Trichon et al. 1998, Hessburg et al. 1999, Salvador-Van Eysenrode et al. 2000). The wealth of studies on spatial distribution of canopy gaps was carried out in tropical forests and mostly observed clustered canopy gaps.

Various methods were suggested to capture the spatial distribution of canopy gaps. They range from landscape indices to nearest neighbour distances and point processes. Landscape indices as employed by Hessburg et al. (1999) rather measure the diversity and intermixing of patch types than solely the spatial distribution of patches. Landscape indices are, therefore, not useful for studies focused on the analysis of the spatial distribution of canopy gaps. Frelich and Lorimer (1991) investigated spatial patterns of 46 plots in the Porcupine Mountains using Moran's *I* to test for spatial autocorrelation. If Moran's *I* is calculated over a range of scales the size of influence of an ecological process can be estimated from the ranges with significant autocorrelation. Detailed information on the spatial distribution cannot be gained. Hemispherical photographs (Trichon et al. 1998) and nearest neighbour distances (Poorter et al. 1994, van der Meer and Bongers 1996, Salvador-Van Eysenrode et al. 2000) provide information only about the immediate vicinity of the considered point. Point pattern analysis in contrast provides a useful framework for investigating the pattern at multiple scales by considering the distances between all pairs of points. A set of tools for analysing the spatial distribution of discrete points is available (Ripley 1981, Stoyan and Stoyan 1994, Perry et al. 2002, Møller and Waagepetersen 2007, Illian et al. 2008). Second-order statistics, such as Ripley's *K* function or the pair-correlation function, have proved to be particularly useful in ecological research (Getzin et al. 2006, Perry et al. 2006, Atkinson et al. 2007, Longuetaud et al. 2008, Picard et al. 2009). Lawton and Putz (1988) used canopy gap centres as points and adopted Ripley's *K* to examine gap dispersion. This approximation may lead to valid results if the size of objects is small in comparison with the spatial scales investigated but may obscure the real spatial relationships at scales in the same range as the size of objects (e.g. Simberloff 1979, Prentice and Werger 1985). Accordingly, Lawton and Putz (1988) mention that their results "must be interpreted with an eye to the gap sizes". Furthermore, Wiegand et al. (2006) found that point approximation produces misleading results if the object size varies substantially. The size and irregular shape of canopy gaps are obvious obstacles to the application of classical point pattern analysis for exploring their spatial distribution.

A first approach to account for the size of objects while investigating their spatial distribution was introduced by Simberloff (1979). He approximated the objects by circles and proposed corrected statistics for nearest neighbour methods. Additionally, two different approaches for extending the classical point process analysis for objects of finite size were proposed. Prentice and Werger (1985) suggested adapting the null model used for hypothesis testing instead of the pattern itself in order to account for the average size of the objects. Using non-overlapping circles instead of points in the null models prevents from the false conclusion objects are a minimum distance apart. This approach corresponds to models with no or less than expected short distances, meaning with a strict or soft minimum distance between points, namely hard- and soft-core models (e.g. Matérn 1986, Cressie 1991). Wiegand et al. (2006) suggested a grid-based approach to not only account for the size but also the shape of the objects in the pattern. Following this approach, objects are approximated by groups of cells in a categorical raster map. Single objects may occupy several adjacent cells depending on their size and shape. The resulting point pattern comprises all cell centres being part of an object. The number of points is, therefore, much higher than the number of objects. Null models for complete spatial randomness are constructed by rotating and shifting the objects in the raster map. Wiegand et al. (2006) found that their approach does not produce undesirable and misleading pseudo hard- and soft-core distances caused by the size and shape of the objects. However, the approximation of the object's size and shape by a group of points makes it hard to interpret the pair-correlation function at small scale. The distance between two objects is no longer one discrete value but a distribution of distances measured between all cells of one object and all cells of the other object. Furthermore, even the distances between all cells belonging to one object are counted. This leads to a huge number of small distances masking the real interaction effect in this range. The range of scales affected is controlled by the object sizes.

Therefore, we propose a new extension of the classical point pattern analysis for objects of finite size and irregular shape. In our approach, objects are characterised by their boundary polygon instead of groups of cells in a categorical raster map or their centroid. Only one distance is considered for each pair of objects and calculated as the shortest distance between the borders of the objects. This approach avoids pseudo hard- and soft-core effects and is able to describe the real interaction effect at small scales. For the construction of null models we also resort to random rotation and positioning within the study area.

We chose the pair-correlation function, which has become a popular tool for analysing mapped point patterns (Schurr et al. 2004, Getzin et al. 2006, Perry et al. 2006, Li and Zhang 2007). The pair-correlation function $g(r)$ is related to the derivative of the widely used K-function (Ripley 1976, Ripley 1981) and can be interpreted as the expected number of points per unit area (intensity) at a given distance r of an arbitrary point, divided by the intensity λ of the pattern (Stoyan and Stoyan 1994). The pair-correlation function is considered to be more powerful in detecting spatial patterns across scales, because it indicates precisely the spatial scales at which the null model is violated (Wiegand and Moloney 2004, Perry et al. 2006). The pair-correlation function thus correctly identifies the length of the interval, where the function deviates from the null model, in contrast to Ripley's K, which confounds the effect at large distances with the effect of small distances (memory effect) complicating its interpretation (Condit et al. 2000, Schurr et al. 2004).

We first introduce our proposed adaptation of the classical point pattern analysis and subsequently compare it to the pair-correlation functions calculated using the point approximation and the grid-based approach suggested by Wiegand et al. (2006). For the comparison, a suite of three simulated datasets having a regular, random, and clustered pattern, respectively, will be used. A case study with data from a near natural beech forest demonstrates the suitability of the proposed adaptation of the pair-correlation function for the analysis of the spatial distribution of canopy gaps.

5.2 Material and methods

5.2.1 Simulated data

To compare our proposed adaptation of the pair-correlation function with the point approximation and the grid-based approach, we generated three datasets with different spatial distributions. The spatial distribution of the objects should be as different as possible to test the proposed method. Thus we chose a strictly regular, a random, and a clustered distribution of objects. The study area is in all three cases 100 m × 100 m. Since the object area percentage, the size distribution, and the shapes of the objects have a strong influence on the performance of the methods, we first generated a set of n = 100 objects and placed the identical set of objects subsequently according to the designated spatial distribution. The size distribution and shapes of the objects are inspired by measurements of canopy gaps. The areas of the objects range from 1.6 m^2 to 57.7 m^2 with an arithmetic mean of 9.7 m^2 and a median of 5.5 m^2. The total area of all objects is 969.7 m^2, meaning 9.7% of the study area is covered by objects.

For the first dataset, the objects were arranged in a strict regular manner. A centric systematic grid was constructed, and the objects of the set were then randomly rotated and randomly placed by locating the centroids of the objects exactly on the matching randomly numbered grid points, resulting in a regular arrangement of objects with a constant distance of the centroids of 10 m (Fig. 5.1a). For the second dataset with randomly distributed objects, we generated a realisation of the Binomial process with intensity 0.01 m^{-2}, meaning one point per 100 m^2. The objects were again randomly rotated and numbered and objects put on matching points with their centroid as close to the point as possible without overlapping other objects (Fig. 5.1b). The third dataset represents a clustered configuration. Again, we first created a point pattern with 100 points and then put the randomly numbered objects on the points. The point pattern was a realisation of Matérn's cluster process with $\omega = 0.0006^{-2}$ or 6 cluster centres per ha, a dispersion radius of R = 10 m and on average g = 16.6 points per cluster

(Fig. 5.1c). We used the R-package spatstat (Baddeley and Turner 2005) for simulating the Binomial process and Matérn's cluster process. The polygon datasets were finally converted to categorical raster maps and the centroids of the polygons to points for the purpose of the grid-based and the centroid-based point pattern analysis, respectively.

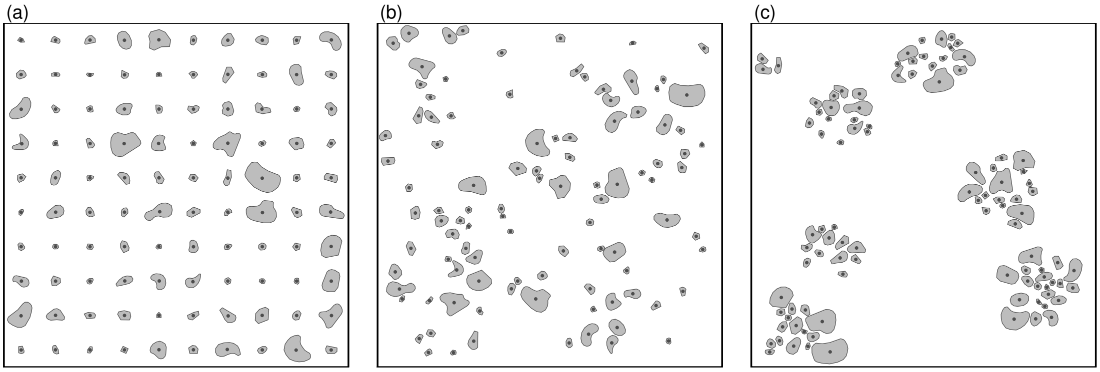

Figure 5.1: Simulated datasets: Within the 100 × 100 m study area the same set of polygons is laid out in a (a) regular, (b) random and (c) clustered arrangement. Placement of the objects is based on (a) a regular pattern with 10 m spacing, (b) a Binomial process with intensity 0.01 m^2 and (c) a Matérn process with parameters $\omega = 0.0006^{-2}$, $R = 10$ m and $g = 16.6$. The centroids of the objects are marked with small dots.

5.2.2 Case study

The case study is based on data from the forest nature reserve "Wiegelskammer", which has been unmanaged for almost 40 years and is now part of the National Park Eifel (Schulte 2003). The forest is located in the south-west of North Rhine-Westphalia (Germany) on a north-facing slope at an altitude of about 400 m. The subatlantic climate of the area is characterised by 750 mm precipitation per year and an annual average temperature of 7.3 °C. (LÖLF 1975). The bedrock of the region is mainly sandstone with additional colluvial layers resulting in a skeletal and well ventilated cambisol with a mull-like mor (LÖLF 1975). The forest is made up of 150–175-year-old beech (*Fagus sylvatica*) with a few sessile oaks (*Quercus petraea*) and is classified as a nutrient-poor beech forest (*Luzulo-Fagetum*) (Schulte 2003). The forest has one dense main canopy layer with a height of about 30 m containing a number of gaps, some of them with already established regeneration.

The canopy gaps of the central 8 ha of the nature reserve were mapped using aerial photographs and a digital stereoplotter. The photographs were taken in summer 2001 with sufficient overlap to provide a stereoscopic view of the canopy surface. We followed Runkle's (1992) gap definition and mapped all areas not covered by trees of the main canopy layer as gaps (Fig. 5.2). Vegetation within the gap was regarded as belonging to the main canopy if it was higher than $2/3$ of the stand height. The size of mapped canopy gaps ranges from 5 to 650 m², the lower limit being set as the minimum gap size for mapping. A total of n = 72 gaps were found, which cover 5.5% of the study area.

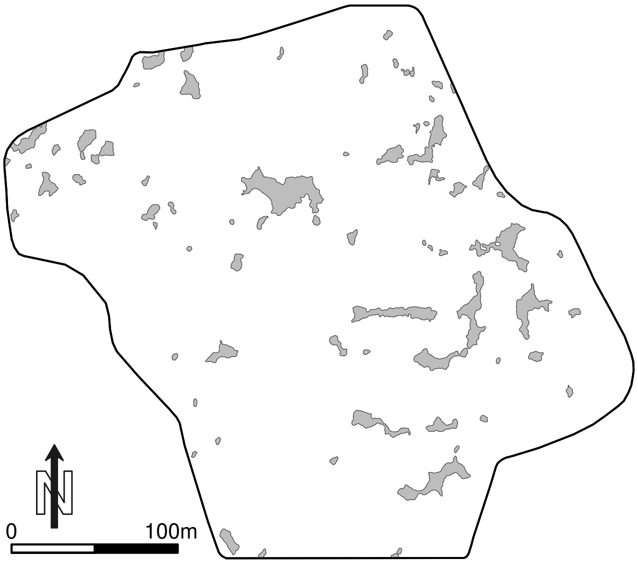

Figure 5.2: Canopy gaps of the core area of the forest nature reserve "Wiegelskammer" mapped from aerial photographs taken in summer 2001.

Before performing a spatial analysis of this dataset, the fundamental assumption of stationarity must be addressed. Illian et al. (2008) recommend justifying stationarity based on nonstatistical arguments, since it is impossible to prove rigorously that a specific point pattern is a sample from a stationary point process. The study site is the core area of a forest nature reserve and thus not influenced by silvicultural treatment or edge effects. The trees of the main canopy layer are about the same height throughout the study area. The study site being quite small is under the same climatic conditions, and the soil does not vary considerably within the area. Moreover, the pair-correlation function of this dataset approaches one for larger distances (cf. Fig. 5.5), a typical property of stationary point processes. Although natural environments are rarely totally homogeneous, we consider the assumption as met.

5.2.3 Adaptation of the pair-correlation function

The pair-correlation function *g(r)* is based on object-to-object distances and describes regularity and aggregation at a given radius r. For a completely random point process (i.e. a homogeneous Poisson process), *g(r)* is equal to 1. If $g(r) > 1$, the interobject distances around *r* are relatively more frequent than they would be under complete spatial randomness; if this is the case for small values of r, it suggests clustering. Values of $g(r) < 1$ indicate that the corresponding inter-object distances are relatively rare, which suggests regularity. The pair-correlation function can take any value between zero and infinity; as *r* increases, *g(r)* typically approaches 1 (Stoyan and Stoyan 1994).

We adapted the pair-correlation function, basically, by describing the objects by their boundary polygons instead of their centroids. Accordingly, the distances between objects are calculated as length of the shortest straight line between polygons. This new distance concept implies that the estimation of the pair-correlation function can no longer be based on the well-known estimator

$$\hat{g}(r) = \sum_{i=1}^{n} \sum_{j=1, i\neq 1}^{n} \frac{\omega(r_{ij} - r)}{\hat{\lambda}^2 \, 2\pi r \, s(r)}, \quad r > 0 \tag{5.1}$$

suggested by Penttinen et al. (1992), as it is the case for the point approximation. Therefore, that estimator has to be appropriately adapted to the modified distance concept. In Eq. (5.1) r_{ij} is the distance between points *i* and *j* of the point pattern, $\hat{\lambda}$ the estimated point intensity, $s(r)$ an edge correction, and $\omega(\cdot)$ a kernel function. The kernel function weights point pairs according to the deviation of their inter-point distance r_{ij} from *r*. That way not only point pairs with exactly $r_{ij} = r$ are counted but also those with r_{ij} close to *r*, leading to a smoother pair-correlation function.

In order to explain the implications of the polygon approach, we first simplify (5.1) by ignoring the edge correction factor, that is replacing *s(r)* by the area *A* of the study region, and using the simple rectangular kernel function

$$\omega(x) = \begin{cases} \frac{1}{2\Delta}, & \text{if } -\Delta \leq x \leq \Delta \\ 0, & \text{otherwise} \end{cases}$$

putting equal weights of $1/(2\Delta)$ on all point pairs, whose interpoint distance deviates not more than Δ from *r*. Using $\hat{\lambda} = n/A$ as an estimate of the overall intensity, we obtain the intuitive estimator for point patterns

$$\hat{g}(r) = \frac{1}{n} \sum_{i=1}^{n} \frac{\#\{j : r - \Delta \leq r_{ij} \leq r + \Delta\}}{\hat{\lambda}\, 2\pi r\, 2\Delta}, \; r > 0,$$

where the function $\#\{j : r - \Delta \leq r_{ij} \leq r + \Delta\}$ counts the objects *j* within the given distance interval. It shows that the estimated pair-correlation function can simply be interpreted as the mean ratio of the number of points observed within a small distance interval $[r - \Delta, r + \Delta]$ related to a given point *i* of the pattern (numerator) and of the expected number of points within that interval in case of a homogeneous Poisson pattern (denominator).

In the new polygon approach, we replace the numerator by the number of polygons within the distance interval using the polygon distance defined above. Accordingly, we should also replace the denominator by the expected number of polygons within that distance interval under a completely random process, but the latter can no longer be estimated by $2\pi r\, 2\Delta$ times the number of objects (polygons) per unit area, $\hat{\lambda}$, as it is done for the point approximation. The expected number of polygons is difficult to determine in a closed form and even distance dependent as will be shown later by simulation of completely random polygon patterns. It means that, under the polygon approach, the intuitive estimator, as well as (5.1), yields a biased estimator $\hat{g}_{biased}(r)$ of the pair-correlation function, which has to be corrected by a distance dependent correction factor. The latter will be derived by Monte Carlo simulation of the null model.

Since the pair-correlation function is a density function, we return to estimator (5.1) together with the frequently used and more efficient Epanechnikov kernel (Silverman 1986, Stoyan and Stoyan 1994)

$$\omega_E(x) = \begin{cases} \frac{3}{4\delta}\left(1 - \frac{x^2}{\delta^2}\right), & \text{if } -\delta < x < \delta \\ 0, & \text{otherwise} \end{cases}$$

and an appropriate edge correction, instead of using the intuitive estimator. The Epanechnikov kernel is a weight function putting maximal weight to point pairs with distance exactly equal to *r* but also incorporating point pairs only roughly at distance *r* with reduced weight. This weight falls to zero if the actual distance between the points differs from *r* by at least δ, the so-called bandwidth parameter, which determines the degree of smoothness of the function. We set δ between $0.1/\sqrt{\lambda}$ and $0.2/\sqrt{\lambda}$ as suggested by Penttinen et al. (1992) and Stoyan and Stoyan (1994). Then the adapted pair-correlation function can be estimated as

$$\hat{g}(r) = \sum_{i=1}^{n} \sum_{j=1, i \neq 1}^{n} \frac{\omega_E(r_{ij} - r)}{\hat{\lambda}^2 \, 2\pi r \, p_{ij}}, \; r > 0 \tag{5.2}$$

with p_{ij} being the edge correction replacing *s(r)* based on suggestions by Ripley (1981). For each pair of objects *i* and *j*, a buffer with buffer distance r_{ij} is constructed around the object *i*. The object *j* is then weighted by the inverse of the proportion p_{ij} of the buffer perimeter being within the study area. That way we account for the reduced probability of finding objects close to the edge of the study area. We emphasize that (5.2) is still biased for the polygon approach if the kernel function is evaluated using the polygon distance and $\hat{\lambda}$ estimated by the number of polygons per unit area as described above. Before we will develop the bias-correction factor, we describe the Monte Carlo method for the simulation of the null model and the construction of confidence envelopes.

To test for the significance of regularity or clustering within a point process, as expressed by the *g(r)* function, it is necessary to compare the results to an appropriate null model. Complete spatial randomness usually serves as the null hypothesis for a univariate point process. Confidence envelopes are computed using Monte Carlo simulation. Each simulation generates an estimation of the pair-correlation function. Approximate confidence envelopes to the significance level α are calculated from the $(k+1)\alpha/2$ and $k-((k+1)\alpha)/(2)+1$ lowest value of $\hat{g}(r)$ taken from k simulations of the null model (Besag and Diggle 1977, Stoyan and Stoyan 1994).

In this case, the 5th smallest and the 5th largest values of 199 randomisations provide a 95% confidence envelope. If the estimated pair-correlation function of the investigated pattern has some part outside of that envelope, it is judged to be a significant deviation from the null model.

Following Wiegand et al. (2006), we constructed the null model for complete spatial randomness by random rotation and positioning of the original objects. Beginning with the largest object, all randomly rotated objects are placed randomly inside the study area until the smallest object is set. If the current object overlaps with already placed objects, another attempt at placing the object is made.

The simulation of the null model allows for the estimation of a correction factor which removes the bias inherent in (5.2). If the uncorrected estimator $\hat{g}_{biased}(r)$ were unbiased for each distance *r*, the mean of all simulated realisations of $\hat{g}_{biased}(r)$ under the null model would be close to one. Instead, according to Fig. 5.3a depicting the 95% confidence envelope of $\hat{g}_{biased}(r)$ under the null hypothesis, we found that it is mostly above one and increases monotonously for $r \to 0$. This means that the expected number of polygons having distance *r* to a given polygon *i* under the null model is larger than for point patterns, where it can unbiasedly be estimated by $2\pi r \, 2\Delta \, \hat{\lambda}$. This can be explained by the size of the given polygon: the closed curve connecting all points of distance *r* to that polygon is longer than the circumference $2\pi r$ of a circle with radius *r* around its centre point and increases the probability of encountering another polygon with distance *r* to the centre polygon. This effect obviously becomes weaker for larger *r*, since the ratio of the length of that curve and $2\pi r$ decreases.

The mean $c(r) = \bar{\hat{g}}_{biased}(r)$ of the simulated realisations of $\hat{g}_{biased}(r)$ under the null model is, by definition of $\hat{g}_{biased}(r)$, an appropriate Monte Carlo estimator for the ratio

$$\frac{\begin{array}{c}\text{expected number of polyggons having distance } r\\ \text{to a given object under the null model}\end{array}}{2\pi r 2\Delta\hat{\lambda}}$$

and serves as a bias correction factor in the final estimator

$$\hat{g}(r) = c^{-1}(r)\sum_{i=1}^{n}\sum_{j=1,i\neq 1}^{n}\frac{\omega_E(r_{ij}-r)}{\hat{\lambda}^2\,2\pi r\,p_{ij}},\ r > 0 \tag{5.3}$$

for the pair-correlation function *g(r)* of the polygon approach. The corrected pair-correlation function and its confidence envelope are shown in Fig. 5.3b.

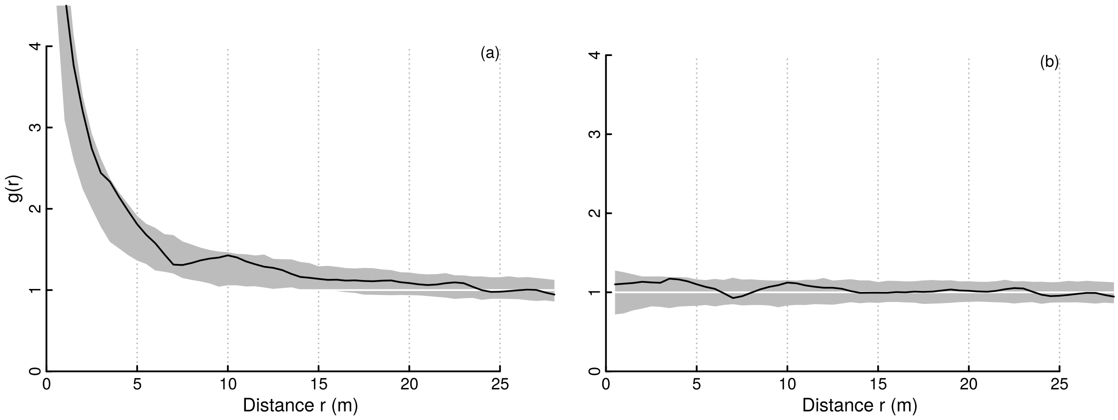

Figure 5.3: Pair-correlation functions of the simulated dataset with randomly distributed objects (cf. Fig. 5.1a) in (a) uncorrected and (b) corrected form. Black line: estimated function; white line: theoretical value of the function under the null hypothesis of complete spatial randomness; grey area: 95% confidence envelope under the null hypothesis, computed by Monte Carlo simulation using 199 replicates. Values $g(r) < 1$ suggest inhibition between points and values $g(r) > 1$ suggest clustering.

The calculation of the distances and the creation of the null models were carried out using functionality of GEOS (Geometry Engine Open Source) within PostGIS, which adds support for geographic objects to the PostgreSQL database

(PostGIS Development Team 2008). The calculation of the pair-correlation function and the confidence envelopes were done with the statistical software R (R Development Core Team 2008).

The grid-based estimation of the pair-correlation function was carried out using the software Programita developed by Wiegand et al. (2006). This estimation of the pair-correlation function faces the same problem as the polygon approach. The expected number of cells having distance r to a given cell can also not be estimated simply via the overall density $\hat{\lambda}$. Therefore, we applied here as well the previously described correction by a distance dependent factor derived from Monte Carlo simulation of the null model.

The estimation of the pair-correlation function based on the point approximation was done with the R-package spatstat (Baddeley and Turner 2005).

5.3 Results

5.3.1 Simulated data

The estimated pair-correlation functions of the simulated datasets show the typical shapes of random, regular, and clustered distributions of objects (cf. Fig. 5.4). The pair-correlation function of the randomly distributed objects estimated by means of the polygon-based approach is, as expected, over all scales close to one and thus indicates a random pattern (Fig. 5.4b). The grid-based pair-correlation function does not deviate from the confidence envelopes either. Only the centroid-based pair-correlation function shows a typical soft-core effect caused by the object sizes and departs from the confidence envelopes up to 2.5 m.

The regular pattern is picked up very well by all three methods (Fig. 5.4a) and the pair-correlation functions show accumulations of certain distances while other distances have obviously less counts than expected under complete spatial randomness. The pair-correlation function using the centroids shows a first maximum at approximately 10 m. This is caused by the distance between centroids of two adjacent objects, which is exactly 10 m. The next peak is at 14 m reflecting the distance to the nearest neighbours in diagonal direction in the square grid. The last maximum with a double peak has its highest point at 21.5 m and represents the next but one object in a straight line and the next object in a diagonal direction with a more acute angle. The pair-correlation functions of the other two methods display accumulations at corresponding scales but with lower and wider peaks. The polygon-based pair-correlation function also shows a shift of the peaks towards smaller scales.

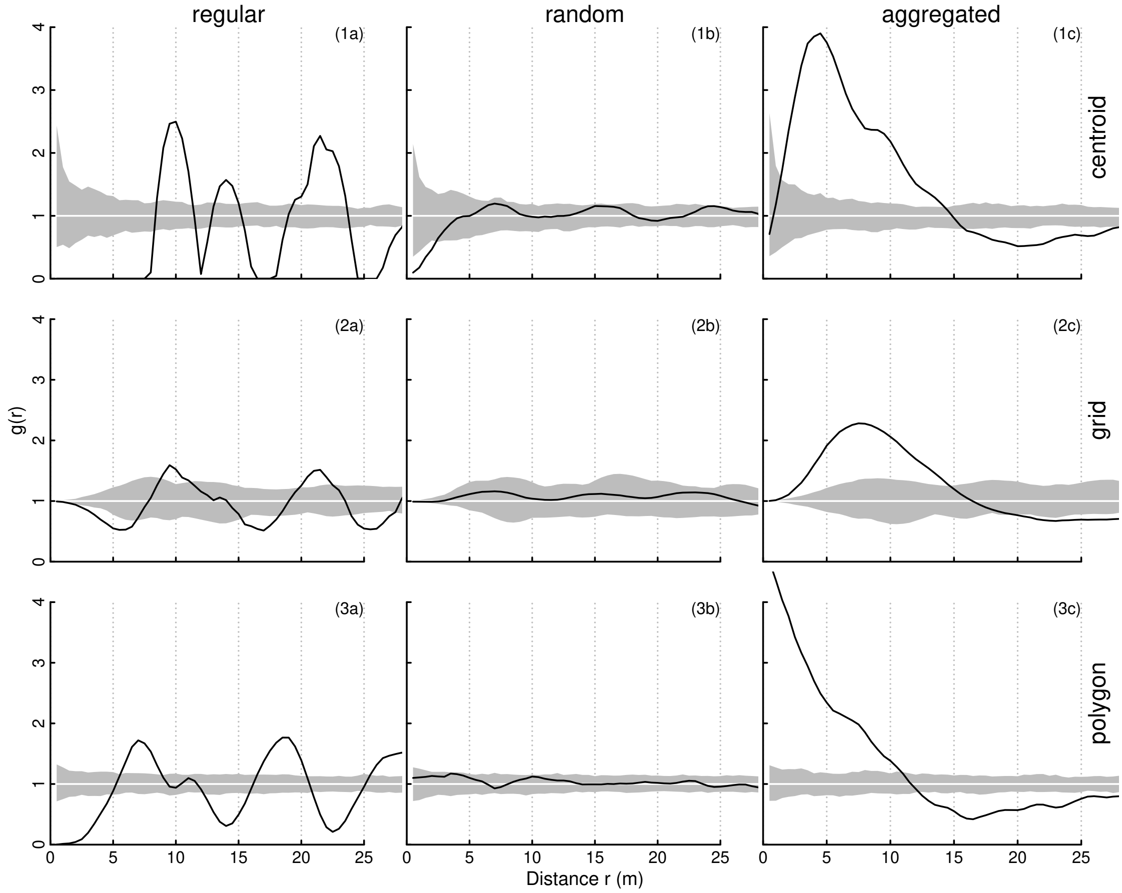

Figure 5.4: Pair-correlation function of the simulated datasets having (a) regular, (b) random, and (c) clustered objects using the (1) point approximation, (2) grid-based and (3) polygon-based approach. Black line: estimated function; white line: theoretical value of the function under the null hypothesis of complete spatial randomness; grey area: 95% confidence envelope under the null hypothesis, computed by Monte Carlo simulation using 199 replicates. Values $g(r) < 1$ suggest inhibition between points and values $g(r) > 1$ suggest clustering.

In Fig. 5.4c, the pair-correlation functions of all three methods display an accumulation of short distances, while long distances are rare, as expected for a clustered configuration. Only the centroid-based estimation of the pair-correlation function starts with less distances than expected under complete spatial randomness, which is again a depiction of a soft-core effect. The positive deviation from the confidence envelopes reaches up to one and a half times the cluster radius for the centroid- and grid-based estimation of the pair-correlation function, whereas the polygonbased estimation deviates only up to the order of the cluster radius from the confidence envelope.

The differences arising from the different approaches to calculate the pair-correlation function can be clearly seen in Fig. 5.4. The pair-correlation function based on the point approximation suggests a soft-core distance of 4.5 m (Fig. 5.4, 1b and c) which is not pointed out by the other two methods. The grid-based approach produces empirical pair-correlation functions close to one for very small scales for all three simulated datasets. The interaction effect at small scales, inhibition for the regular and attraction for the aggregated pattern, becomes only visible in the further shape of the curve, thus obscuring the real small-scale effect. The peaks in the pair-correlation function of the regularly distributed objects are varyingly distinct in the different methods and, with the polygon approach, shifted towards smaller scales.

5.3.2 Case study

The spatial distribution of the canopy gaps of the forest nature reserve "Wiegelskammer" shows no large deviations from the confidence envelopes and thus from complete spatial randomness (Fig. 5.5). The grid-based estimator does not show any deviations from the confidence envelopes and the point approximation and the polygon-based approach have only two minor deviations. Those small but nominally significant departures from a random distribution occur in the polygon-based approach at the scales from 9.8 to 12.3 m and less pronounced from 15.7 to 18.2 m.

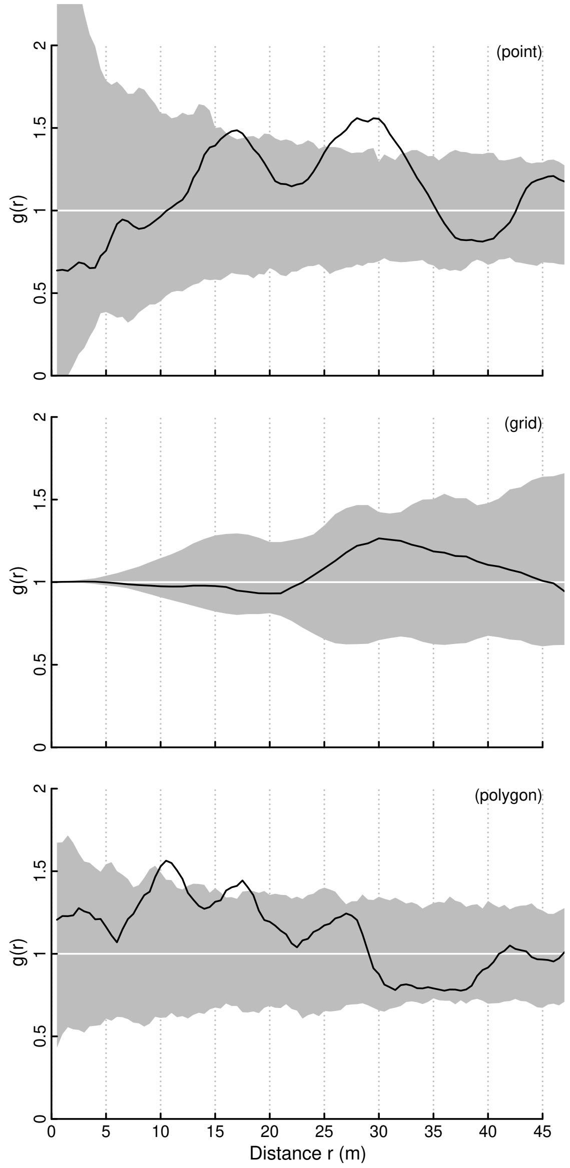

Figure 5.5: Pair-correlation function of the canopy gaps of the forest nature reserve "Wiegelskammer" using the point approximation (centroid), the grid-based (grid) and the polygon-based approach (polygon). Black line: estimated function; white line: theoretical value of the function under the null hypothesis of complete spatial randomness; grey area: 95% confidence envelope under the null hypothesis, computed by Monte Carlo simulation using 199 replicates. Values $g(r) < 1$ suggest inhibition between points and values $g(r) > 1$ suggest clustering.

The pair-correlation function using the point approximation deviates from the confidence envelopes at the scales from 16.1 to 17.8 m and more clearly from 25.3 to 32.2 m indicating an accumulation of the corresponding distances. The function values of the grid-based estimator stay very close to the reference value one for scales up to 23 m. The curve then stays above the reference line for the range from 23 to 46 m having a peak at 30 m. The pair-correlation function using the point approximation shows a soft-core effect, whereas the function values of the polygon-based estimator are continuously larger than one for distances up to 29 m but mostly without significant differences. These distances are more frequent than expected under complete spatial randomness and suggest a trend towards clustering.

5.4 Discussion

First we cover the influence of the different methods on the pair-correlation function using simulated data with a random, regular, or clustered distribution. Subsequently, we address the suitability of the methods presented for analysing the spatial distribution of canopy gaps.

5.4.1 Comparison of methods

The different representation of objects implies different approaches to the estimation of the pair-correlation function. The pair-correlation function based on the point approximation describes the distribution of distances between the centroids of the considered objects. The grid approach dissects the objects in individual cells and calculates the distances between all cells of the objects. The pair-correlation function estimated with the polygonbased approach provides information about the distribution of distances from the boundary of one object to the boundary of another object and hence information about the space between the objects. The different approaches affect the shape of the pair-correlation function considerably as can be seen in Fig. 5.4.

The grid-based estimation of the pair-correlation function has a lower amplitude, deviates less but still clearly from the confidence envelopes and peaks are spread out over a larger range. This is because the distance of two objects is measured between the individual cells of the two objects. These distances are scattered around the corresponding distance between the centroids. Therefore, the range where distances are more frequent than under complete spatial randomness is not as sharply delimited as with the centroid-based distance measure. Thus, the effect of the spatial configuration of the objects is less clearly visible.

The differences between the three approaches are particularly recognisable at small scales. The grid-based approach produces function values close to one at very small scales and approaches one for $r \to 0$. The length of this effect is about the same size as the diameter of the larger objects of the simulated patterns, which is about 7 m. The function values close to reference value one at small scales are caused by the cell representation of objects. Since both the null models and the original data have a nearly equal large number of short distances, the pair-correlation function takes values close to one. The large numbers of short distances are mainly caused by distances between cells of the same object, since the grid-based approach considers distances between all cells. These distances are obviously short and range between the size of a cell and the maximum extension of the objects. The obfuscating effect of this behaviour is obvious in the regular and the aggregated patterns (cf. Fig. 5.4a and c).

The pair-correlation functions estimated based on the centroids of the objects have at small scales usually function values considerably below the confidence envelopes. These low values are caused by the fact that objects do not overlap, so that their centroids have a minimum distance according to the size of the two objects. This is the so-called soft-core distance, which should not be detected in the simulated data, since there is no such effect at the scale of the objects in the simulated dataset. The point approximation as well as the grid-based approach is affected by the size of the objects, although in different ways. If the size of the objects has no meaning in the research question at hand, the size effect leads to difficulties while interpreting the pair-correlation function, because the effect caused by object sizes interferes with the effect of the spatial distribution of the objects of interest.

Using the adapted pair-correlation function of the polygon approach, no specific function values are expected at small scales. There can be high values in case of clustered objects as well as very small values or zero detecting a segregation effect at small scales. Each pair of objects has the same influence on the pair-correlation function in the point- and polygon-based pattern analysis, since there is only one unambiguously identifiable distance. But the grid-based estimation of the pair-correlation function takes several distances into account for every pair of objects. Hence, large objects contribute more distances to the estimation of the pair-correlation function than smaller objects. The influence of the individual objects on the pair-correlation function is not the same but rather weighted by their sizes. This is the so-called weighting effect (cf. Wiegand et al. 2006). As a consequence, a few large, regularly distributed objects can for example overpower the effect of a large number of smaller, clustered objects resulting in a pair-correlation function showing, unexpectedly, a regular pattern.

Besides the estimation of the pair-correlation function, it is important to choose an appropriate null model for hypotheses testing. Therefore, null models representing completely randomly distributed objects are generated for each approach. A comparison of these null models is not easily available, since they are constructed differently. The null models for the grid- and polygonbased approach are generated by relocation of the original objects, whereas for the centroid-based analysis a homogeneous Poisson process was used to generate null models. Strictly speaking, the usage of a Poisson process for objects approximated by points gives a wrong impression of the distribution of the objects, since the Poisson process allows points to be arbitrarily close to each other, which should not be possible, if the represented objects are not allowed to overlap. This leads to deviations from the confidence envelopes at small scales showing an undesirable soft-core effect which is only caused by the size of the objects. A way to account for this effect would be to use soft-core models (cf. Prentice and Werger 1985, Matérn 1986, Cressie 1991) as null models or to construct null models with circular objects of the same size, although these methods do not allow for irregular shapes of the objects. The grid- and the polygon-based approach on the other hand consider the soft-core effect implicitly.

The polygon approach as well as the grid-based approach are applicable only together with the Monte Carlo simulation of the null model, needed to construct the distant dependent correction factors for the inappropriate estimation of the expected number of objects under complete spatial randomness in a distance interval via the intensity of object centroids, $\hat{\lambda}$. That way the expected number of polygons under complete spatial randomness within a distance interval can be estimated in accordance with the intuitive estimator of the pair-correlation function and the pair-correlation function in its original definition in the theory of point processes.

All three approaches show the essential characteristics of the simulated patterns. Thus, they are all capable of describing the main trend of the pattern. Nevertheless, the issues described above, which are particularly noticeable at small scales, have to be considered while choosing an appropriate method and interpreting the results. While analysing patterns with small objects and large distances the differences between the methods are less pronounced, but the differences have a noticeable impact on the outcome of the analysis if patterns of large objects with small inter-object distances are studied. In the former case, it might be advisable to use the point approximation, since the method is less computationally intensive and implemented in common statistical software. However, the bigger the objects in relation to the inter-object distances the more inappropriate is the point approximation. Even in the extreme case where objects are almost touching, the pair-correlation function using the point approximation would still report almost exclusively soft-core distances. This becomes even more problematic if the pattern has a large range of object sizes causing the soft-core distances and spatial effects to become indistinct.

To avoid the above mentioned issues arising from the use of classical point pattern analysis, one should revert to other methods to analyse patterns of large objects with an irregular shape and small inter-object distances. Since the grid-based approach considers distances for all cells of an object and even distances between cells of the same object, it emphasises large objects. Thus larger objects have a greater influence on the corresponding pair-correlation function. If this weighting effect is not wanted, it poses an obstacle to the interpretation of the pair-correlation function, because it hides spatial effects occurring at small scales and blurs the true range of effects. Furthermore, the size and interaction influences are difficult to separate while interpreting the pair-correlation function. Particularly problematic are long and small objects, because they influence a large range of scales. The polygon-based method eliminates the size of objects, so that the pair-correlation function for small scales is only influenced by the spatial distribution of objects. Using the polygon-based method is recommendable for patterns with a large range of object sizes or if one is interested in effects at scales smaller than the average diameter of the objects.

5.4.2 Case study

The fall of a tree generates a gap of at least the size of its crown, which, for old beech trees, is about 12 m in diameter (Nagel 1999). Furthermore, the investigated forest has also canopy gaps with a length of up to 50 m, while the distances between the gaps measure sometimes just a few meters. Thus, canopy gaps are large objects in comparison to the inter-object distances and the considered scales. Considering this constellation, the point approximation would be an oversimplification having the already discussed issues. The two main effects, the shift of the peaks towards larger scales and the soft-core effect, can clearly be seen in Fig. 5.5. The grid-based estimator is, at small scales, affected by the large number of small distances caused by the cell representation of the objects. Since canopy gaps are relatively large and irregularly shaped objects, this effect influences a range of scales up to 20 m. For the same reason the weighting effect leads to a very wide peak instead of a number of narrow ones. Since effects in the magnitude of the size of gaps must be expected, the application of the grid approach is not advisable in this case. Thus, the estimation of the pair-correlation function using the polygon-based approach seems to be the appropriate choice for analysing the distribution of canopy gaps of the natural forest reserve “Wiegelskammer”.

The canopy layer is made up of the crowns of individual trees and gaps in the canopy arise through the death or fall of a tree or major parts of a tree crown.

Canopy gaps, therefore, can only be bordered by tree crowns or parts thereof (e.g. a large branch). Since crowns have a non-negligible diameter, we would have expected to find this distance as a soft-core effect in the pair-correlation function. But this is not the case; the pair-correlation function shows rather an accumulation of short distances. This suggests that canopy gaps are often separated by single large branches or by trees with elongated and very narrow crowns. The peak of the pair-correlation function at 11 m represents a large number of distances of this magnitude meaning many gaps are about 11 m apart, which is about the crown diameter of a large beech tree (Nagel 1999).

The pair-correlation function showing no considerable deviation from the confidence envelopes suggests that the canopy gaps of the researched forest are at least approximately randomly distributed. This agrees with other studies in temperate forests (Runkle and Yetter 1987, Runkle 1990, Frelich and Lorimer 1991). Tropical forests in contrast seem to show mostly clustered canopy gap patterns. Whether these most different patterns are caused by different single tree stability or topographic or edaphic factors needs further research (Fujita et al. 2003, de Lima and de Moura 2008).

5.5 Conclusions

The comparison of the methods to estimate a pair-correlation function using simulated datasets shows that all three methods have the ability to show the most important characteristics of the spatial distribution of objects of finite size and irregular shape. However, the pair-correlation functions estimated by the different methods vary considerably in their explanatory power and suitability. The differences between the methods we pointed out are caused by the different construction of the estimators, namely the dissimilar distance concepts. The shift of peaks or the distracting shape of the curves at small scales may be of varying size depending on the object sizes but will nevertheless remain. The choice of an appropriate approach should be based on the characteristics of the investigated pattern, particularly the size of the objects in relation to the inter-object distances, the object shapes and the present research question.

Depending on the question at hand a weighting of the objects by their size might be needed or obstructive. The grid-based approach does weight objects by their size, larger objects, thus, have more influence on the pair-correlation function. The polygon-based pair-correlation function, in contrast, describes the spatial distribution of objects without being influenced by their size. This facilitates the investigation of the space between the objects without mixing size and interaction effects. According to that characterization, a final and generally valid ranking of the three approaches is not possible.

With regard to the analysis of the spatial distribution of canopy gaps, where no weighting is wanted, the polygon-based approach provides meaningful results and even reveals the interaction of objects at small scales, which was not possible using the point approximation or the grid-based approach. Hence, the adapted pair-correlation function proves to be a useful analytical tool for analysing the spatial distribution of canopy gaps.

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6 Gap disturbance patterns in an old-growth sessile oak (*Quercus petraea* L.) – European beech (*Fagus sylvatica* L.) forest remnant in the Carpathian Mountains, Romania

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Own contributions: Analysis, interpretation and discussion of the canopy gap patterns, contribution to writing of the manuscript and revisions, preparation of all figures, finalization of the manuscript.

Abstract

In recent decades, natural forest remnants have become increasingly important as reference objects for maintaining or restoring old-growth characteristics in managed forests. Canopy gaps play an important role in forest regeneration, particularly for the establishment and development of tree species with different ecological recruitment patterns. Yet quantitative descriptions of such patterns are still scarce, particularly for oak-dominated forests. The old-growth sessile oak–European beech forest remnant in the Runcu-Grosi Natural Reserve provided a unique opportunity to study natural disturbance regimes with minimal human influence in an ecosystem type rarely investigated. The study site comprised the best preserved part of the Reserve. Its 32.3 ha are dominated by sessile oak. A complete gap survey was carried out. The size, shape, spatial pattern and traits of the gapmakers of all 321 gaps were recorded. Additionally, the gap age as well as the structure and composition of gapfillers were investigated in 70 randomly sampled expanded gaps.

The canopy gaps and the expanded gaps covered 12.8% and 28.5% of the study site, respectively. The frequency distribution of the canopy gap sizes corresponded to the negative exponential distribution, with most of the gaps (60%) smaller than 100 m^2, 34% between 100 and 300 m^2 and only 2% larger than 500 m^2. Canopy gaps smaller than 300 m^2 were responsible for 71% of the total gap area, suggesting a dominance of small and intermediate gaps in this forest. The pattern of the canopy gaps is characterized by a pronounced soft-core effect, and in one part of the study area a tendency towards regularity. Most of the gaps (84%) were caused by more than one gapmaker and seemed to be created in more than one disturbance event since, in 72% of the gaps, gapmakers of at least two different decay classes were found. The disturbance regime was driven by the mortality of sessile oaks, the main gapmaker species, caused mostly by uprooting. The other main canopy tree species was European beech, which died often by snapping. It was less common as gapmaker (20%), but was the main gapfiller (91%). In contrast sessile oak was almost absent among the gapfillers.

These results suggest that the current small-scale disturbance pattern dominating this old-growth forest is more suitable for shade–tolerant species such as European beech, accentuating the already steady decline of oaks in mixed sessile oak–European beech stands.

Keywords: Mixed sessile oak–European beech forest, *Quercus petraea*, *Fagus sylvatica*, Old-growth forest, Spatial statistics, Canopy gaps

6.1 Introduction

In recent decades, natural forest remnants have become increasingly important as reference objects for maintaining or restoring old-growth characteristics in managed forests (Bauhus et al. 2009, Keeton et al. 2010). This has coincided with the introduction of the silvicultural concept "close to nature" (Commarmot et al. 2005). Among all processes in natural forests, the formation of canopy gaps is recognized as a crucial disturbance process in many forest ecosystems (Runkle 1990, Lertzman and Krebs 1991, McCarthy 2001, Nagel and Svoboda 2008). It is a vital component of forest dynamics (Mountford 2001) since canopy gaps "drive the forest cycle" (Whitmore 1989) by creating environmental heterogeneity, especially in terms of light availability. The gap phase plays an important role in forest regeneration, particularly in the establishment and development of tree species with different ecological recruitment patterns (Runkle 1989, Peterken 2001, Ritter et al. 2005, Mountford et al. 2006).

Most studies of gap disturbance carried out in Europe (e.g. Tabaku and Meyer 1999, Zeibig et al. 2005) have focused on characteristics such as gap size distribution, formation rate and proportion in virgin forests. A smaller number of studies have investigated the ecological conditions within the gaps and their implications for tree regeneration (e.g. Mountford et al. 2006, Rozenbergar et al. 2007). Other studies used time series of aerial photographs (e.g. Tanaka and Nakashizuka 1997, Kenderes et al. 2009, Torimaru et al. 2012) or dendroecological techniques to quantify the disturbance events (Rozas 2003, Nagel and Diaci 2006, Firm et al. 2009). These previous studies have shown that dynamics in European temperate natural forests are driven particularly by small canopy gaps, but occasionally also by intermediate and large-scale disturbances (Drößler and von Lüpke 2005, Nagel and Diaci 2006, Nagel and Svoboda 2008, Kucbel et al. 2010).

Important characteristics of disturbances are, besides the size and severity, also the temporal and spatial distribution of events (Pickett and White 1985, Coates and Burton 1997). Spatial distribution of canopy gaps has not been given much attention so far. Most of the early studies were carried out in tropical forests or North America (e.g. Runkle and Yetter 1987, Lawton and Putz 1988, Frelich and Lorimer 1991, van der Meer and Bongers 1996). Manifold methods have been suggested to capture the spatial pattern of canopy gaps, such as hemispherical photographs (e.g. Trichon et al. 1998), landscape indices (e.g. Hessburg et al. 1999), spatial autocorrelation (e.g. Frelich and Lorimer 1991), nearest neighbor distances (e.g. Poorter et al. 1994, van der Meer and Bongers 1996, Salvador-Van Eysenrode et al. 2000), and point processes (e.g. Garbarino et al. 2012). In contrast to most methods, point pattern analysis allows the investigation of the spatial distribution of objects at multiple scales. Second-order statistics, such as Ripley's K function, the related L-function or the pair-correlation function have proven useful in ecological research (e.g. Perry et al. 2006, Picard et al. 2009) and a rich set of tools is readily available (e.g. Ripley 1981, Stoyan and Stoyan 1994, Perry et al. 2002, Baddeley and Turner 2005, Møller and Waagepetersen 2007, Illian et al. 2008, Law et al. 2009).

Since classical point pattern analysis deals only with point objects, canopy gaps must be reduced to their center points. This approximation may obscure the real spatial relationships if the sizes of the gaps are in the same range as the spatial scales investigated (e.g. Simberloff 1979, Prentice and Werger 1985, Nuske et al. 2009). Therefore we employ the adapted pair-correlation function proposed by Nuske et al. (2009). The pair-correlation function is considered to be more powerful in detecting spatial patterns across scales because it indicates precisely the spatial scales at which the null model is violated (Condit et al. 2000, Schurr et al. 2004, Wiegand and Moloney 2004, Perry et al. 2006). In contrast to classical point pattern analysis, objects are characterized by their boundary polygon, and distances are calculated as the shortest distance between the borders of the objects. This approach remediates artefacts at small scales avoiding pseudo hard- and soft-core effects.

In spite of an increasing number of canopy gap investigations in European virgin forests in recent times, results from unmanaged forest are still scarce and focus primarily on European beech stands in Albania (Tabaku and Meyer 1999), Slovenia (Zeibig et al. 2005), Slovakia (Drößler and von Lüpke 2005), or on European beech–silver fir forests in Bosnia–Herzegovina (Nagel and Svoboda 2008, Nagel et al. 2010), Slovenia and Croatia (Rozenbergar et al. 2007) and Slovakia (Kucbel et al. 2010) and more recently on mixed European beech, silver fir and Norway spruce forests in Bosnia Herzegovina (Bottero et al. 2011, Garbarino et al. 2012) and the Czech Republic (Kenderes et al. 2009). Although Romania has the largest area of virgin forests in Europe (Veen et al. 2010), no investigation of gap dynamics has been conducted to date.

Moreover, most of the European studies have been concerned with forests of shade–tolerant species (i.e. European beech or silver fir), while the information about canopy gap dynamics or, more generally, disturbance regimes of forests dominated by more shade–intolerant tree species are still lacking. The Runcu-Grosi Natural Reserve (western Romania), one of the best preserved natural mixed sessile oak forests in Europe, provided an opportunity to fill this gap in knowledge and gain insight into disturbance regimes of European natural forests dominated by rather lightdemanding species.

The objectives of this study were: (1) to evaluate and describe the characteristics of the gap disturbance regime (i.e. gap fraction, gap size distribution, gap age), (2) to analyze the spatial pattern of canopy gaps, (3) to characterize the gapmakers and identify common mortality processes (endogenous vs. exogenous) responsible for gap formation and (4) to analyze the composition of the regeneration within canopy gaps.

6.2 Materials and methods

6.2.1 Study area

Our study area is located in the Runcu-Grosi Natural Reserve (western Romania). The Reserve (261.8 ha) exhibits typical oldgrowth characteristics such as a high volume of living trees, a highly differentiated diameter distribution, an abundance of large-diameter trees and a large amount of coarse woody debris. It is dominated by *Fagus sylvatica* and *Quercus petraea*, but other species such as *Carpinus betulus*, *Quercus cerris*, *Acer pseudoplatanus*, *Prunus avium*, *Tilia cordata* and *Sorbus torminalis* are also present (Petritan et al. 2012). The climate is temperate continental with a mean annual precipitation of 687 mm and a mean annual temperature of 9.8 °C according to records from the closest hydrometric station (Monorostia, 150 m a.s.l.). Parent substrate consists of impermeable rocks like crystalline schists overlayered by cambisols and luvisols.

Figure 6.1: Canopy gaps within the study site mapped terrestrially during the summer of 2012. The dashed line marks the border between the northern (a) and the southern part (b).

The area investigated (22.1276E 46.1722N, Fig. 6.1) was 32.2 ha. The site had a south-westerly aspect with an average slope of 16° and elevation ranged from 442 to 680 m a.s.l. According to the forest management plan, in contrast to other forest stands in the reserve, this stand had only one, low intensity management intervention in 1977, and sessile oak comprises 90% of the total volume over 7 cm at smaller end of the investigated stand.

6.2.2 Field methods

A complete gap survey was carried out in summer 2012. The entire study site was walked systematically along a 100 × 100 m grid to map all openings in the main canopy layer. Both canopy gaps and expanded gaps were recorded using the integrated FieldMap Data Collector (IFER 2013). The area confined by the vertical projection of the crowns of the surrounding trees was recorded as a canopy gap, and the area delimited by the position of their trunks as an expanded gap according to Runkle (1992). We defined a canopy gap as an opening in the forest canopy >10 m^2 caused by the mortality of one or more trees in the upper canopy layer with remnants of the gapmaker still detectable. The canopy gaps were considered as closed when the regeneration in the gap reached the height of 20 m, similar to the definition used by Bottero et al. (2011) and Nagel and Svoboda (2008). Each gap was mapped by measuring several radii from the approximate gap center to the edge of the tree crowns and to the bole of the surrounding trees. All surrounding trees were identified and the species registered. For each gap, the gapmakers were identified and species, diameter at breast height (DBH), type of mortality (i.e. standing dead, uprooted, snapped, and partially uprooted) and state of decay (four classes according to Albrecht, 1991) were recorded.

Of the 321 gaps recorded, 70 (approximately 22%) were selected for more detailed investigations of the expanded gap area, since expanded gaps constitute the area in which understory vegetation is directly and indirectly influenced. Thus all gaps with an expanded gap size greater than 800 m^2 were included in addition to a random sample of gaps with an expanded area less than 800 m^2 (selection probability equal to the relative frequency of the size class). Over the entire area of the 70 expanded gaps, new tree generation was assessed in two categories: saplings (>1.3 m height and <7 cm DBH) and gapfillers (all trees >7 cm DBH and <20 m height). For the gapfillers, we recorded the species, DBH and height, whereas for the saplings we recorded only species. To determine the age of the gapfillers, and to quantify radial growth release characteristics necessary for the gap age estimation, we collected one increment core from 3 to 8 (varying with size of canopy gaps) of the largest and tallest gapfillers at 100 cm above ground (cf. Bottero et al. 2011, Schliemann and Bockheim 2011).

6.2.3 Data analysis

The complexity of gap shapes was quantified by comparing the perimeter–area ratio of canopy gaps with the values of circles of equal area (Lertzman and Krebs 1991). The correlation analysis of the canopy gap traits was carried out using Pearson's correlation coefficient (r) and if the assumptions, especially normal distribution of the variables, were not met, we reverted to Spearmann's correlation coefficient (ρ). The statistical analysis of gap characteristics (e.g. sizes, shapes) was performed in Statistica 7.1 (StatSoft Inc. 2005).

6.2.4 Dendroecological analysis

The increment cores were air-dried, glued onto a base and sanded. The ring widths were measured using the WinDENDRO software (Regents Instruments Inc. 2005) with a precision of 0.01 mm. Incomplete cores were either abandoned (rotten cores) or repeated during later collection of cores in the field (cores missing the pith). Of all the increment cores collected, 231 could be analyzed. To detect radial growth releases, we analyzed the ringwidth measurements to determine percentage growth change (PGC) using the 10-year running mean method developed by Nowacki and Abrams (1997). The PGC values were computed in Excel using a formula from Nowacki and Abrams. These values represented the percentage change in mean annual increment between two 10-year intervals (10 years earlier and later than a given year). A major release event was identified as the period in which the PGC was at least 50% greater than the 10-years running mean for at least five consecutive years (Buchanan and Hart 2012). A distinct major growth release event was not found in increment cores from three of the gaps and consequently these gaps were excluded from further analysis.

The age of a canopy gap was estimated by the most recent (youngest) major growth release event found in common in more than 50% of all sampled gapfillers in a gap (Bottero et al. 2011). Although, all major growth releases were identified, information on how previous disturbances affected current gap characteristics was unavailable. Therefore, we chose the last major growth release as the most reliable indicator for age of that gap. All age determinations (gap age and gapfiller age) were obtained from cores taken at 100 cm height and no correction for the coring height was applied.

6.2.5 Analysis of the spatial pattern of canopy gaps

The adapted pair-correlation function $g(r)$ describes the spatial distribution of objects of finite size and irregular shape at a given radius r. Distances between objects are calculated as length of the shortest straight line between the boundaries of the objects. Since the adapted pair-correlation function deals with objects of finite size. Since the expected number of objects under complete spatial randomness in a distance interval is difficult to determine in a closed form and is even distance-dependent, a correction factor is derived from the Monte Carlo simulation of the null model and subsequently applied to the estimated pair-correlation and the confidence envelopes. An approximate 99% confidence envelope is provided by the 5th smallest and the 5th largest values of 999 randomizations (Besag and Diggle 1977, Stoyan and Stoyan 1994). We constructed the null model for complete spatial randomness by random rotation and positioning of the original objects (cf. Wiegand et al. 2006). The adapted pair-correlation function is described in detail in Nuske et al. (2009).

To address the fundamental assumption of stationarity (Illian et al. 2008), we divided the study site into a northern and a southern part because the southern part was slightly steeper and the gap density lower (Fig. 6.1). The northern part (Fig. 6.1a) comprised 250 canopy gaps on 21.7 ha, whereas the southern part (Fig. 6.1b) contained only 71 on 10.6 ha. Within the two parts, the gap density was quite homogeneous. Thus, we considered the assumption as met although natural environments are rarely totally homogeneous.

The calculation of the adapted pair-correlation function was carried out using functionality of GEOS – Geometry Engine Open Source within PostGIS, which adds support for spatial and geographic objects to the PostgreSQL database (GEOS Development Team 2013, PostGIS Development Team 2013) and the statistical software R (R Development Core Team 2013).

6.3 Results

6.3.1 Characteristics of canopy gaps

On the 32.3 ha study site, a total number of 321 gaps were recorded, amounting to 10 gaps per hectare on average. Canopy gaps and expanded gaps comprised 12.8% and 28.5% of the study area respectively. The median ratio of expanded gap to canopy gap size was 2.6, with a minimum of 1.4 and maximum of 10.7. The size of both the canopy gaps and expanded gaps was highly variable (Table 6.1).

Table 6.1: Characteristics of canopy gaps and expanded gaps within the study site, a sessile oak– European beech old growth forest in the Runcu Grosi Natural Reserve, western Romania.

Characteristics	Canopy gaps	Expanded gaps
Gap size (m^2) median (min–max)	79.7 (11.4–1387.6)	220.8 (38.5–2144.1)
Gap perimeter (m) median (min–max)	38.9 (15.4–220.6)	60.4 (29.9–257.4)
Gap fraction (%)	12.8	28.5

The frequency distribution of canopy gap sizes showed a negative exponential curve, with the parameters $\lambda = 0.0077$ ($\chi^2 = 10.51$, *df* = 4, $p < 0.05$). Most of the canopy gaps (60%) were smaller than 100 m^2, 34% were between 100 and 300 m^2, and only 2% larger than 500 m^2. The distribution of expanded gap sizes corresponded to the lognormal distribution with the parameters $\mu = 5.43$ and $\sigma = 0.43$ ($\chi^2 = 3.71$, *df* = 6, $p > 0.05$). The majority of the expanded gaps (57%) were between 100 and 300 m^2, with a maximum in the class 100–200 m^2 (Fig. 6.2).

Despite the very high proportion of small gaps (area <100 m^2), these contributed minimally to the total canopy gap area (Fig. 6.2). Nevertheless the proportion of canopy gaps <300 m^2, which accounted for 94% of the gaps by number, made up 71% of the overall gap area. The canopy gaps >500 m² contributed only 24% to the total gap area. Similarly the size classes between 100 and 300 m², which had the highest gap frequency, comprise about 54% of the overall expanded gap area.

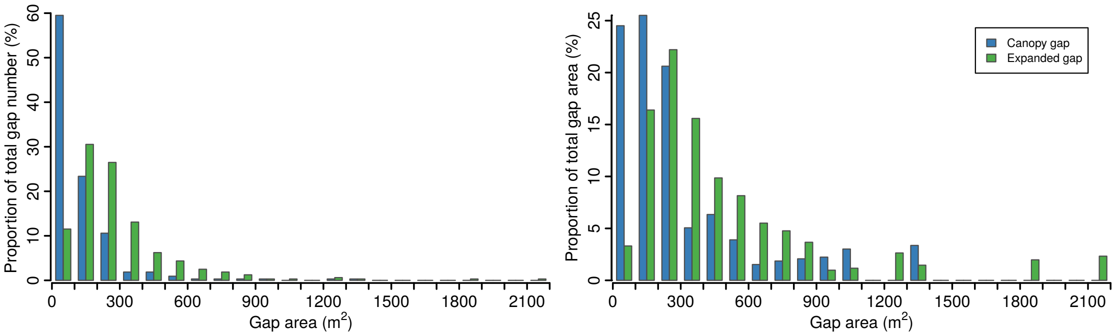

Figure 6.2: Proportion of canopy gaps and expanded gaps (top panel) and proportion of total gap area (bottom panel) by gap size classes.

The perimeter–area ratio of the canopy gaps increases faster than that of circles of equal size (Fig. 6.3). Canopy gaps become more irregular with increasing gap size.

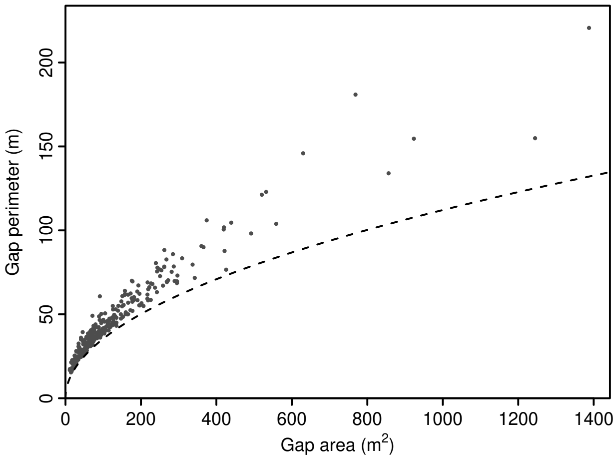

Figure 6.3: Canopy gap shape complexity measured by the perimeter–area ratio. The dashed line shows the area–perimeter relationship of a circle of equal size.

6.3.2 Spatial pattern of canopy gaps

The spatial arrangement of the canopy gaps in the northern and southern part of the study site differed markedly (Fig. 6.4). Due to the larger number of gaps analyzed in the northern part, the confidence envelope (Fig. 6.4a) is also smaller. The estimated pair-correlation function describing the spatial arrangement of the canopy gaps in the southern part (Fig. 6.4b) does not deviate significantly from the confidence envelopes, and therefore the null hypotheses of complete spatial randomness cannot be rejected over the entire range of scales. In contrast the pair-correlation function for the northern part crosses the confidence envelopes a number of times indicating deviations from the null model at various scales (Fig. 6.4a). Distances up to 3 m are less frequent than expected, meaning gaps are rarely very close to each other. This is often described as soft-core effect. The deviation from the confidence band in the ranges 6–9 m and 26–27 m indicate that these distances are more frequent than expected. The distances of 6–9 m are within the range of typical crown sizes, which is about 7.6 m in this stand, suggesting that many gaps are separated just by one crown width.

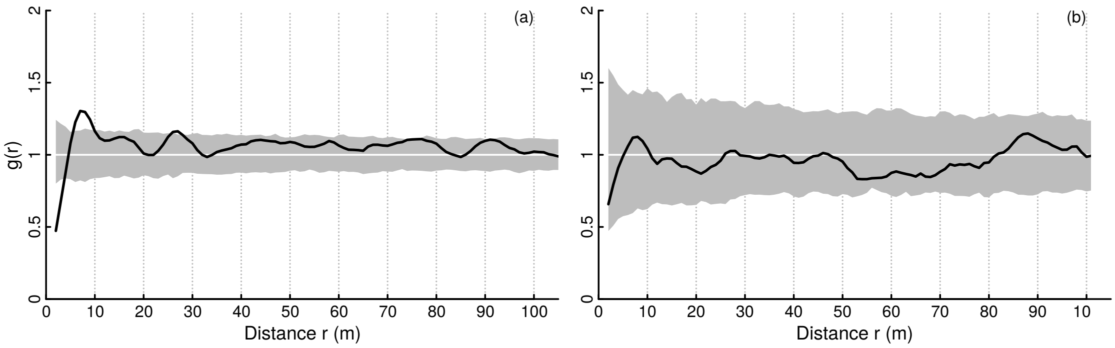

Figure 6.4: Adapted pair-correlation function of the canopy gaps for the northern (a) and the southern part (b). Black line: estimated function; white line: theoretical value of the function under the null hypothesis of complete spatial randomness; grey area: 99% confidence envelope under the null hypothesis, computed by Monte Carlo simulation using 999 replicates. Values $g(r) < 1$ suggest inhibition between points and values $g(r) > 1$ suggest clustering.

6.3.3 Gapmaker mortality

The number of trees involved in the formation of a gap ranges from 1 to 18 with a median of 3 (Fig. 6.5). Gaps with two gapmakers were most common (22%). More than half of the gaps were created by death of 2–4 trees and only 16% by a single canopy tree. The gaps with 8 or more gapmakers were less frequent (about 11%). On the one hand more gapmakers per gap were found with increasing gap sizes. On the other hand the number of gapmakers was highly variable, especially in small gaps. In gaps <100 m², the number of gapmakers varied between 1 and 9 with 76% of the gaps having at least 2 gapmakers. The highest variability in number of gapmakers was found in gaps with an area between 100 and 300 m² (1–13 gapmakers per gap).

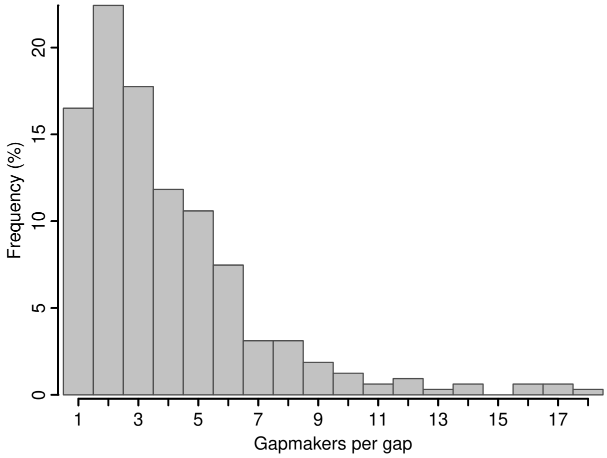

Figure 6.5: Distribution of the number of gapmakers per gap of all canopy gaps.

The gapmakers in each gap often belonged to different decay classes: in 37% of the gaps, the gapmakers belonged to two different decay classes; in 35% of the gaps, gapmakers were characterized by the presence of three or four decay classes; and in the remaining 28%, either one gapmaker, or more, which had created the gap, belonged to the same decay class. Furthermore in most gaps at least two mortality types were identified.

Of the total 1269 gapmakers, 80% were *Q. petraea*, 19% were *F. sylvatica* and only 1% was a less abundant species like *C. betulus*, *P. avium*, *Betula pendula*, *Populus tremula* or *Ulmus glabra* (Table 6.2). If trees which formed the expanded gap

(N = 2475), were used for the estimation of the canopy composition, the proportion of *F. sylvatica* gapmakers was lower than its proportion in the canopy (44%), whereas the proportion of *Q. petraea* was higher than its proportion in the canopy (54%). The mean diameter of *F. sylvatica* gapmakers (50.8 cm) was similar to the mean diameter of *Q. petraea* (49.1 cm), but that of the European beech gapmakers was more variable (coefficient of variation (CV) of 50%) than sessile oak (CV = 29%). The diameter distributions of the gapmakers differentiated into the two main species are presented in Fig. 6.6. While European beech gapmakers were approximately evenly distributed across the moderate and large diameter classes with a higher representation in the smaller classes (negative exponential distributed, $\lambda = 0.0196$ ($\chi^2 = 202.11$, $df_{(adjusted)} = 9$, $p < 0.05$), most sessile oak gapmakers had diameters of 30–60 cm (normally distributed, $\mu = 49.13$ and $\sigma = 208.91$ ($\chi^2 = 91.38$, $df = 5$, $p < 0.05$).

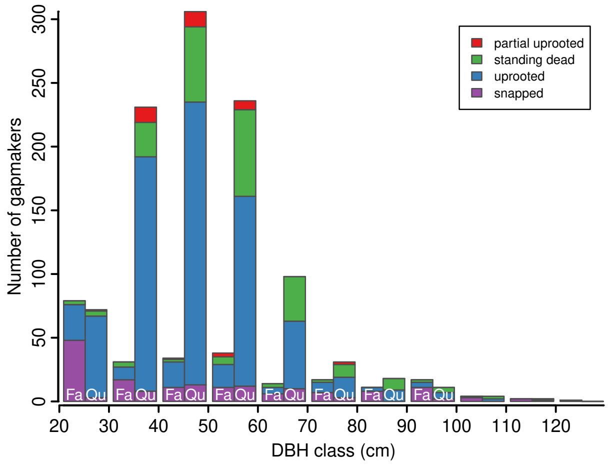

Figure 6.6: Diameter distribution of the two most frequent gapmaking tree species (*Fagus sylvatica*: Fa and *Quercus petraea*: Qu) differentiated by mortality type and diameter class.

The primary mortality type of the gapmakers was uprooting (64%), followed by standing dead (19%) and snapped (14%), the remaining 3% were partially uprooted (Table 6.2). The two principal gapmaker tree species differed in their mortality While snapping was the primary cause of European beech mortality (51% of all European beech gapmakers), most sessile oak gapmakers had been uprooted (73%). The second most common mortality type was uprooting for European beech (38%) and standing dead for sessile oak (22%, Table 6.2).

The standing dead trees have the highest mean diameter (54.6 cm) and the uprooted trees the lowest (47.3 cm). The main tree fall directions of the snapped and uprooted trees were southwest and south.

Table 6.2: Summary characteristics of the gapmakers (species, mortality types and decay classes).

	Fagus sylvatica		*Quercus petraea*		Other Species	
	No.	%	No.	%	No.	%
Mortality type						
Standing dead	22	9	219	22	2	15
Snapped	126	51	52	5	3	23
Uprooted	94	38	705	70	8	62
Partially uprooted	4	2	34	3	0	0
Decay class						
Fresh dead	76	31	115	11	4	31
Moderate decay	51	21	187	19	3	23
Advanced decay	47	19	271	27	3	23
Strong decomposed	72	29	437	43	3	23

6.3.4 Gap age

The gap ages varied from 6 to 39 years, while most of the gaps were less than 20 years old (Fig. 6.7). The number of major growth releases was found to correlate positively and significantly with canopy gap size ($\rho = 0.328$, $p < 0.05$) and the number of different decay classes per gap ($\rho = 0.295$, $p < 0.05$). No significant correlation was found between gap age and gap size.

6.3.5 Saplings and gapfillers

The average density of gapfillers, and saplings in gaps was 233 ha^{-1}, and 1070 ha^{-1} respectively, and the number of individuals ranged from 0 to 584 gapfillers per hectare, and from 0 to 6898 saplings per hectare. European beech was the most common species, accounting for 91% of all gapfillers and 88% of all saplings. The remaining 9% of the gapfillers were *C. betulus*, while other species like *Q. petraea*, *T. cordata*, *P. avium*, *Sorbus aucuparia* were very rare (together less than 1%). The mean DBH of the European beech gapfillers was 12.3 cm and of hornbeam 15.6 cm. Their diameter distributions followed a negative exponential distribution. 16% of all gapfillers were damaged (10% broken and 5% bent over).

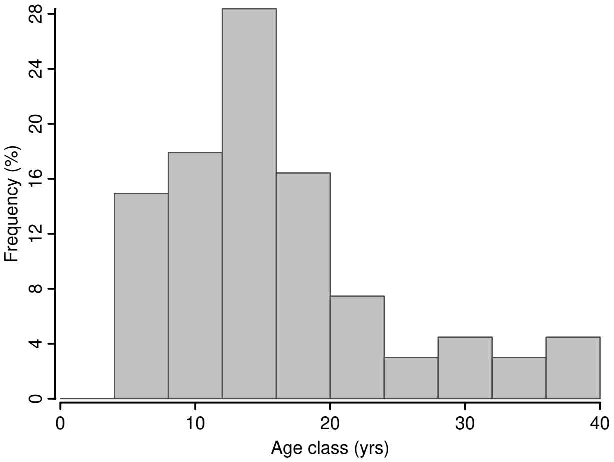

Figure 6.7: Age distribution of 67 canopy gaps where age could be determined from increment cores taken from the regeneration.

In addition to European beech (88%) saplings, other sapling species were present like *C. betulus* (4%), *Q. petraea* (3%), *A. pseudoplatanus* (3%), *T. cordata* (1%), *P. avium* (1%), and very rarely by *S. aucuparia* and *U. glabra* which made up the remaining 1%. While the density of gapfillers was not correlated with gap size, a weak correlation between gap size and saplings density was found ($r = 0.25$, $p < 0.05$). Moreover gap size significantly influenced the tree species richness growing in the gap ($r = 0.36$, $p < 0.05$ for gapfillers and $r = 0.74$, $p < 0.05$ for gap saplings).

Distribution of gapfillers per age classes and species is shown in Fig. 6.8. The age of the dominant European beech gapfillers was normally distributed, with a maximum at the age of 50 years. The oldest gapfiller was a wild service tree of 173 years. European hornbeam had approximately the same low level of establishment between 30 and 70 years, while wild cherry, and small-leaved lime appeared with very low participation rate at 30, and 70 years respectively.

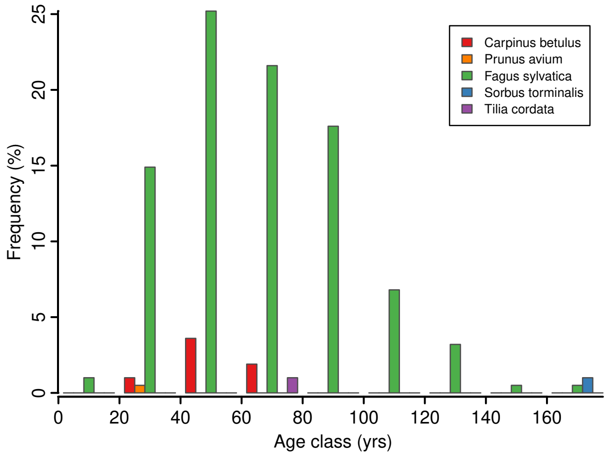

Figure 6.8: Species distribution of gap-filling trees per age class of all canopy gaps: percentage frequency indicates the number of gapfillers in each class as a percentage of the total number of gapfillers.

6.4 Discussion

6.4.1 Gap disturbance regime

Recent studies on disturbance regimes in European temperate, old-growth forests have revealed that the proportion of the forest area found in canopy gaps varies not only among stands with different tree species compositions, but also among stands with the same compositions. Consequentially, the canopy gap fraction in European beech virgin forests ranges from 3.3–6.6% in Albania (Tabaku and Meyer 1999) through 5.6% in Slovenia (Zeibig et al. 2005) to 14.6–16% in Slovakia (Drößler and von Lüpke 2005). In mixed old-growth forests of European beech and silver fir or silver fir and Norway spruce, the gap fraction is generally higher: between 9% (Kenderes et al. 2009) and 19.3% (Bottero et al. 2011). The canopy gap fraction of 12.8% observed in the sessile oak–European beech old-growth forest at our study site in Runcu-Grosi Reserve is within the reported range. On one hand the canopy gap fraction found in this study is in the lower part of the range given for mixed old-growth forest with European beech. On the other hand, Cho and Boerner (1991) reported a canopy gap fraction lower than 3% for two old-growth forests dominated by oak in North America.

The expanded gap fraction (28.5%) measured in the study site was lower than comparable values in the literature such as the European beech–fir forest of Perucica [Bosnia and Herzegovina; 37.8%, (Nagel and Svoboda 2008) or Badinsky prales (Slovakia; 37.9%, Kucbel et al. 2010), the European beech–fir–spruce forest of Lom [Bosnia and Herzegovina; 41.4%, (Bottero et al. 2011), and particularly the European beech virgin forest of Slovakia (50– 55%, Drößler and von Lüpke 2005). The low expanded gap fraction in this study as well as the low expanded gap-canopy gaps ratio may be caused by the higher proportion of sessile oak among the surrounding trees delimiting the expanded gap. Sessile oaks have smaller crowns compared to European beech in this area (unpublished data). Furthermore the European beech crowns have a higher plasticity and, even at a rather old age, respond more quickly when growing space becomes available compared to oak.

The lognormal or negative exponential distribution of the frequency distribution of gap sizes is reported in numerous studies (e.g. Runkle 1982, Lertzman and Krebs 1991, Drößler and von Lüpke 2005, Nagel and Svoboda 2008, Kucbel et al. 2010). Our findings confirmed this typical feature. Most of the canopy gaps were smaller than 100 m^2 and the number of gaps decreased strongly with rising gap size. Half of the canopy gaps had an area smaller than 79.7 m^2. This is similar to the median of canopy gap sizes of other studies carried out in Central and Southeast Europe (Nagel and Svoboda 2008, Bottero et al. 2011), indicating a disturbance regime dominated by small-scale disturbances. In the Runcu Grosi Natural Reserve the small gaps showed not only the highest frequency of occurrence, but also accounted for a higher proportion of the total gap area (25% compared to only 20% in other studies, Nagel and Svoboda 2008, Kucbel et al. 2010). Moreover, canopy gaps smaller than 300 m^2 made up 71% of the total gap area, while those larger than 500 m^2 accounted for 24%, and those larger than 1000 m^2 only for 8%. These results emphasize the importance of the small to intermediate disturbance in our sessile oak-dominated stands. A similar pattern was observed in the European beech–fir–spruce old-growth forest of Lom Reserve (Bottero et al. 2011), whereas in the European beech–fir old-growth forest in Perucica (Nagel and Svoboda 2008) or in Badinsky prales (Kucbel et al. 2010), larger gaps accounted for about 40% of the total canopy gap area.

6.4.2 Spatial pattern of canopy gaps

Gaps in the canopy layer arise through the death or fall of a tree or a major part of a tree crown. Canopy gaps are always surrounded by crowns. Therefore, two gaps can never touch and are usually separated by one or more crowns or larger parts thereof. Distances between canopy gaps will, therefore, never be zero and seldom smaller than a typical crown diameter. This is reflected in the pair-correlation function as there were fewer short distances (zero to crown diameter) than expected under complete spatial randomness. Since a crown diameter is not a fixed width, the pair-correlation function slowly approaches one, while the distance increases from 0 to a typical crown diameter. This is called soft-core effect because there is a minimum distance between two objects which, in contrast to the hard-core effect, is not fixed. This effect can be seen in the pair-correlation function for the northern part of the study site (cf. Fig. 6.4a). Three distinct peaks at 8, 15, and 25 m can be identified, with two of them deviating significantly from the confidence envelope, caused by distances between canopy gaps being more frequent than expected. These distances relate to multiples of the typical crown size, meaning that gaps are very often separated by about one crown and less often by two, three or more crowns. This may suggest a slight tendency towards regularity.

The frequent, short inter-gap distances and small gaps sizes found in this study suggest that the trees surrounding the canopy gaps are not more susceptible to dying than trees in the middle of the stand, which means that the gaps, by virtue of their presence, do not lead to increased rates of gap expansion. The small-scale disturbance regime seems to eliminate only the weak or predisposed individuals. The observed slight tendency to regularity might thus be a consequence of the stand being a mixture of sessile oak and European beech. Consequentially, this is in contrast to studies in more homogeneous forest stands (e.g. Frelich and Lorimer 1991, Nuske et al. 2009).

The pair-correlation function of the southern part (cf. Fig. 6.4b) does show a weak soft-core effect, but the function never deviates from the confidence envelopes and hence suggests that the canopy gaps of this part are at least approximately randomly distributed. The slightly steeper slopes and, consequentially, shallower soils in the southern part might lead to trees being more susceptible to uprooting (Zeibig et al. 2005) and thus larger more randomly distributed gaps.

The adapted pair-correlation function, employed in this study, describes the spatial distribution of canopy gaps without being influenced by their size or shape and all gaps have the same influence on the shape of the function regardless of their size. This approach provides meaningful results and even reveals the interaction of gaps at small scales, which the uncorrected (polygon based) *L*-function or the *O*-ring function (cf. Law et al. 2009, Garbarino et al. 2012) are unable to do.

6.4.3 Gapmaker mortality

Most of the gaps were caused by death of at least two canopy trees, in spite of the predominance of small canopy gaps in the study area. Canopy gaps with one gapmaker accounted only for 16%, the lowest value reported so far in European beech-dominated forests in Europe. Furthermore, the frequency distribution of gapmakers in our study differed from the inverse J-shaped curve often reported (Drößler and von Lüpke 2005, Nagel and Svoboda 2008, Kucbel et al. 2010) as they tended to follow a lognormal distribution with a peak in the range of two and three gapmakers (cf. Fig. 6.5).

The expansion of canopy gaps is generally regarded as an important cause of the formation of larger gaps both in Europe (Nagel and Svoboda 2008, Kucbel et al. 2010) and in North America (Worrall et al. 2005). The positive correlation between canopy gap size and number of releases underpins this finding. Although not many large gaps were found in the study area, subsequent expansion after initial formation of small canopy gaps did not seem to be unusual, since the majority of gaps (>70%) were formed by gapmakers from at least two decay classes and the regeneration originated from more than one growth release. In addition the gapmakers within the same gap often died differently, predominantly from combinations of uprooting and standing mortality, followed by the combination of uprooting and snapped types.

The process of gap formation in the investigated old-growth forest is also influenced by the different contributions of the canopy tree species and by the different causes of mortality. The principal tree species of the gapmakers was sessile oak (80%), which died prevalently uprooted and sometimes standing. In contrast, in European beech mortality occurred frequently due to snapping, but also uprooting. Furthermore the two tree species differ in their decay process. While the reported decay time for European beech does not exceed 25–50 years depending on site conditions (Müller-Using and Bartsch 2003, Christensen et al. 2005), Vandekerkhove et al. (2009) using results of Schowalter et al. (1998) estimated a duration for a complete decay of more than 150 years for large oak trees.

The mortality types uprooting and snapping (together >3/4 of all gapmakers) dominated the cause of death of the gapmakers in the study site, suggesting that exogenous disturbances like wind or snow govern the gap forming process in this forest. But the considerable occurrence of standing dead trees (19% most of them oaks) and the fact that we could not determine whether uprooted trees were alive or dead before the incident leads to the presumption that the role of endogenous mortality is not negligible in this forest stand. As in other old-growth forests (Nagel and Svoboda 2008, Bottero et al. 2011) the different fungi or pathogen agents and insect pests probably increase the susceptibility of standing trees to wind or snow-related mortality. Moreover, Peterken (2001) and Vandekerkhove et al. (2009) found that the majority of trees in oak forests die standing. Due to their root anchorage system and the slow decay process, the dead standing sessile-oak trees need several decades before they fall over (Vandekerkhove et al. 2009). Conversely, standing dead European beech trees need only 10 years to fall over (Korpel 1995, Oheimb et al. 2007).

6.4.4 Tree regeneration in canopy gaps

The reported positive correlation between the irregularity in gap shapes and the complexity in gap formation and multiple expansion events (Lertzman and Krebs 1991, Nagel and Svoboda 2008) was confirmed by our results. Besides the gap size, the complexity in the gap shape influences the regeneration through the control of the light environment (Rozenbergar et al. 2007). By creating environmental heterogeneity, especially in terms of light availability, the gap phase plays an important role in forest regeneration, and in the establishment and development of tree species with different ecological recruitment patterns (Runkle 1989, Peterken 2001, Mountford et al. 2006). The larger the gap size and greater the gap complexity, the higher the species richness found in the sapling and gapfiller layers.

But the current predominantly small-scale disturbance was illsuited for the ascent of sessile oak into the subcanopy or canopy of the stand. Although *Q. petraea* is the most common tree species in the canopy layer today and a particularly common gapmaker, it was seldom a gapfiller. Its higher frequency of occurrence among the saplings and especially among the seedlings (personal observation) suggests that the lack of Quercus individuals as gapfillers is not a consequence of a lack of seedlings. In a companion study (Petritan et al. 2012) carried out in the same Reserve but over an entire area not just in gaps, the authors found that in the oak-dominated plots, the regeneration consisted predominantly of sessile oaks, but most of them were smaller than 1.3 m. Von Lüpke (1995) stated that sessile oak regeneration is feasible in gaps with diameters as small as 17–20 m (≈300 m^2), whereas most canopy gaps in this study are smaller than this. The low presence of sessile oak among the saplings and especially among gapfillers confirms the frequently reported steady decline of the Quercus species and their replacement by more shade-tolerant species in the natural reserves in Central Europe (e.g. Sielhorst et al. 2009, Rohner et al. 2012) as well as in the oak forests in North America (Cho and Boerner 1991, Nowacki and Abrams 1997, Aldrich et al. 2003). The failure of oaks to regenerate can not only be explained by the small canopy gap fraction (Cho and Boerner 1991), but also by the nowadays common small-scale disturbance regimes which predominantly create small canopy gaps that do not provide enough light requirements for relatively shade–intolerant species (Aldrich et al. 2003, Cowell et al. 2010). In a comprehensive study of canopy disturbance reconstructions in 44 old-growth oak stands in the eastern United States, Buchanan and Hart (2012) also revealed a “steady decline in large gap-scale disturbances beginning in the mid-1600s", which was associated with a loss of shade–intolerant species like oaks. The fact that disturbance regimes dominated by small canopy gaps are more suitable for the regeneration of shade-tolerant species (Runkle 1985) is also supported by our investigation. European beech, due to its high shade tolerance (Ellenberg and Leuschner 2010), regenerated continuously under the current disturbance regime (large age variation of the gapfillers up to 165 years) and became the main gapfiller species (91%). The proportion of European beech in the regeneration was much larger than in the canopy (44% of the surrounding trees) and particularly among gapmakers (only 9%). This suggests that the abundance of European beech will continue to increase in the Runcu Grosi Natural Reserve. Although the proportion of *C. betulus* in the main canopy was very low, it accompanied European beech regeneration (9% of gapfillers) recruited during the last 3–7 decades. Its lower participation among the saplings (4%) suggests a better survival and growth under present light conditions compared to other species such as *Q. petraea* and *A. pseudoplatanus*, which together amounted to 6% of the saplings in the gaps, but were almost absent among the gapfillers.

In summary, the small-scale disturbance pattern found in the study area in the Runcu Grosi Natural Reserve is more suitable for the shade-tolerant European beech to regenerate and recruit to the canopy layer, accentuating the already steady decline of oak in the mixed sessile oak–European beech stands.

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7 Using unmanned aerial vehicles (UAV) to quantify spatial gap patterns in forests

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Abstract

Gap distributions in forests reflect the spatial impact of man-made tree harvesting or naturally-induced patterns of tree death being caused by windthrow, inter-tree competition, disease or senescence. Gap sizes can vary from large (>100 m^2) to small (<10 m^2), and they may have contrasting spatial patterns, such as being aggregated or regularly distributed. However, very small gaps cannot easily be recorded with conventional aerial or satellite images, which calls for new and cost-effective methodologies of forest monitoring. Here, we used an unmanned aerial vehicle (UAV) and very high-resolution images to record the gaps in 10 temperate managed and unmanaged forests in two regions of Germany. All gaps were extracted for 1-ha study plots and subsequently analyzed with spatially-explicit statistics, such as the conventional pair correlation function (PCF), the polygon-based PCF and the mark correlation function. Gap-size frequency was dominated by small gaps of an area <5 m^2, which were particularly frequent in unmanaged forests. We found that gap distances showed a variety of patterns. However, the polygon-based PCF was a better descriptor of patterns than the conventional PCF, because it showed randomness or aggregation for cases when the conventional PCF showed small-scale regularity; albeit, the latter was only a mathematical artifact. The mark correlation function revealed that gap areas were in half of the cases negatively correlated and in the other half independent. Negative size correlations may likely be the result of single-tree harvesting or of repeated gap formation, which both lead to nearby small gaps. Here, we emphasize the usefulness of UAV to record forest gaps of a very small size. These small gaps may originate from repeated gap-creating disturbances, and their spatial patterns should be monitored with spatially-explicit statistics at recurring intervals in order to further insights into forest dynamics.

Keywords: autonomous flying, biodiversity, canopy gaps, drone, polygon-based pair correlation function, remotely piloted vehicles, RPV, unmanned aircraft systems, UAS, UAV

7.1 Introduction

Gaps in forest canopies play a key role in the regeneration of trees and generally for the diversity of understory biota. Forest management via thinning intensity may greatly influence canopy cover and, subsequently, species diversity and the cover of ground vegetation (Augusto et al. 2003, Boch et al. 2013). Gap formation, whether induced by management or by natural causes, such as windthrow, insects, disease or competition, largely regulates the below-canopy supply and spatial distribution of central abiotic factors, such as solar energy, water and nutrients. The overstory layer operates as a filter by intercepting the incoming light signal, and therefore, controls the structural complexity of the understory layer (Proulx and Parrott 2008). For example, if gap sizes become too small in beech forests, beech seedlings may wither, but if gap sizes are too large, beech seedlings may be ineffective at reaching the gap center, due to increased competition with, e.g., bramble, ash or maple (Mountford et al. 2006). In addition to size, the shape complexity of gaps determines biodiversity and woody regeneration, because it likely influences the competitive or facilitative relationships of plant species in the understory (Getzin et al. 2012).

The spatial distribution of gaps has implications for seed establishment and, therefore, the formation of future spatial patterns (Koukoulas and Blackburn 2004, Koukoulas and Blackburn 2005). Spatial aggregation of forest structure may strongly regulate understory light and its spatial variation in the forest (Kuuluvainen and Linkosalo 1998). Bright environments with sufficient light influx are especially possible if retained trees are clumped rather than dispersed uniformly and gaps between clumps are relatively large (Drever and Lertzman 2003). In both coniferous and deciduous forests, patch removal and resulting aggregated canopy structure have been found to be important for sufficient recruitment of tree species via increased light penetration (Battaglia et al. 2002, Coates et al. 2003). Connectivity within the distribution of canopy structures need not entail physical linkages, because it is the functional connectivity that is ultimately important. Functional connectivity, however, is highly scale-dependent, since it depends on the scale at which individuals perceive and interact with canopy structures. This scale is difficult to assess a priori and has to be identified by testing for a correlation between population-dynamic features of interest and structural characteristics at different spatial scales (Wiegand et al. 1999).

The spatially-explicit distribution of gaps at typical plot sizes of one hectare or more cannot efficiently be quantified with traditional ground-based methods, such as the vertical projection of the tree crowns or hemispherical photographs (Proulx and Parrott 2008). Those methods are tedious and error prone when the goal is to map the pattern of all gaps extensively at spatially-continuous scales. Even tools, such as terrestrial laser scanners, are unsuitable for this purpose, because the tripod with the laser needs to be repeatedly relocated in order to get a free view of all gaps. This is ineffective for monitoring gaps, especially when foliage cover in the mid- and under-story is high (Ramirez et al. 2013). The most efficient tool for spatially-explicit mapping of canopy gaps is based on remote sensing. In the past, this has been traditionally done with aerial photographs during manned flights; however, the resolution of such standard images is, with 20 cm/pixel, generally too coarse in order to record the detailed shape complexity of small canopy openings. However, it is important to monitor also very small gaps, because understory species richness is positively related to the variability of diffuse radiation (Montgomery and Chazdon 2002, Moora et al. 2007). Airborne LIDAR (light detection and ranging) provides much more detailed resolutions for recording even small gaps (Vepakomma et al. 2008, Boyd et al. 2013), but its main disadvantage is the high monetary costs.

A new solution to these problems comes nowadays with the availability of unmanned aerial vehicles (UAVs), which can be used to accurately map all gaps of a forest plot at high precision levels. An important novelty of UAV-acquired images lies in their very high resolution. For example, it has been demonstrated that resolutions of 7 cm/pixel permit the identification of highly-detailed gap structures and gaps as small as 1 m^2, which can be used for assessing understory biodiversity in forests (Getzin et al. 2012). Anderson and Gaston (2013) suggested that "unmanned aerial vehicles will revolutionize spatial ecology [because these] offer ecologists new opportunities for scale-appropriate measurements of ecological phenomena". These UAVs are not only cost-effective for usual plot sizes, but flight missions can be timed very flexibly, and due to low flying altitudes, images are rarely affected by cloud cover. This makes them ideal tools for monitoring ecological objects of interest and for natural resource management and conservation in all biomes, from temperate systems to the tropics (Koh and Wich 2012, Wing et al. 2013).

In this study, we demonstrate how UAV images can be used for scale-appropriate analyses of canopy gap spatial patterns in 10 exemplary 1-ha forest plots. These plots include managed and unmanaged deciduous forests of two regions in Germany. Our primary goal is not to relate the gap patterns directly to management causality, but rather to emphasize the spatial pattern analysis and related difficulties that may arise. For example, we will show how the application of different spatial statistics reveals different types of negative or positive correlation between gaps. We demonstrate the use of a recently-developed polygon-based pair correlation function, which is especially suitable for gap patterns (Nuske et al. 2009). Furthermore, we test the hypothesis that very small gaps are particularly frequent in the study plots (see, e.g., Boyd et al. (2013). Finally, we illustrate how the spatial information of gaps obtained through pattern analysis can be used to relate them to some ecological phenomena, such as gap formation.

7.2 Materials and methods

7.2.1 Study sites

The study sites were located within beech-dominated deciduous forests of the so-called Biodiversity Exploratories in Germany. These are long-term research platforms embedded in natural landscapes to investigate the effects of varying land-use intensities on functional biodiversity response (Fischer et al. 2010). For our canopy gap analyses, we selected three 1-ha plots of mature and mainly single-layered stands in the exploratory “Schwäbische Alb” in southwestern Germany and, similarly, seven plots in the “Hainich-Dün” in central Germany about 300 km away. Average annual precipitation in the Alb is 700–1,000 mm and in the Hainich 500–800 mm. Soils of the Alb are rich in clay and are dominated by Cambisols and Leptosols on limestone. Soils of the Hainich have a loamy texture and are dominated by Luvisols and Stagnosols on loess. Our selected sites were located on relatively level topography. These 10 exemplary 100 m × 100 m plots represent different land-use intensities, such as traditionally managed age-class forest ($n = 3$ in Schwäbische Alb and $n = 2$ in Hainich), selection-cutting forest in the Hainich ($n = 2$) and unmanaged, near-natural forest of the Hainich National Park ($n = 3$). Thus, we have chosen a set of different forest plots that are characterized by different gap fractions, gap shapes and gap distributions, which are considered suitable for demonstrating different results in spatial pattern analysis.

7.2.2 Aerial images

Very high-resolution RGB images (≈7 cm/pixel) were taken at the end of the summer in 2008 and 2009 with the UAV "Carolo P200" (Böhm et al. 2008) above the centers of the 1-ha forest plots at flying altitudes of ≈250 m (Figure 7.1a,b). The UAV weighs 6 kg and has a wing span of 2 m. It can fly autonomously for a time span of 60 min along any predefined spline-based trajectory and takes an image every three seconds. All images were orthorectified based on data recordings of the internal UAV orientation, GPS position and a digital terrain model. Orthophotos were converted into binary images, and gap polygons were manually delineated as accurately as possible using ArcGIS 9.3 and saved as shapefiles (a geospatial vector data format). To assess the accuracy of our image-based method, the delineated gaps were compared to some available gap maps obtained for the same study plots with a manned LIDAR flight (Figure 7.1c; details in Nieschulze et al. 2012). Due to the very high image resolution, we were able to delineate gaps as small as 1 m^2 in size. We segmented all gaps of a plot (Figure 7.2), but included in the analysis only gaps whose center of mass was inside the plot boundaries. More details can be found in Getzin et al. (2012).

7.2.3 Spatial statistics

We applied three spatial correlation functions for the analysis of gap distributions. At first, we used the "conventional" pair correlation function (PCF) to assess whether gap patterns were random, aggregated or regularly spaced at continuous neighborhood scales up to $r = 50$ m. For analyses with the conventional PCF (and the mark correlation function (MCF), see below) we used the center of mass of the gap polygons as the x,y-location. The pair correlation function $g(r)$ is the expected density of points at a given distance r of an arbitrary point, divided by the intensity λ of the pattern (Illian et al. 2008). The PCF is non-cumulative and, thus, particularly suitable to reveal critical scales of the pattern (Stoyan and Stoyan 1994, Getzin et al. 2008). Under complete spatial randomness (CSR), $g(r) = 1$. Values of $g(r) < 1$ indicate regularity, while values of $g(r) > 1$ indicate aggregation.

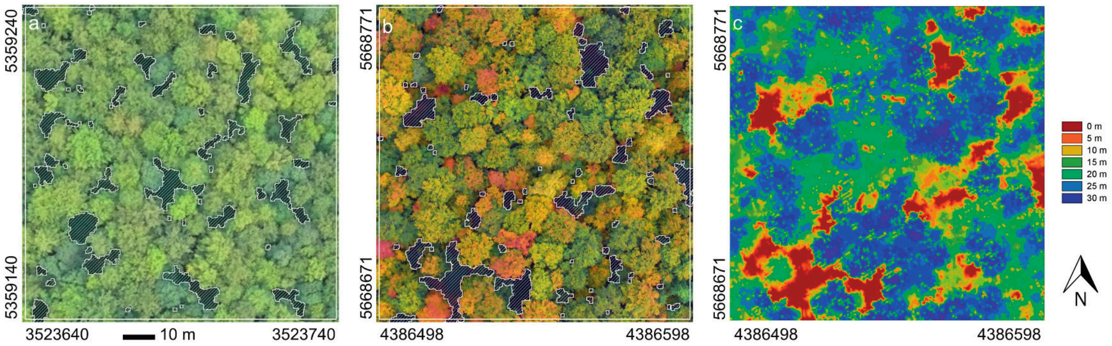

Figure 7.1: Example of a UAV image of the study plot, named AEW20, a traditionally managed age-class beech forest of the Schwäbische Alb (a). Shown are the delineated gaps, which range in size from 81.7 m² to 1.1 m². The image was taken on 2 September 2009. UAV image of the plot HEW31, a selection-cutting forest in the Hainich (b). Colors are more intense, since the image was taken later in the season on 8 October 2008. Shown are the segmented gaps whose spatial structure closely resembles the gaps of the same plot, HEW31, mapped in August of the same year with a manned LIDAR flight (c). The legend on the right is based on the z-coordinate for the uppermost surface measured with LIDAR. The Gauss–Krüger coordinates are given in meters and depict the corners of the 100 m × 100-m study plots.

The pair correlation function is usually applied in ecology to plants, i.e., the *x,y*-location of the stem base, such as a tree trunk. The simplified assumption of a point-centered location is justified because the actual measurement error of the *x,y*-location of the stem base is approximately equal to the magnitude at which the physical size of the, for example, tree trunk may exceed the concept of the actual point measurement. For analyses of forest gaps, however, this concept appears unsuitable, because gap sizes may be very large, and the center of the gap may be far away from the gap edges. Therefore, the pair correlation function needs to be adapted to adequately deal with the real sizes and shapes of gaps (Wiegand et al. 2006, Nuske et al. 2009). For this purpose, we use a recently modified version of the PCF that is particularly suitable for analyzing objects of finite size and irregular shape, such as forest gaps (Nuske et al. 2009). The polygon-based pair correlation function *Polygon g(r)* is defined as the expected density of objects at a given distance r of an arbitrary point, divided by the intensity λ of the pattern. Since the polygon-based PCF deals with objects having a finite size, the expected number of objects under complete spatial randomness in a

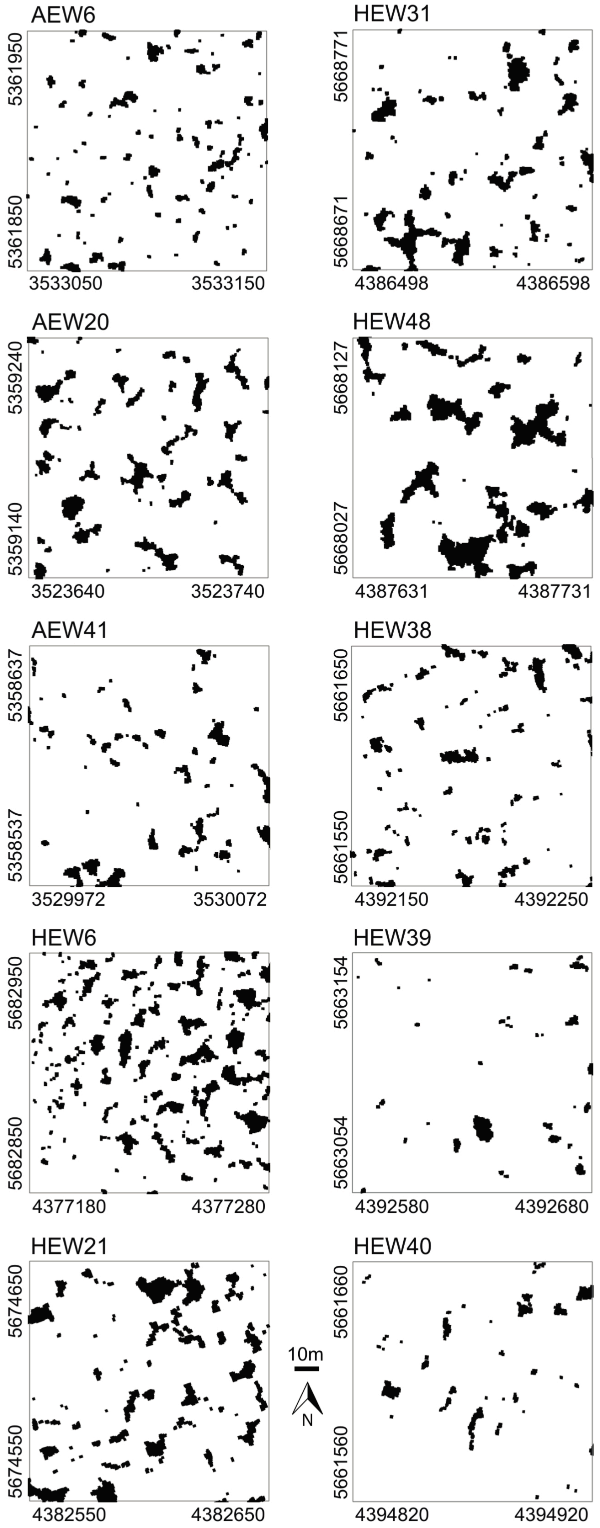

Figure 7.2: Delineated gap patterns of the 1-ha study plots. (Left) Age-class forest. (Right) Selection-cutting forest (upper two) and unmanaged forest (lower three). The Gauss–Krüger coordinates are given in meters and depict the corners of the 100 m × 100-m study plots.

distance interval is difficult to determine in a closed form and even distance dependent. Thus, a correction factor is derived from the Monte Carlo simulation of the null model (see below) and subsequently applied to the estimated pair correlation function and the simulation envelopes. Distances between objects are calculated as the length of the shortest straight line between the boundary polygons. The polygon-based PCF can then be estimated as:

$$Polygon\, \hat{g}(r) = c^{-1}(r) \sum_{i=1}^{n} \sum_{j=1, i \neq 1}^{n} \frac{\omega(r_{ij} - r)}{2\pi r \cdot p_{ij} \cdot \hat{\lambda}^2}, \; r > 0 \qquad (7.1)$$

where $c^{-1}(r)$ is the correction factor described above, $\omega(\cdot)$ the Epanechnikov kernel, a frequently used kernel function for estimating the pair correlation function (Stoyan and Stoyan 1994), and p_{ij} is the edge correction. We set the bandwidth parameter δ of the Epanechnikov kernel to $0.2/\sqrt{\lambda}$ (Stoyan and Stoyan 1994, Stoyan and Penttinen 2000). The edge correction is based on the proportion p_{ij} of the perimeter of a r_{ij}-buffer around each considered object i within the study area, as suggested by Ripley (1981). For a more detailed explanation, please refer to Nuske et al. (2009). The calculation of the polygon-based PCF was performed using GEOS 3.3.8 within PostGIS 2.0.3 (GEOS Development Team 2014, PostGIS Development Team 2014) and the statistical software, R 3.0.2 (R Development Core Team 2013).

Finally, to quantify also the spatial distribution of gap sizes, we analyzed the gap patterns with the mark correlation function (MCF) for continuous marks (Penttinen et al. 1992, Stoyan and Stoyan 1994). This function does not quantify the distance correlation between gaps per se, but assesses whether there is spatial correlation between the gap sizes (area) in dependence of the gap distances r. The mark correlation function $\kappa_{mm}(r)$ is the mean value of the test function $t_1(m_i, m_j) = m_i m_j$ of the marks of two points i and j that are separated by distance r, normalized by the mean value of the test function taken over all i-j pairs in the study plot (Getzin et al. 2008, Illian et al. 2008). If the marks show no spatial correlation, we find $\kappa_{mm}(r) = 1$; if $\kappa_{mm}(r) < 1$, there is negative correlation between the marks at scale r, and if $\kappa_{mm}(r) > 1$, there is a positive correlation between the marks at scale r. The mark correlation function can therefore reveal if gaps that are relatively close to each other are smaller or larger than expected, given the average gap size in the plot.

Monte Carlo simulations of a homogenous Poisson process were applied for the PCF and polygon-based PCF in order to assess significant departure from the null model of complete spatial randomness. We used the fifth-lowest and fifth-highest values of 199 simulations to generate approximately 95% simulation envelopes. Note that we are here mainly interested in comparing the different functional behavior of the two PCFs and not in strict null hypothesis testing. The null model for complete spatial randomness for the polygon-based PCF was constructed by random rotation and positioning of the original objects (Wiegand et al. 2006). Significant departure of the mark correlation function from the independence of the marks was similarly estimated based on random shuffling of the gap sizes.

7.3 Results

7.3.1 Structural properties of gaps

In the five age-class forests, the gap fraction ranged from 4.9% to 13.9%, which reflects past intensities of logging. Furthermore, the mean gap sizes were quite variable in these managed forest plots (Table 7.1). In our exemplary study, the five age-class forests had a larger number of gaps than the less intensively managed selection-cutting or unmanaged forests, respectively. The number of gaps for age-class forests ranged from 56 to 134 (mean = 82.6), while for the selection-cutting and unmanaged forests, it ranged from 31 to only 66 (mean = 47.2). In the selection-cutting forests of the Hainich, mean gap sizes ranged from 14 to 43 m^2. These two plots had the highest maximal gap shape complexities with values of 2.7 and 2.9, respectively. In the unmanaged forest plots of the Hainich National Park, canopy gap fraction had a mean of only 3%, ranging from 2.2% to 5.7% (Table 7.1). Furthermore, mean gap sizes were altogether lowest in the unmanaged plots of the national park.

Table 7.1: Gap structural properties of the 1-ha forest plots. Overview of the most important gap structural properties per 1-ha forest plot (AEW: Schwäbische Alb; HEW: Hainich). The gap fraction is the sum of the area of all gaps in a plot, divided by 100. The GSCI is the gap shape complexity index ($GSCI = perimeter/sqrt(4\ \pi\ area)$), whose smallest reference value is 1.0 for describing a circle. A value of, e.g., 2.5 means 150% complexity (see also Getzin et al. (2012)).

Plot (Management Type)	# of Gaps	Gap Fraction (%)	Gap Size (m^2) Mean/Max	% gaps < $5m^2$	GSCI Mean/Max
AEW6 (age class)	88	5.6	6.4/39.7	64.8	1.3/2.1
AEW20 (age class)	56	9.8	17.5/81.7	42.9	1.5/2.4
AEW41 (age class)	56	4.9	8.7/50.7	55.4	1.3/2.0
HEW6 (age class)	134	13.9	10.4/73.2	63.4	1.4/2.5
HEW21 (age class)	79	12.0	15.2/150.0	51.9	1.4/2.4
HEW31 (selection cutting)	65	9.2	14.1/163.5	60.0	1.4/2.9
HEW48 (selection cutting)	31	13.4	43.3/244.0	41.9	1.6/2.7
HEW38 (unmanaged)	66	5.7	8.6/65.0	59.1	1.4/2.3
HEW39 (unmanaged)	33	2.2	6.6/64.5	69.7	1.3/1.7
HEW40 (unmanaged)	41	2.8	6.9/39.9	65.9	1.3/2.1

Overall, the proportion of very small gaps with a size <5 m² made up on average 57.5% of all 10 forest plots with a tendency of having the largest proportion (≈65%) in the unmanaged forests (Table 7.1). This result is in agreement with our hypothesis.

7.3.2 Spatial patterns of gaps

For the five age-class forests, gap distributions analyzed with the conventional pair correlation function revealed for three plots random spatial patterns and two plots small-scale regularity (Figure 7.3a–e). The same plots analyzed with the polygon-based PCF showed contrasting results (Figure 7.3f–j). For example, there was small-scale regularity (AEW20 plot) or aggregation (AEW41), even though the conventional PCF indicated randomness. In terms of indicating deviation from the null model of complete spatial randomness, results obtained with both types of pair correlation functions differed in four out of five age-class forests. There was only general agreement for the plot HEW21 (Figure 7.3e,j). The mark correlation function indicated for the five age-class forests that gap sizes (areas) were uncorrelated in two plots, but negatively correlated up to a maximum of 9 m in three plots (Figure 7.3k–o).

Compared to the age-class forests that had a high mean number of gaps, there was more agreement in the spatial results between the conventional and polygon-based PCFs for the selection-cutting and unmanaged forests with less numerous gaps (Figure 7.4a–j). Especially when gap numbers were low, i.e., ranging from 31, to 33 and 41 in the plots HEW48, HEW39 and HEW40, respectively, the conventional and the polygon-based PCFs showed a highly similar behavior. For example, gaps were aggregated at small scales in the two unmanaged forests, HEW39 and HEW40. When the gap number was higher, as in HEW31 and HEW38, differences between both types of pair correlation function were more pronounced, with the polygon-based version showing slight regularity or aggregation (Figure 7.4f,h) when the conventional PCF indicated no significant deviation from randomness. The mark correlation function showed only for the two plots HEW31 and HEW38 small-scale negative deviation from the null model; otherwise gap sizes were uncorrelated (Figure 7.4k–o).

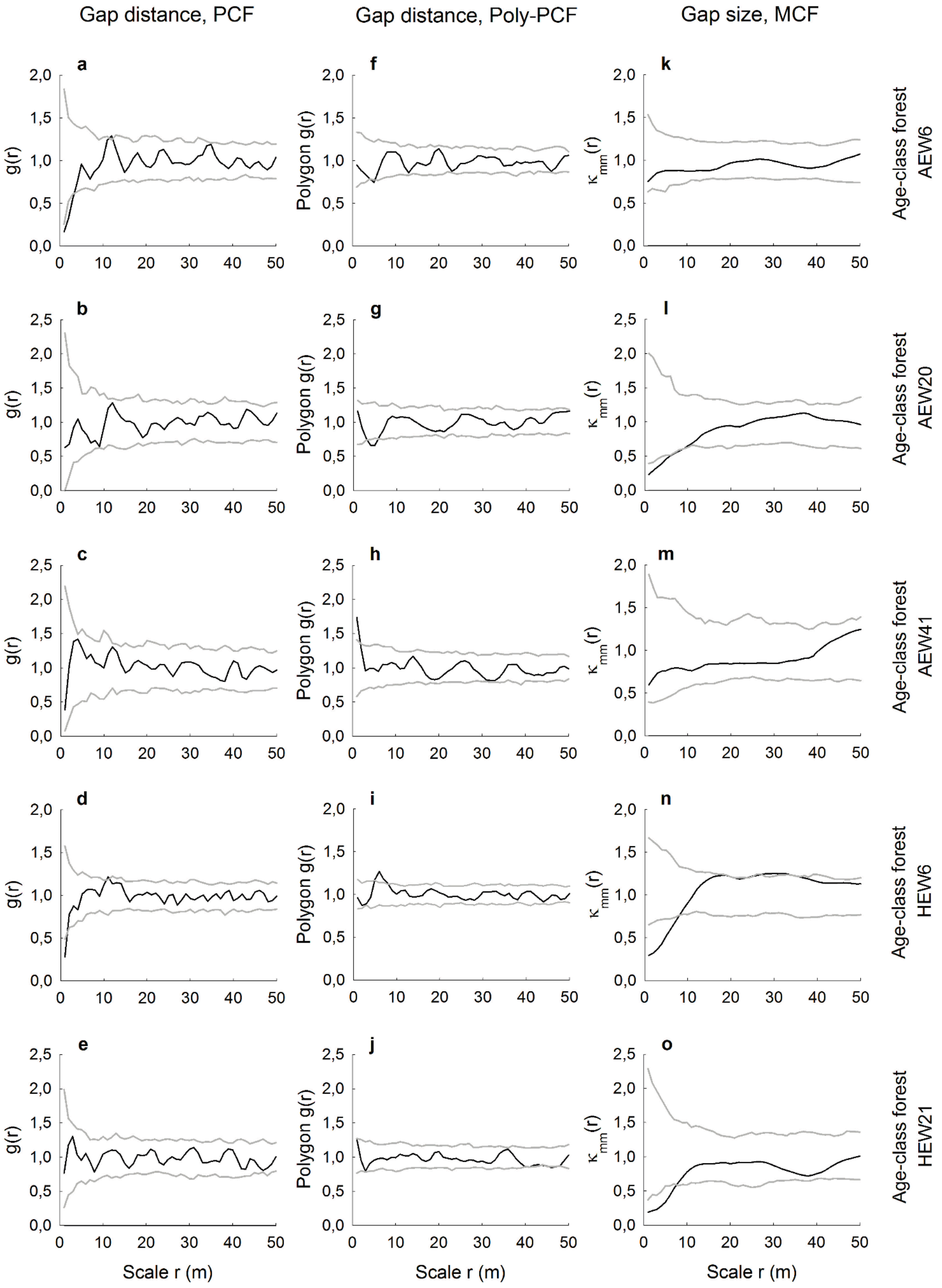

Figure 7.3: Spatially-explicit gap analyses of age-class forests (AEW: Schwäbische Alb; HEW: Hainich) with the conventional pair correlation function (a-e), the polygon-based pair correlation function (PCF) (f-j) and the mark correlation function (k-o). The grey envelopes of the complete spatial randomness (CSR) null model (a-j) and of the null model of random gap-size distributions (k-o) were obtained from the fifth-lowest and fifth-highest values taken from 199 Monte Carlo simulations. If the black line is below or above the null model, gaps were, at neighborhood radius *r*, regularly spaced or aggregated, respectively (a-j), or gap sizes were negatively or positively correlated, respectively (k-o). MCF, mark correlation function.

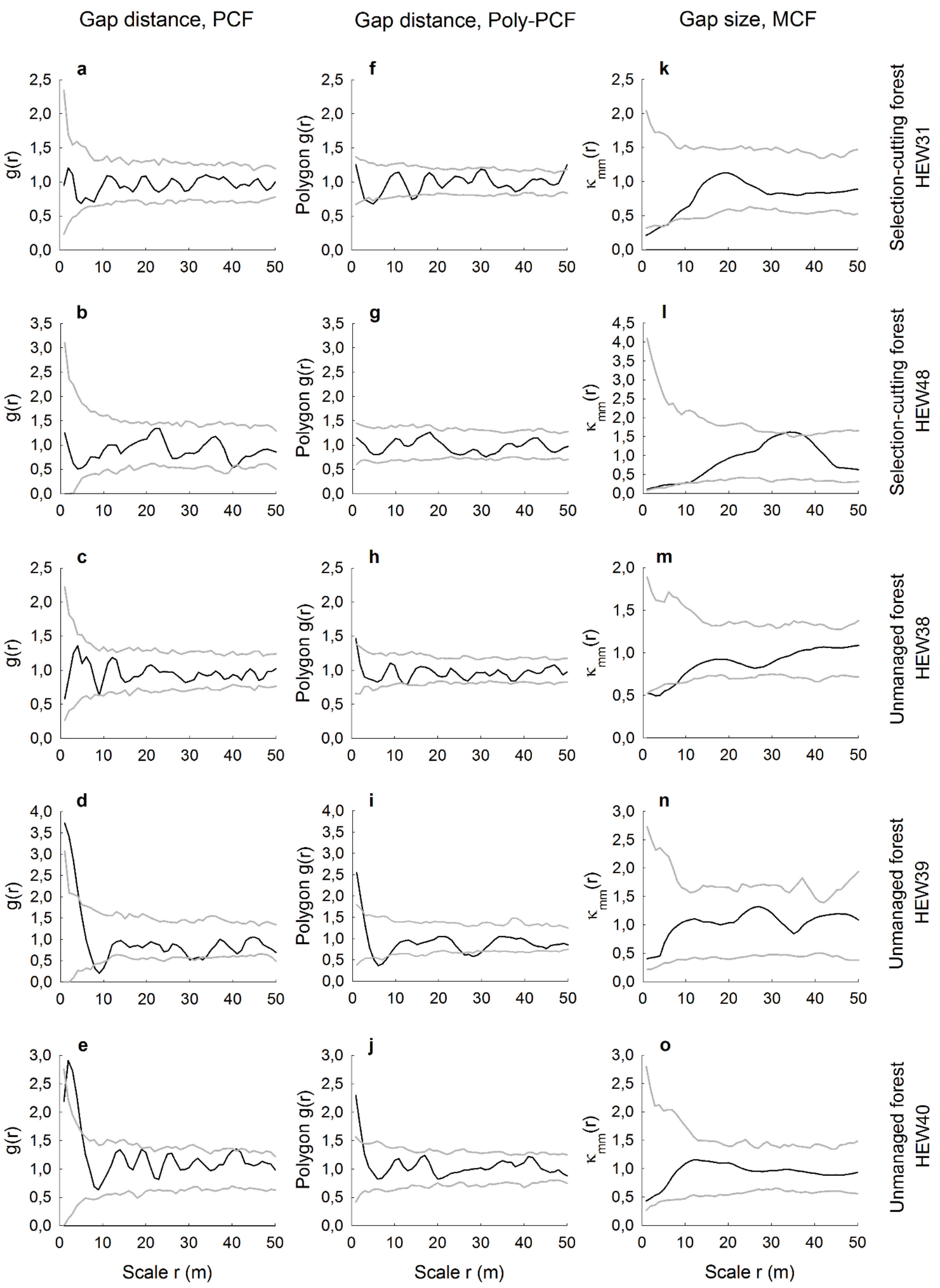

Figure 7.4: Spatially-explicit gap analyses of selection-cutting (upper two rows) and unmanaged forests (lower three rows; AEW: Schwäbische Alb; HEW: Hainich) with the conventional pair correlation function (a-e), the polygon-based PCF (f-j) and the mark correlation function (k-o). The grey envelopes of the CSR null model (a-j) and of the null model of random gap-size distributions (k-o) were obtained from the fifth-lowest and fifthhighest values taken from 199 Monte Carlo simulations. If the black line is below or above the null model, gaps were, at neighborhood radius *r*, regularly spaced or aggregated, respectively (a-j), or gap sizes were negatively or positively correlated, respectively (k-o).

7.4 Discussion

Depending on the shade-tolerance and dispersal mode of understory species, gaps are perceived either as a suitable or as non-suitable micro-habitat for regeneration, growth and survival. For example, in a study on the spatial distribution of gaps, Koukoulas and Blackburn (2004, 2005) have shown that gaps containing mainly grass were randomly distributed at all scales, but gaps dominated by bracken (Pteridium aquilinum) were highly clustered for scales over 30 m. The dominance of bracken in clustered gaps was due to its vegetative spread via below-ground rhizomes, which creates large contiguous patches across gaps where tree regeneration is severely inhibited. This demonstrates that the horizontal pattern of gaps in the canopy layer is a fine-scale spatial structure that influences the recruitment success of understory individuals (Kuuluvainen and Linkosalo 1998). The scale-dependent functional connectivity of the gap locations is therefore one of the drivers for tree recruitment and understory biodiversity in forests (Moora et al. 2007, Tinya et al. 2009, Getzin et al. 2012). However, since the scale at which individuals perceive and interact with canopy structures depends on the species, it needs to be identified by testing for a correlation between population-dynamic features of interest and structural characteristics at different spatial scales (Wiegand et al. 1999). Doing so, knowledge of the gap distribution pattern can thus be used either to better understand successional dynamics and changes of biodiversity in forests or to actively influence and control those dynamics via silvicultural prescriptions and rules for spatial tree retention and gap creation.

So far, the spatial distribution of gaps has seldom been quantified in a spatially-explicit manner (but see Koukoulas and Blackburn 2005, Nuske et al. 2009, Petritan et al. 2013). One obvious reason for this is that terrestrial mapping of the patterns of gaps is very time-consuming and, thus, done rarely on continuous neighborhood scales. Another reason is that the resolution of conventional aerial (20 cm/pixel) or satellite images (≥50 cm/pixel) is too coarse to permit delineating gaps as small as 1 m^2. However, some ecological phenomena, such as the canopy-structural dependencies of certain understory species, are only observable at small scales and, hence, only quantifiable if enough gaps would contribute to the small-scale spatial pattern analysis. Here is the advantage of using unmanned aerial vehicles for the mapping of gaps. Images taken at low flying altitudes have such a high resolution (usually <10 cm/pixel), that minimal gap sizes of 1 m^2 and their shape can be safely mapped and included in the data set for assessing gap distributions. This inclusion of the smallest gaps will not only lead to a sufficient sample size to permit spatially-explicit analyses, but also, to new possibilities of ecological inference.

As to the definition of gaps, others have identified minimal gap sizes of 5 m^2 using airborne LIDAR information, but this size was "chosen arbitrarily" (Vepakomma et al. 2008) and does not reflect vegetation response to certain threshold values of minimal gap sizes. In fact, there is as yet no rule based on ecological mechanisms to decide whether gap recordings should be restricted to thresholds of 5 m^2 or 1 m^2. This is because research on revealing the ecological importance of very small gaps is so far relatively rare. Nieschulze et al. (2012) have, for example, extracted gaps with LIDAR for some of the same forest plots used here, but they have not defined a typical minimum size limit or the cause of the canopy openings. Likewise, Boyd et al. (2013) used LIDAR data to identify smallest gap sizes of 1 m^2 for a 24-km^2 area in tropical Peru. They further investigated the smallest gap sizes up to 2 m^2 for an extended landscape of more than 140 km2 and found that small gaps dominated, while those gaps being larger than 100 m^2 made up only 0.45% of all documented canopy openings. Overall, there seems to be a trend that, with the availability of increasingly higher 2D or 3D image resolutions, gap definitions are being adapted to suit the emphasis on spatial phenomena and light-dependent processes that could not be analyzed previously.

Here, we found evidence in support of our hypothesis (and in overall agreement with the results of Boyd et al. 2013): the very small gaps of a size <5 m^2 made up the largest proportion of all gaps found in the study plots. This was particularly the case for the three unmanaged forests where gaps are naturally induced, mainly by disturbance. Indeed, very small gaps may also be important for forest dynamics. Very small gaps belong often to repeated gaps that occur along the edges of old gaps. They are primarily formed by the lateral expansion of branches following the destruction of these branches. Torimaru et al. (2012) have demonstrated that most repeated gaps were smaller than 10 m^2 in deciduous and coniferous forests and that “future analyses [...] should pay attention to repeated gap formation events and their spatial patterns”. While we have not analyzed aerial images in consecutive years, it is quite likely that the very small gaps detected here are part of repeated gap formation induced by small-scale disturbance. For example, trees of gap peripheries are more vulnerable to mortality and injury than interior canopy trees, which could lead to small openings (Vepakomma et al. 2010). Overall, it has been shown that repeated disturbances are important for the regeneration of species that can tolerate intermediate light levels and that are able to survive several periods of suppression from neighboring trees before growing into the canopy (Runkle and Yetter 1987). So far, small gaps are often neglected in forest studies, but they are also structural drivers for forest dynamics. With reference to the traditional framework for studies of forests based on schematic gap dynamics and discrete phases from gaps to mature forest, Torimaru et al. (2012) emphasize that “repeated gap-creating disturbances commonly occur, so schematic gap dynamics do not always provide realistic descriptions of forest dynamics”. Furthermore, Tanaka and Nakashizuka (1997) found a high probability of repeated gap disturbance for a deciduous temperate forest, and they postulated that the “high occurrence of disturbances around the existing gaps should not be explained simply as gap expansion, but should be considered an important factor in canopy dynamics”. We agree with these statements and recommend that more studies should be undertaken to quantify repeated gap formation and the spatial patterns. It would be especially interesting to link in consecutive years of monitoring the spatial patterns of gaps to regeneration and successional dynamics in the understory. This will help to better understand the relative importance of traditionally recorded larger gaps vs. the ecological importance of small repeated gaps.

In our study, we included gap sizes as small as 1 m^2, because these smallest gaps are important determinants of regeneration, since the variability of diffuse radiation does influence understory biodiversity (Moora et al. 2007). The importance of such fine-scale information on the spatially-implicit properties of gaps, including detailed descriptions on their shape complexity, has recently been demonstrated for determining understory biodiversity in temperate forests (Getzin et al. 2012). However, also in tropical forests, the fine-scale properties of gaps may be important drivers of understory vegetation. For example, Montgomery and Chazdon (2002) have shown that the growth of tropical tree seedlings in low light environments is highly sensitive to light availability and that shade-tolerant species vary in these responses. Thus, very small gaps causing light heterogeneity in the understory may induce light-gradient partitioning and affect recruitment processes for shade-tolerant tree species.

We demonstrated how spatially-explicit, i.e., scale-dependent, information on gap distributions can be extracted from very high-resolution images. Pair and mark correlation functions have the ability to quantify positive or negative distance and size correlations, respectively, for a continuous range of neighborhood scales. However, we have shown that it may depend on the type of pair correlation function used whether gap patterns may be random, regularly distributed or aggregated. The conventional PCF is based on the point approximation and, thus, measures the distances between centroids of the gaps. This may lead to the indication of the small-scale regularity of the centroids in cases where gaps are indeed randomly distributed, because the physical size and shape of the gaps prevent measuring short neighborhood distances. Such unwanted artifacts in the PCF resembling a so-called “soft-core process” have been shown for artificial data (Nuske et al. 2009), but are also visible in our real data. For example, it is likely that the gaps in the plots AEW6 and HEW6 are not regularly spaced at smallest scales up to approximately $r = 3$ m, but are, rather, random at that scale (Figure 7.3f,i). This is because the polygon-based PCF provides information about the distribution of distances from the boundary of a gap to the edge of another gap and, thus, measures the space between the gaps. While the conventional PCF could partly account for that with a special soft-core null model, the approach of the polygon-based PCF is much more straightforward. Furthermore, we found that differences between the conventional and the polygon-based PCF were smallest when the number of gaps per plot was very low, such as in the two unmanaged plots of the Hainich National Park. This could indicate that the likelihood of biasing effects from soft-core processes becomes smaller when there are relatively few gaps in a plot. The agreement or disagreement between both PCF versions does also depend on the size and the actual shape of the gaps, i.e., whether the shape eccentricity causes large deviations between distance measurements of gap centers vs. gap boundaries.

More robust against these problems of physical object sizes in spatially-explicit analyses is the use of the mark correlation function. The MCF is typically applied to, for example, the diameters of tree trunks (Penttinen et al. 1992), but it has also been recently used to assess the size correlation of tree crowns (Getzin et al. 2008). However, application of the MCF to forest gaps seems to be a novel approach. Here, we found that gap sizes were in five plots independent of scale and in another fives plots negatively correlated at small neighborhood scales up to a maximum of 9 m. The absence of positive size correlations indicates that particularly large gaps with above-average size never occurred in clusters. Otherwise, four of the five negative gap-size correlations occurred in managed plots. This may reflect tree retention patterns and the spatial signature of thinning carried out by the forester. For example, small gaps with below-average sizes may be relatively close to each other when the forester undertakes single-tree harvests or removes thin trees or trees of low crown vitality around preferred target trees (Battaglia et al. 2002).

Overall, we want to emphasize that our comparison of gap structures and spatial patterns in differently managed forests can only be viewed as a first exemplary study. In order to allow more thorough insights on gap dynamics evolving under different land-use intensities, larger datasets need to be sampled to permit generalizations.

From a technical point of view, we recommend undertaking UAV flights only under relatively cloudy conditions without direct sunlight. Such diffuse sky radiation will help to avoid misclassifications of gaps caused by the hard shadows of neighboring trees, which would appear as dark patches. In our study, we have avoided such unwanted effects and were thus able to delineate the gaps accurately so that they matched the gaps recorded with a manned LIDAR flight (cf. Figure 7.1). Furthermore, we recommend undertaking flights, especially with rotary-wing UAVs, rather under calm wind conditions, so that the UAV system will remain horizontally stable (roll and pitch angles) while photographing gaps. This is required, because for spatially-explicit gap analyses, as undertaken here, forest images need to be well orthorectified, so that all gap locations and their distances between them are up to scale.

7.5 Conclusions

Unmanned aerial vehicles are highly suitable tools for mapping small gaps, repeated gap formation and spatial canopy structures in general. With our study, we have shown that they provide not only very high-resolution images to record gap openings as small as 1 m^2 (Getzin et al. 2012), but they can be used very flexibly for monitoring purposes (Anderson and Gaston 2013). For example, the low monetary costs required for a flight mission with a UAV makes it possible to record the spatial dynamics of repeated gap formation on an annual basis. Spatially-explicit analyses, such as applied here, can be used to monitor the change in distance and size correlation of gaps. These changes can then be related either to the initial state of tree-harvesting patterns in managed forests or to the successional dynamics of the understory in unmanaged forests. With our unique study, which applied for the first time UAV technology in combination with spatially-explicit gap analyses, we have demonstrated how gap patterns can be related to the spatio-temporal dynamics of forests. Of course, as UAVs and their on-board sensors are currently rapidly advancing, new technology will soon allow even higher image resolutions and more refined canopy segmentations. Furthermore, as portable payloads on UAVs are constantly increasing, new sensors, such as LIDAR for 3D mapping of gaps, will become more common in such applications. Successful trials with LIDAR sensors attached to UAVs have been already undertaken (Lin et al. 2011, Wallace et al. 2012), and additional information on true canopy height will allow even more accurate gap mappings in the near future.

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Author contributions

Stephan Getzin proposed the study, acquired the data, supervised the canopy gap delineation, analyzed the canopy gap patterns using the traditional pair correlation function and the mark correlation function, interpreted the results and wrote the manuscript. Robert Nuske analyzed the patterns using the polygon-based pair correlation function, interpreted the results and contributed in manuscript writing and revision. Kerstin Wiegand advised on the study design and interpretation and contributed to manuscript writing and revision.

The authors declare no conflict of interest.

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8 Spatial distribution of canopy gaps of Hessian beech-dominated strict forest reserves

8.1 Introduction

Disturbances in Central European forests, be they natural or anthropogenic, usually cause the loss of one or a few trees and create in this way gaps in the main canopy layer. The pattern of canopy gaps in a forest is, thus, the outcome of past disturbances. Canopy gap patterns lend themselves in particular to study the spatial characteristics of disturbance regimes, which is an important aspect besides frequency and severity of disturbances (Pickett and White 1985, Frelich 2002, Turner 2010). Spatial characteristics are, for instance, area, shape and spatial distribution of gaps (White et al. 2018). Many authors explicitly include the spatial arrangement as an important part of the spatial aspect of disturbances (e.g. Pickett and White 1985, Coates and Burton 1997, White et al. 1999, Mori 2011).

There are a number of studies on mean gap sizes, gap size distributions, proportion of forest area in gaps and sometimes even gap shapes and gap ages from Southeast and Central Europe (e.g. Tabaku and Meyer 1999, Drößler and von Lüpke 2005, Zeibig et al. 2005, Kenderes et al. 2009, Kucbel et al. 2010, Bottero et al. 2011, Diaci et al. 2012, Petritan et al. 2013, Rugani et al. 2013, Hobi et al. 2015, Feldmann et al. 2018). However, the spatial distribution of canopy gaps in temperate forests has been largely neglected so far. Only a few studies dealt with the spatial distribution of gaps in these forests (e.g. Runkle and Yetter 1987, Runkle 1990, Nuske et al. 2009, Garbarino et al. 2012, Petritan et al. 2013, Getzin et al. 2014).

Hessburg et al. (1999) conjectured that forest management regimes might be detectable in canopy gap patterns and Puettmann et al. (2008) stated that the size distribution and spatial arrangement of gaps tend to be more uniform in selectively logged stands. However, comprehensive studies on the spatial distribution of canopy gaps in old-growth forests or with regard to silvicultural treatment are still lacking. This may be because the analysis of the spatial distribution of canopy gaps is more demanding since it needs continuous canopy gap maps. Such canopy gap maps of entire forest stands, a sufficiently large core area or forest landscape are seldomly available from field surveys, exceptions being Zeibig et al. (2005) and Petritan et al. (2013). Most seamless canopy gap maps are acquired by remote sensing (e.g. Brunig 1973, Kenderes et al. 2009, Wu et al. 2016).

The airborne laser scanning data covering entire Hesse provided a good basis for mapping canopy gaps based on a relatively homogeneous data source with one method for larger areas. The created canopy gap maps of beech-dominated strict forest reserves (see Chapter 4) could provide useful reference values for close-to-nature forest management. Such canopy gap maps of sufficiently large continuous areas permit the characterization of the spatial distribution of canopy gaps.

Various methods have been proposed to describe the spatial distribution of canopy gaps, such as hemispheric images (e.g. Trichon et al. 1998), landscape indices (e.g. Hessburg et al. 1999, Wu et al. 2016), spatial autocorrelation (e.g. Frelich and Lorimer 1991), nearest neighbor distances (e.g. Poorter et al. 1994, van der Meer and Bongers 1996, Salvador-Van Eysenrode et al. 2000) and point processes (e.g. Nuske et al. 2009, Garbarino et al. 2012, Petritan et al. 2013, Getzin et al. 2014, Silva et al. 2019). In contrast to most methods, the point pattern analysis allows to investigate the spatial distribution of objects on several scales. In classical point pattern analysis, objects of interest are assumed to be points.

Therefore, canopy gaps have to be reduced to points, e.g. the center of mass, which can obscure the real interactions at the scale of gap sizes (e.g. Simberloff 1979, Prentice and Werger 1985, Nuske et al. 2009).

Nuske et al. (2009) suggested representing objects by their outer boundary instead of their center points and to measure distances between the boundaries of the objects. Based on this, they presented an adaptation of the pair-correlation function for polygons. This approach avoids pseudo hard- and soft-core effects and is able to describe the real interactions at small scales. In conclusion, it allows the analysis of patterns of objects of finite size and irregular shape with interactions at the scale of gap sizes.

The implementation of the adapted pair-correlation function presented in Nuske et al. (2009) relied heavily on the geodatabase PostGIS for all geometrical processing and randomizations of the pattern for constructing a null model of complete spatial randomness and R for calculating and plotting of the pair-correlation function based on the raw distances (PostGIS Development Team 2019, R Core Team 2019). The easy access to many geoprocessing functions within PostGIS allowed for a quick implementation of the suggested method. However, creating larger numbers of randomized patterns (e.g. 999 randomizations for a 99% pointwise confidence envelope) and processing of more than a few patterns comprising about 100 gaps was unwieldy and prohibitively slow. The processing time increased exponentially with the number of randomizations (see Figure 8.1). Furthermore, the spread over several software environments hindered the automation of the process. PostGIS, being an extension to the PostgreSQL database, caused quite some administrative overhead. Thus, an easier to use and faster implementation of the adapted pair-correlation function was needed to process the 22 patterns from Hessian beech-dominated strict forest reserves with up to 462 gaps in one pattern (cf. Chapter 4).

Therefore, the adapted pair-correlation function was re-implemented as the R package “apcf” (Nuske 2019a) using the geoprocessing library GEOS (GEOS Development Team 2019), which is also the basis of PostGIS. The geoprocessing library is accessed directly from C++ code, reducing the overhead of data transformations. The package is accompanied by comprehensive help pages and an introductory vignette and is available from the comprehensive R archive network (CRAN, Nuske 2019b).

This study investigates the spatial distribution of canopy gaps of 22 stands from beech-dominated strict forest reserves in Hesse using the adapted pair-correlation function. It also demonstrates the capability of the new implementation of the adapted pair-correlation function as an R package to analyze large and complex canopy gap patterns.

8.2 Material and methods

8.2.1 Canopy gap maps

The study comprises 22 canopy gap patterns from Hessian beech-dominated strict forest reserves (see Chapter 4). The canopy gaps were mapped using a two-part relative threshold based on a standard airborne laser scanning data product created by the Hessian land surveying office. Although the airborne laser scanning data were acquired on different flight missions, the characteristics of the provided ALS data allowed mapping of canopy gaps with the same method in 22 stands. The fully automated mapping permits consistent detection and delineation of canopy gaps over all stands. Refer to Chapter 4 for a more detailed description.

The areas of the mapped stands ranged from 5.3 ha up to 40.2 ha with 6 to 462 canopy gaps and gap fractions of 0.2% to 20.6%. Mean gap sizes were 7.1-151.2 m^2. A detailed description of the canopy gap sizes and figures of all canopy gap maps can also be found in Chapter 4.

8.2.2 Analysis of the spatial distribution

The adapted pair-correlation function $g(r)$ describes the spatial distribution of objects of finite size and irregular shape at a given radius r. Distances are measured between the outer boundaries of the objects. Since the expected number of objects under complete spatial randomness in a distance interval is difficult to determine in a closed form and is even distance-dependent, a correction factor is derived from Monte Carlo simulations of the null model and subsequently applied to the estimated pair-correlation function and the confidence envelope. An approximate 99% pointwise confidence envelope is provided by the 5th smallest and the 5th largest values of 999 randomizations (Besag and Diggle 1977, Stoyan and Stoyan 1994). The null model for complete spatial randomness was constructed by random rotation and positioning of the original objects within the study area (cf. Wiegand et al. 2006). A step size r of 1 m and a Stoyan parameter s of 0.15 was chosen for the calculation of the adapted pair-correlation functions. For a more detailed explanation, please refer to Nuske et al. (2009).

The calculation of the adapted pair-correlation function was carried out using the package "`apcf`" 0.1.3 (Nuske 2019a) within the statistical software R 3.4.4 using GEOS 3.5.1 and GDAL 2.2.2 (GDAL/OGR contributors 2019, GEOS Development Team 2019, R Core Team 2019). The new implementation of the adapted pair-correlation as R package "`apcf`" was driven by the goal to speed up the processing and to simplify the usage. Faster processing permits the analysis of larger and more complex canopy gap patterns and confidence envelopes with higher confidence levels. The PostGIS database was discarded and the GEOS and GDAL libraries on which PostGIS is based were integrated directly. That way, the entire algorithm could be written in C++ and wrapped in an R package. The integration of the C++ code in R was made feasible by the package "`Rcpp`" (Eddelbuettel and François 2011). Missing functionality, like bounding boxes and turning and shifting of entire polygons, was implemented in the package based on vertex functions offered by GEOS. By means of the package "`apcf`", the entire process from mapping gaps over randomizations, calculation of distances and derivation of the pair-correlation function up to plotting of the adapted pair-correlation function can be done from R.

The code was meticulously profiled to find and reduce time-consuming processes. The time needed for creating a new simulated pattern by randomly turning and positioning the existing gaps depended on the shape of the study site (the further from a rectangle the longer it takes), the gap density, gap sizes and the gap shapes (random positioning of complex objects without overlap needs more work in a crowded space). However, for most study sites the most time-consuming processes are related to geoprocessing. That comprises the calculation of the distances of the considered object to all other objects within a user defined maximum distance as well as the buffering of the considered object with the distances and determining the proportion of the buffers within the study site by intersection of buffer and study site.

Performance tests of the PostGIS and the new C++/R implementation were done on an Ubuntu 16.04 GNU/Linux with R 3.4.4, PostgreSQL 9.5 and PostGIS 2.4.2 with an Intel Xeon E5-2695 v3 2.30 GHz CPU and 192 GB RAM doing 3 repetitions of 10 to 250 randomizations. The new implementation of the adapted pair-correlation function (Nuske 2019a) scales much better for larger numbers of randomizations than the original implementation (see Figure 8.1).

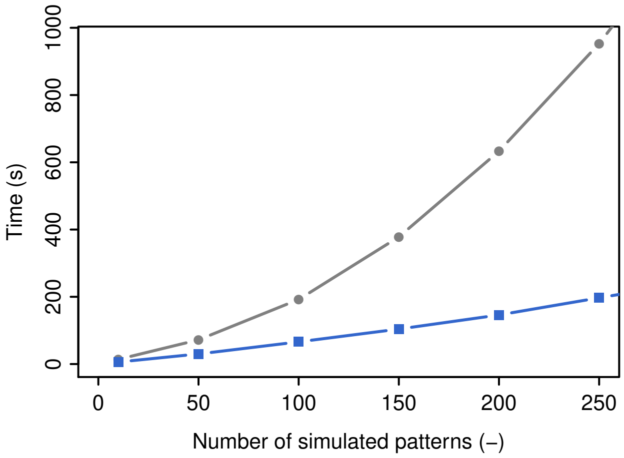

Figure 8.1: Processing times for an example dataset (see Nuske et al. 2009). Depicted are mean values of three runs of PostGIS (gray) and R package “apcf” (blue) implementations of the adapted pair-correlation function.

8.3 Results

The spatial distribution of the canopy gaps differed markedly for the 22 sites from the Hessian beech-dominated strict forest reserves (see Figures 8.2, 8.3 and 8.4). No sensible confidence envelopes could be calculated for the site 15 having only six gaps. The site 12 also has a very large and the sites 5, 18 and 20 have fairly large confidence envelopes because of their low number of gaps (23, 39, 48 and 45). The estimated pair-correlation functions of the canopy gap patterns of the sites 3, 4, 5, 10, 11, 12, 15 and 16 do not deviate significantly from the confidence envelopes. Therefore, the null hypothesis of complete spatial randomness cannot be rejected over the entire range of scales. The pair-correlation function of the stands 1, 17, 18 and 20 show many more short distances than expected under complete spatial randomness, indicating a clustered distribution of gaps. The wave-like shape of the estimated pair-correlation function of stands 2, 4, 7, 12, 13 and 17 indicate regular distributions of gaps. The pair-correlation function of the stands 2, 6, 7, 9 and 21 exhibit a soft-core effect, with short distances less frequent than expected under complete spatial randomness.

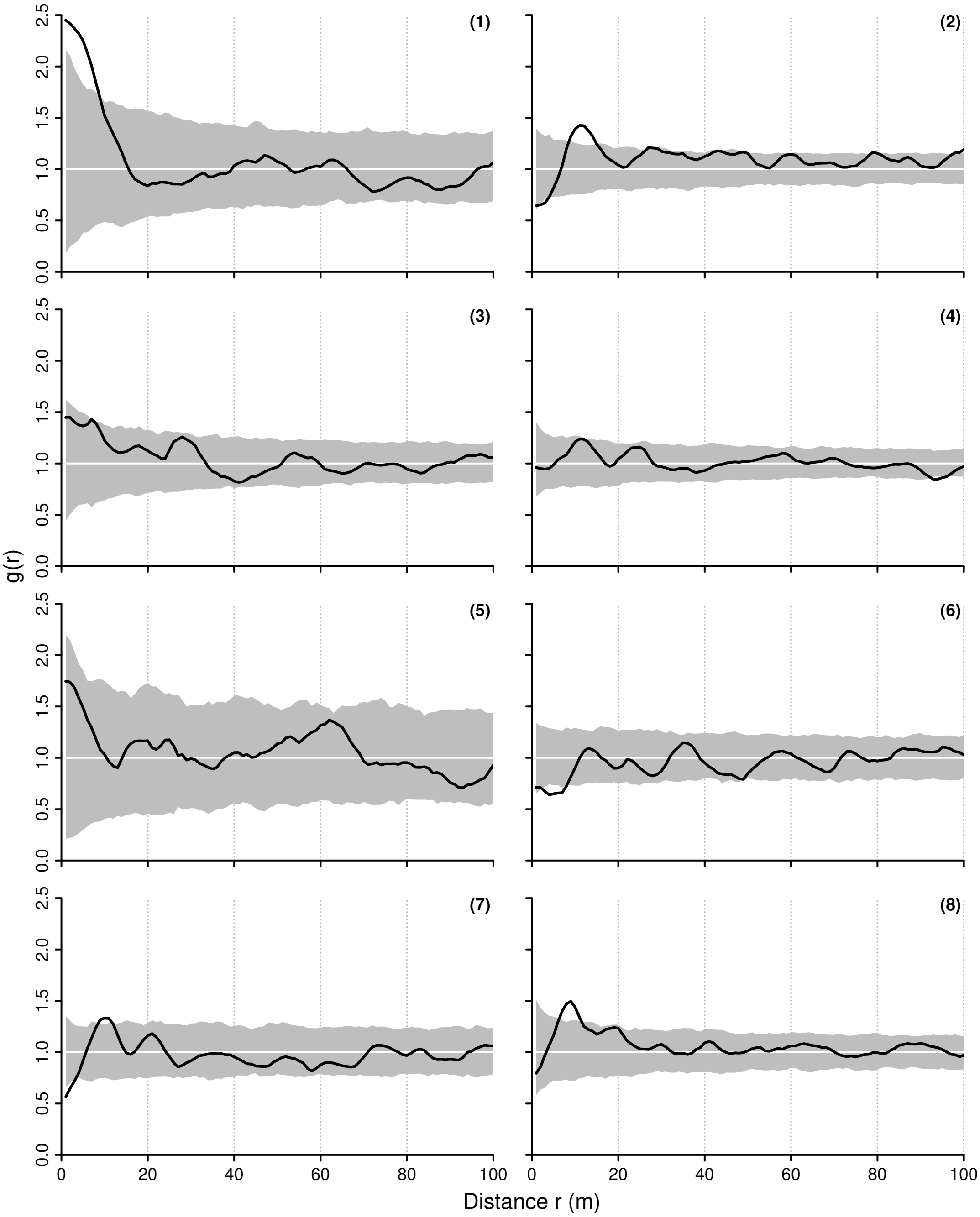

Figure 8.2: Adapted pair-correlation function of canopy gap patterns of the sites 1 to 8. Black line: estimated function; white line: theoretical value of the function under the null hypothesis of complete spatial randomness; gray area: 99% confidence envelope under the null hypothesis, computed by Monte Carlo simulation using 999 replicates. Values *g(r)* < *1* suggest inhibition between points and values *g(r)* > *1* suggest clustering.

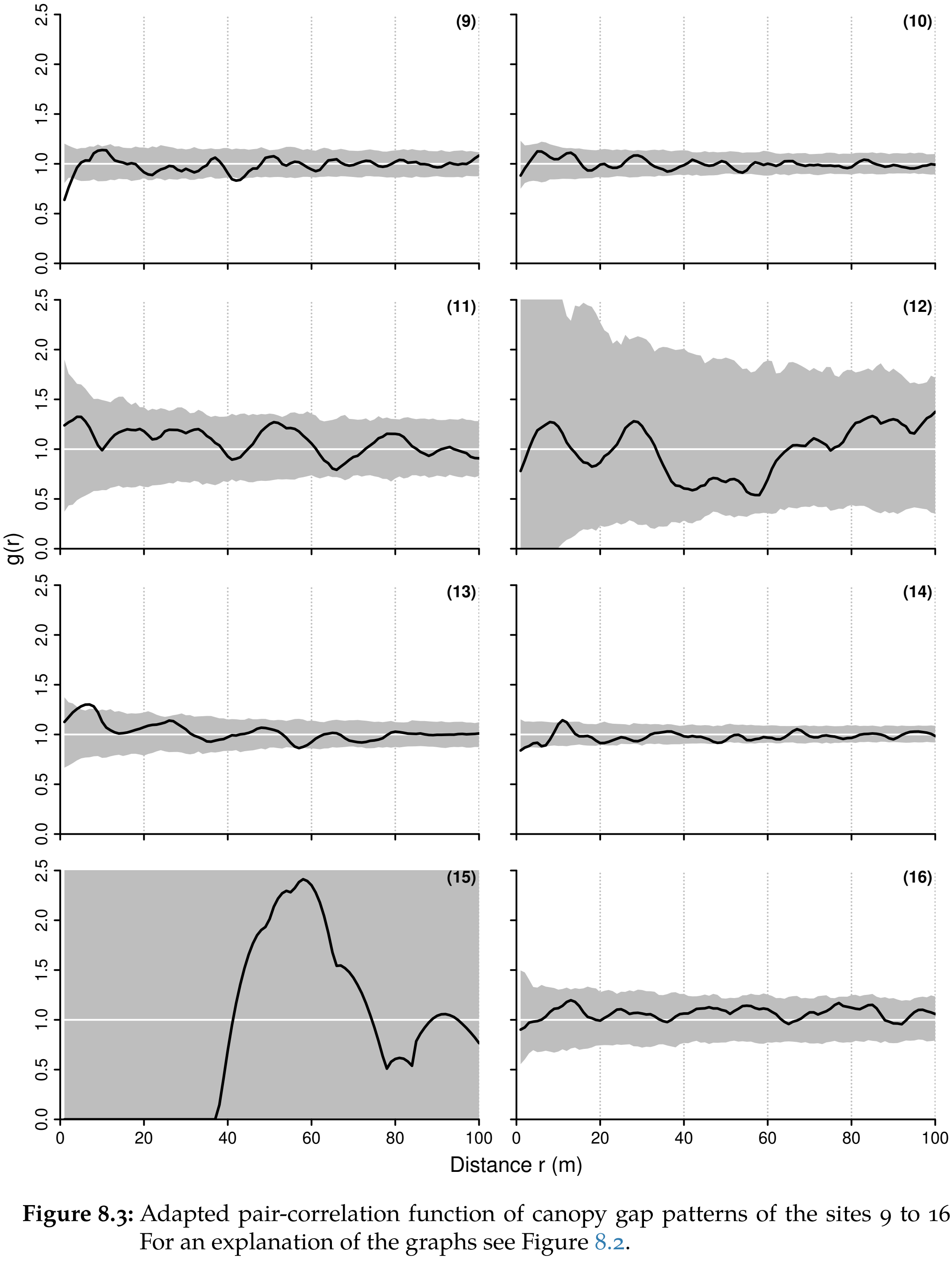

Figure 8.3: Adapted pair-correlation function of canopy gap patterns of the sites 9 to 16. For an explanation of the graphs see Figure 8.2.

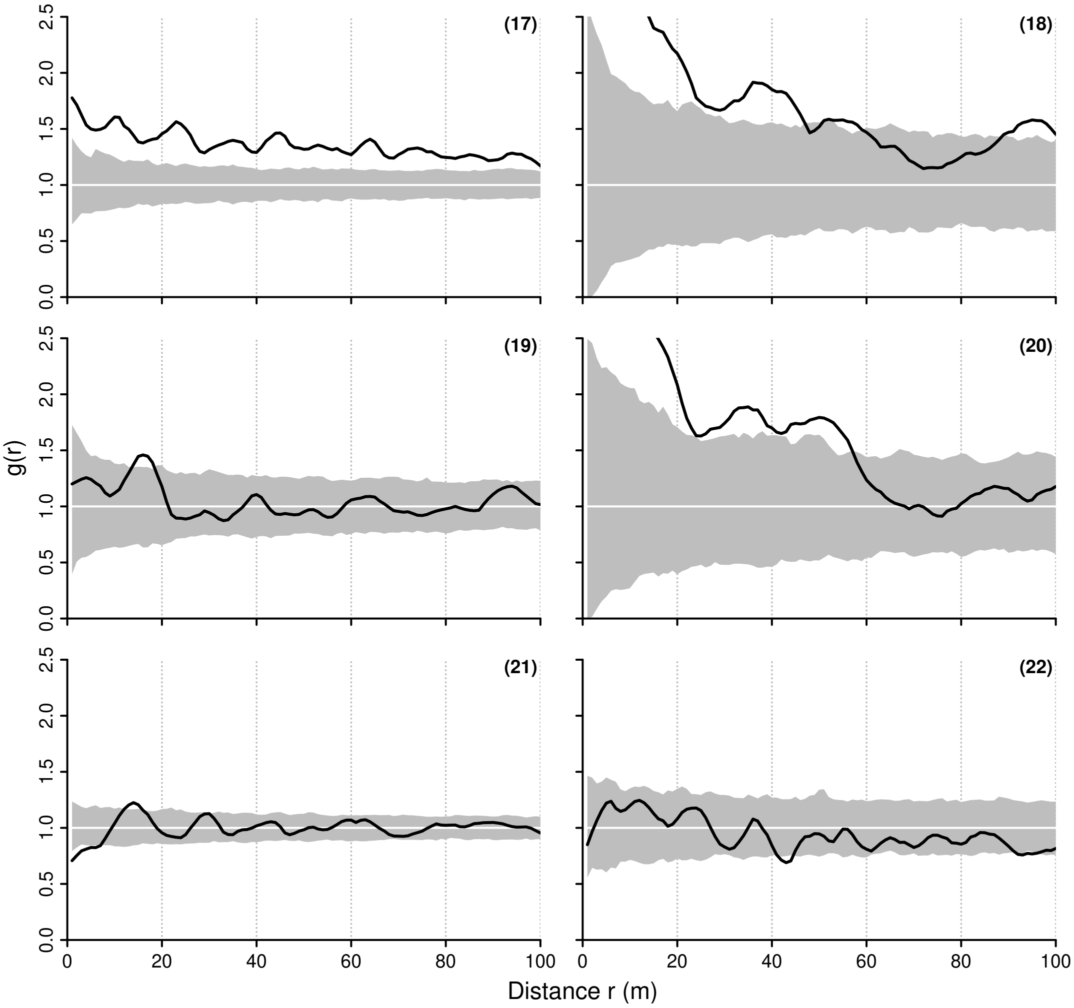

Figure 8.4: Adapted pair-correlation function of canopy gap patterns of the sites 17 to 22. For an explanation of the graphs see Figure 8.2.

8.4 Discussion

Processing of 22 canopy gap patterns from Hessian beech-dominated strict forest reserves with a high number of randomizations was possible due to the re-implementation of the adapted pair-correlation functions. The manifold increase of processing speed was possible by abandoning the database, less memory usage and optimization of the geoprocessing. All distance calculations, buffering, intersections and randomizations are done entirely in C++ using the GEOS library. The geodata (study area and gap pattern) are transferred and translated to the GEOS vector data format only once. This eliminates the need for a large amount of time-consuming and repeated transmissions of geodata, which would have been necessary if the processing of the geodata would have been done in R using packages such as "rgeos" or "sf". The usability of the method improved considerably by being implemented as an R package accompanied by help pages and an introductory vignette. Availability from CRAN makes it much easier for potential users to obtain the method and use it for their own studies. The need for database administration, shell scripting and the transfer of intermediate results from one environment to another was eliminated. This way, only knowledge of R is needed for using adapted pair-correlation function.

In its current implementation, the entire process uses only one core of the CPU, although the randomizations and the processing of the simulated patterns are totally independent of each other and as such lend themselves to parallelization. Future versions of the "apcf" package should support parallelization either by third party tools such as OpenMP, R packages like "snow" or "foreach" or within the C++ code of the R package "apcf". Since the pointwise confidence envelopes are constructed from numerous randomizations involving very many random turning and positioning steps, the random number generation is of great importance. Currently, the "Mersenne Twister 19937 generator" from the C++ 11 random library is employed. It is seeded once within the C++ code for every calculation of an adapted pair-correlation function. There will be, although very small, differences between the confidence envelopes of repeated runs because it is at the moment not possible to set a seed manually.

The adapted pair-correlation function describes the spatial distribution of canopy gaps without being influenced by their size or shape and all gaps have the same influence on the shape of the function regardless of their size. Thus, it truthfully reports the spatial configuration of objects of finite size and irregular shape and even reveals interactions of gaps at small scales, which the uncorrected (polygon based) *L*-function or the *O*-ring function (cf. Law et al. 2009, Garbarino et al. 2012, Silva et al. 2019) are unable to accomplish.

The canopy gap maps of 22 sites from Hessian beech-dominated strict forest reserves exhibit very different pair-correlation function shapes and confidence envelope sizes. It is obvious from the extremely large confidence envelopes of the sites 12 and 15 and the fairly large confidence envelopes of the sites 5, 18 and 20 that at least 30 but better still 50 gaps are needed for meaningful confidence envelopes. All major types of spatial distributions were found, such as no deviation from complete spatial randomness, clustering, soft-core effects and regular arrangement (cf. Nuske et al. 2009). This might be due to the fact that the stand ages varied from 65 to 220 years and the stands had large structural differences at the time of the designation (cf. Chapter 4). After all, the strict forest reserves are just about 30 years left to develop freely, the reserves "Hunsrück" and "Weserhänge" are even younger (cf. Chapter 4). Set aside forests will initially continue to show the effects of past management, e.g. absence of old-growth structures and lack of senescence phases (Peterken 1996, Winter et al. 2010, Meyer and Schmidt 2011).

Other studies of using the adapted pair-correlation function found also often found no significant deviations from confidence envelopes across all investigated scales (Nuske et al. 2009, Petritan et al. 2013, Getzin et al. 2014). The investigation of the two parts of the old-growth sessile oak–European beech forest remnant in the Carpathian Mountains, Romania, reported that one of the two patterns did not deviate from the confidence envelopes and the other had fewer short distances as expected, which is called a soft-core effect (Petritan et al. 2013). The 1-ha plots from beech-dominated forest of the Biodiversity Exploratories "Hainich-Dün" and "Schwäbische Alb" in Germany seemed to suggest a more random distribution of canopy gaps in managed forests and the unmanaged forest showed a slight tendency to clustered gaps (Getzin et al. 2014). Begehold et al. (2016) used the Clark and Evans Aggregation index and found no significant differences of canopy gap aggregation between the investigated management types of lowland beech forests in north-eastern Germany. Most gap patterns were randomly distributed with the recently unmanaged forests having a tendency towards regular distribution. Garbarino et al. (2012) analyzed the core area and the buffer zone of an old-growth Fagus-Abies-Picea forest located within the Dinaric Alps in Bosnia using Ripley's *L*-function and the *O*-Ring statistic. They found that gaps in the core area were randomly distributed and clustered in the buffer zone, although the interpretation of the functions generated with a grid-based approach without correction for polygon density are hard to interpret at small scales.

A larger number of canopy gap patterns acquired preferably from remnants of old-growth beech forests, strict forest reserves and managed forest stands with different management regimes would be expedient in order to gain reference values. A first small step in that direction could be made by analyzing published canopy gap maps (e.g. Meyer and Ackermann 2004, Zeibig et al. 2005, Kenderes et al. 2008, Rugani et al. 2013, Begehold et al. 2016) with the adapted pair-correlation function. In order to gain a more general understanding of the disturbance dynamics in natural beech forests, it is further necessary to carry out repeated inventories in additional pure beech and beech-dominated old-growth forests. Furthermore, it has to be emphasized that inventories should give preference to continuous areas whenever possible to allow for the analysis of the spatial distribution of canopy gaps.

8.4.1 Conclusions

The re-implementation of the adapted pair-correlation function allowed the investigation of more and larger canopy gap patterns. The implementation as an

R package simplified the handling and the availability on CRAN allows anyone to take advantage of the adapted pair-correlation function. The pair-correlation functions of the 22 sites from Hessian beech-dominated strict forest reserves indicated very different spatial distributions which is probably mainly due to the differing stand age as well as the forest structure at the time of designation.

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9 General discussion and conclusions

Canopy gaps are an important and crucially influential structural component of forest ecosystems. In particular, the regeneration and thus the further development of forest stands depends substantially on the size, shape and distribution of canopy gaps (Coates and Burton 1997). In present times, tree harvesting is the most important and profound disturbance in European temperate forests (Ammer et al. 2018). Close-to-nature forestry, which gained popularity in European forest practice (Schütz et al. 2016) or is even becoming the norm (von Oheimb et al. 2005, Ciancio et al. 2006), aims to emulate natural forest dynamics. Since the disturbance regime in Central Europe is defined by frequent small and rare intermediate scale disturbances (e.g. Nagel et al. 2006, Fischer et al. 2013), canopy gap dynamics is in the focus of close-to-nature forestry (Wagner et al. 2010, Kucbel et al. 2012, Bauhus et al. 2013). Although close-to-nature forestry aims at mimicking the dynamics of unmanaged forests, reference values for the proportion of forest area in gaps, gap sizes, gap formation and closure rates as well as the spatial distribution of gaps in old-growth forests are still scarce (Ammer et al. 2018, Feldmann et al. 2018).

Canopy gap research is mostly carried out in case studies, because old-growth forest remnants are rare, scattered and often located in remote areas. Furthermore, the delineation of the gaps is labor-intensive and costly. Only a few studies mapped entire forests terrestrially or employed suitable remote sensing data (e.g. Meyer and Ackermann 2004, Zeibig et al. 2005, Kenderes et al. 2008, Petritan et al. 2013, Rugani et al. 2013). In most studies, the canopy gap patterns are characterized by the proportion of forest area in gaps and the distribution of gap size, sometimes accompanied by gap shape and gap age. Although frequently demanded, an adequate description of the spatial distribution of canopy gaps is often lacking.

Consequently, the present thesis (i) contributes to the methodology of canopy gap mapping based on remote sensing data and (ii) suggests a new method to describe the spatial distribution of gaps respecting their finite sizes and irregular shapes. These two aspect are discussed in the following sections.

9.1 Mapping canopy gaps

The traditional and still frequently adopted approach to recording canopy gaps is based on terrestrial field survey methods. Being on the ground permits capturing additional information, such as gap age, species of the gap maker, density and species composition of the regeneration (e.g. Petritan et al. 2013). Nevertheless, field surveys are not always the most reliable source of information because of the danger of overlooking gaps and the difficulty of the ocular evaluation of the exact limits of gaps by experts on the ground (Fox et al. 2000, Bonnet et al. 2015). Fox et al. (2000) found maps generated by interpretation of aerial images to be more accurate with an omission rate of 4.7% compared to 25.6% omission rate of terrestrial surveys. De Lima (2005) found significant differences in gap size estimates using different field-based measurement methods. Moreover, terrestrial surveys cannot be used extensively because of their inherent labor intensity and cost. They are therefore limited in their ability to capture spatial and temporal patterns (Vepakomma et al. 2008). Remote sensing, on the other hand, can cover large areas and detect temporal changes, if time series of remote sensing data are available. If the gap mapping is automated, it allows for a consistent gap mapping without being influenced by subjective expert judgments.

Remote sensing data was used early to map canopy gaps. Brunig (1973) employed a scanning stereoscope to map gaps in a stereoscopic or 3D view. However, not all remote sensing data are suitable. For instance, satellite images do not allow to map the full spectrum of canopy gap sizes because the data quality does not allow mapping small gaps and the methods employed so far rely on detecting more or less bare ground conditions (Garbarino et al. 2012, Hobi et al. 2015). Automated delineation of gaps exclusively based on digital aerial photogrammetry (DAP) height models generated from stereoscopic aerial imagery was not completely successful either. Nevertheless, aerial images offer in many regions the possibility of analyzing long time series because archived aerial imagery was acquired for different purposes in the past. Airborne laser scanning (ALS) data, on the other hand, offer the possibility to delineate even small canopy gaps accurately (White et al. 2018). Nonetheless, ALS is still rarely used because of its higher cost of acquisition, large storage and processing complexities and very short times series (Vepakomma et al. 2008).

Three different approaches to canopy gap mapping based on remote sensing data are presented in the Chapters 2 to 4 of this thesis. All three approaches are fully automated and thus not influenced by per gap or per stand subjective judgments. Chapters 2 and 3 use archived aerial images, whereas Chapter 4 employs ALS data provided as standard data product by the Hessian land surveying office. The Chapters 2 and 3 studied single stands of unmanaged beech forests of strict forest reserves in Lower Saxony and North Rhine-Westphalia. Chapter 4 showcases the opportunities of a fully automated process and covers 22 sites from beech-dominated strict forest reserves throughout Hesse.

The mapping approach presented in Chapter 2 relies exclusively on DAP height models generated from stereopairs of aerial images. To enable the investigation of gap dynamics, archived aerial imagery of a time span of 21 years comprising scanned analog imagery (diapositives) and digital imagery with nominal scales from 1:600 up to 1:10500 were used. The goal was a completely automated detection and delineation of canopy gaps without the subjective judgment of a human interpreter. The employed adaptive median approach aimed at eluding the recognized problems of photogrammetric height models and the varying tree heights within the investigated stands. This approach was able to detect and delineate more small gaps than fixed height thresholds and stand-wide relative thresholds (cf. Nuske and Nieschulze 2005). The automated mapping using the adaptive median approach was able to cope with the different image qualities of archived aerial images. Compared to a reference delineation, conducted on an analytical stereoplotter, a mismatch was still recognizable. Large canopy gaps were mostly detected well and the automatic delineation resembled the manual mapping. Nonetheless, the smaller gaps had many omission and commission errors.

In order to face the shortcomings of the photogrammetric height model, a data fusion approach canopy gap mapping for time series of archived aerial images is suggested in Chapter 3. It combines multiple data sources in order to eliminate their respective shortcomings. The DAP height models provide overall good information but the image matching failed prevalently in the deep shadows within forest gaps and at the sides of the crowns of gap neighboring trees. Other information layers provide good signals at these places. For instance, the quality measure of the photogrammetric height information tend to have low values in deep shadows and at the canopy gap boundaries. Color information can be used to identify deeply shadowed areas, which occur exclusively in gaps within closed canopy forests. Since the variation of color is much higher in gaps compared to the canopy, the texture of every pixel is taken into account as well. Color information of both images of a stereopair are included because the perspective on the forest canopy is different in each. These information layers are used jointly for classifying gap pixel with a support vector machine (SVM).

The SVM needs training areas of canopy and gap to learn the features of the two classes. To avoid human intervention and the need to define training areas for every stand and time step, a self-learning approach is employed: Initially, high probability gap and canopy pixels are selected based on relative color threshold and height values distinctly below or above the median. Additionally, the selected pixels must be among the best 15% in terms of quality. The training areas are subsequently grown in five steps creating contiguous areas at least 2 m apart from areas of the opposite class. That way, the SVM can be trained without providing explicit training areas. It is shown that a canopy gap mapping approach exploiting the combined information provides considerably better results than gap delineations based solely on DAP heights or color information.

Newer machine learning approaches are even better at utilizing the information available in many data layers, such as random forests (Breiman 2001, Schroff et al. 2008) or convolutional neuronal networks (LeCun et al. 1989, Hu et al. 2015). The, datawise quite undemanding, convolutional neural network U-Net (Ronneberger et al. 2015) was tested on the same data set using the training data generated by the self-learning approach. Although the first results seemed promising, more training data would be needed for satisfactory results. Meanwhile, the U-Net proved valuable, for example, in mapping of water bodies or building footprints from remote sensing data (Bai et al. 2018, Feng et al. 2018, Li et al. 2019). This strongly suggests to acquire more training data by pooling aerial images with high quality manual delineation as well as using aerial images together with gap maps based on simultaneously obtained ALS data to test the U-Net for canopy gap mapping once more.

Airborne laser scanning is still a comparatively young remote sensing technology, which had a slow adoption due to its higher acquisition costs. Time series of ALS data long enough for meaningful investigations of canopy gap dynamics are not yet available (but see Vepakomma et al. 2008, Choi et al. 2019). Nonetheless, the high precision of height measurements lead to ALS measures of canopy height becoming the benchmark against which other measures are evaluated (White et al. 2016). Additionally, ALS showed the capacity to systematically and accurately detect and map canopy gaps over large forest areas (White et al. 2018).

Consequently, mapping canopy gap patterns of 22 sites from beech-dominated strict forest reserves throughout Hesse based on a standard data product of the Hessian land surveying office is presented in Chapter 4. The applied mapping approach, employing a two-part relative height threshold, transfers concepts from gap mapping based on DAP height models (cf. Chapter 2) to ALS height models, which is in accordance with a recent comparison of gap mapping methods (White et al. 2018). The approach combines a local adaptive median based on a moving window with a stand-wide global median to classify canopy gaps in a canopy height model. The method provided plausible and realistic canopy gap maps for all 22 sites. The accuracy of the mapping was evaluated visually by overlaying the gap delineation on to the 3D point cloud. Because of the varying pulse density of the ALS data, a relatively large grid size of 1 m had to be chosen. A finer spatial resolution and a more realistic digital surface model could be rendered feasible by using the spike-free algorithm for generating height models from ALS point clouds (Khosravipour et al. 2016).

In order to obtain status-quo canopy gap maps for large areas, for instance for purposes such as auxiliary data for field surveys, explanatory variables for forest ecological studies, or reduction factors for woody biomass estimations, ALS data are very well suited. If, however, the dynamics of the canopy gaps is in the focus, time series of aerial images are still the best data source. In many cases this means to this day manual delineation of gaps on the basis of time series of stereopairs. Automatic mapping of canopy gaps based on aerial images is a very complex task and cannot be solved satisfactorily with color or height information alone. The most promising approach for automating canopy gap detection and delineation are data fusion techniques combining many information layers such as heights, color and texture.

9.2 Spatial distribution of canopy gaps

Canopy gap patterns are characterized by the proportion of the forest area in gaps, gap sizes, gap shapes and gap size distribution. Many studies provide parameters of exponential distributions describing the gap size distributions. In order to characterize the gap size distribution by an ecologically interpretable parameter, Asner et al. (2013) proposed the scaling exponent of the zeta distribution. This is a promising but not yet widely used metric to quantify the negative relationship between canopy gap frequency and size (Asner et al. 2013, Silva et al. 2019). Many studies also reported some measure of canopy gap shapes such as compactness, circularity or less often fractal dimension. An adequate description of the spatial distribution of canopy gaps is often missing. Only a few studies dealt with the spatial distribution of gaps in nemoral temperate forests (e.g.

Runkle and Yetter 1987, Runkle 1990, Nuske et al. 2009, Garbarino et al. 2012, Petritan et al. 2013, Getzin et al. 2014).

To characterize the spatial pattern of canopy gaps, various methods have been proposed, such as hemispheric images (e.g. Trichon et al. 1998), landscape indices (e.g. Hessburg et al. 1999, Wu et al. 2016), spatial autocorrelation (e.g. Frelich and Lorimer 1991), nearest neighbor distances (e.g. Poorter et al. 1994, Begehold et al. 2016) and point processes (e.g. Garbarino et al. 2012, Silva et al. 2019). In contrast to most methods, the point pattern analysis allows investigating the spatial distribution of objects on several scales and has proven itself in ecological research (e.g. Perry et al. 2006, Law et al. 2009, Picard et al. 2009). However, the nature of canopy gaps as objects of finite size and irregular shape is neglected by the above methods. Representing canopy gaps exclusively by a point obscures real interactions if the sizes of the gaps are in the same range as the scales of interest (e.g. Simberloff 1979, Prentice and Werger 1985, Nuske et al. 2009). Simberloff (1979) accounted for the size of the studied objects by approximating them by circles instead of points and Prentice and Werger (1985) used circles of the size of the objects to construct the null model. These two approaches obviously neglected the actual shape of the gaps. Wiegand et al. (2006) suggested a grid-based approach to not only account for the size but also the shape of the objects in the pattern. Distances were then measured between all grid cell centers representing objects. This approach, in contrast to the methods above, does not produce undesirable and misleading pseudo hard- and soft-core distances caused by the size and shape of the objects. However, it is difficult to interpret the pair-correlation function at small scales because the distance between two objects is no longer one discrete value but a distribution of distances measured between all cells representing objects.

An adaptation of the pair-correlation function, accounting for the above outlined shortcomings, is presented in Chapter 5. The method was applied to an old-growth forest remnant in the Carpathian Mountains, Romania (Chapter 6), managed and unmanaged beech-dominated stands of the Biodiversity Exploratories "Hainich-Dün" and "Schwäbische Alb" (Chapter 7) as well as 22 sites from beech-dominated strict forest reserves throughout Hesse (Chapter 8).

The main difference between the adapted pair-correlation function and the other approaches to amending point pattern analysis for objects of finite size and irregular shape is, that objects are represented by their outer boundary polygon instead of circles or groups of grid cells. This approach is compared to the pair-correlation functions using the conventional point approximation (e.g. Ripley 1981, Stoyan and Stoyan 1994) and the grid-based approach suggested by Wiegand et al. (2006). It was shown that the adapted pair-correlation function avoids pseudo hard- and soft-core effects, is able to describe the real interactions at small scales and the size of the effects are not weighted by the size of the objects. All of the above was not possible using the point approximation or the grid-based approach. The application of the adapted pair-correlation function to canopy gap patterns of different nemoral temperate forests proved to be a useful analytical tool for analyzing the spatial distribution of canopy gaps.

The re-implementation of the suggested method as R package “`apcf`” (Nuske 2019a) is presented in Chapter 8. It replaces the old implementation comprising a PostGIS database and an R script (cf. Nuske et al. 2009). The usability as well as the performance of the method increased considerably. This permits the analysis of larger and more complex canopy gap patterns as well as pointwise confidence envelopes with a higher confidence level. This was not possible using the previous implementation. Being available from the comprehensive R archive network (CRAN, Nuske 2019b) it is much easier for potential users to take advantage of the adapted pair-correlation function.

The spatial distribution of canopy gaps is often relevant over a large range of scales. It is thus advised to check at which distances the estimated pair-correlation function approaches the expected density of 1, which all pair-correlation functions eventually reach. For some canopy gap patterns this could be distances up to 100 m. Accordingly, the study areas should have diameters of at least twice the size of the analyzed distances to keep the edge effects at bay. The extents of the pointwise confidence envelopes for patterns comprising as few as 6 and as many as 462 gaps suggested that patterns should at least contain 30 objects to generate helpful confidence envelopes. More meaningful confidence envelopes can be expected if 50 or more objects are available.

So far, it is only possible to analyze unmarked patterns of objects using the "apcf" package. The difficult part of working with polygons to represent objects of finite size and irregular shape is the randomization of the objects, the calculation of distances and the edge corrections. Since this is already solved in the "apcf" package, an obvious extension of the method is the analysis of qualitatively and quantitatively marked patterns of objects with the partial pair-correlation function and the mark correlation function, respectively (Stoyan and Stoyan 1994, Illian et al. 2008). This has been done extensively for point patterns (e.g. Getzin et al. 2014, Velázquez et al. 2016) and would allow quantifying the spatial relationship of gap ages, gapmaker species or density and height of regeneration within gaps.

Another worthwhile usage of the infrastructure provided by the "apcf" package would be the addition of the empty space function (also called "spherical contact distribution function") and the covariance or *two-point probability function* of a random closed set (Ripley 1988, Illian et al. 2008, Chiu et al. 2013). A first test showed promising results, which were comparable with the adjusted pair-correlation function, but not as easy to interpret. The analysis of canopy gap pattern as random closed sets was suggested by Stoyan, who even included the canopy gap pattern of Nuske et al. (2009) in the third edition of the book "Stochastic Geometry and its Applications" (Chiu et al. 2013) as an application example for random closed sets.

In the Chapters 5 to 8, in total 35 forest sites and three simulated patterns were analyzed using the adapted pair-correlation function. They showed a large diversity of distinct function shapes. There were many examples of no significant deviation from the confidence envelopes indicating complete spatial randomness. Pair-correlation functions with more short distances and less short distances than expected under complete spatial randomness were found suggesting a clustered distribution or respectively a soft-core effect. A wave-like shape of pair-correlation functions was also exhibited indicating a regular distribution of gaps.

The samples from the Biodiversity Exploratories (Chapter 7) seem to suggest a more random distribution of canopy gaps in managed forests while the unmanaged forest showed a slight tendency towards clustered gaps. On the other hand, the two parts of the old-growth forest remnant had to very different pair-correlation functions: a random distribution across all scales and a soft-core effect (Chapter 6). The 22 sites from the Hessian beech-dominated strict forest reserves exhibited all possible function shapes (Chapter 8). It has to be concluded that it was not possible using these 35 samples to explain the spatial distribution of canopy gaps simply by the status or management type of the forests. More samples from European remnants of old-growth beech forest, unmanaged forests and managed forest stands with different management regimes are needed to draw conclusions on the influence of stand age, forest structure, species composition, time since abandonment, site quality or management type on the spatial distribution of canopy gaps. A first step towards a larger collection of descriptions of the spatial distributions of canopy gaps could be to analyze published canopy gap maps which have not yet been fully or suitably investigated (e.g. Meyer and Ackermann 2004, Zeibig et al. 2005, Kenderes et al. 2008, Rugani et al. 2013, Begehold et al. 2016).

The particular strength of the adapted pair-correlation function is the analysis of patterns of objects of finite size and irregular shape with interactions at the scale of object sizes. This can be any objects for which outer boundaries can be established such as lakes in Finland, animal herds, schools of fish or forests in a landscape. The present thesis demonstrated the usefulness of the adapted pair-correlation function for the description of canopy gap patterns of nemoral temperate forests.

9.3 Conclusions

Canopy gap research on beech-dominated forests in Europe has experienced a remarkable upswing in the last decades. It helps answering both fundamental ecological questions as well as designing silvicultural interventions according to the widely accepted concept of close-to-nature forest management. The collection of canopy gap characterizations, however, is still heterogeneous due to diverging gap definitions and mapping approaches. The description of the spatial distribution of canopy gaps, although often called for, is rarely done in an adequate manner.

Mapping canopy gaps is a complex task. The experience gained with the three presented approaches to canopy gap delineation suggests that airborne laser scanning data lend themselves to fast and reliable mapping of the status quo while gap dynamics can be successfully investigated based on time series of archived aerial images. Mapping canopy gaps based solely on either the color or DAP height information of aerial images does not provide satisfactory results. Data fusion techniques combining many information layers such as height, color and texture allow for better canopy gap maps than height or color separately. Data fusion seems to be the best way to make effective use of old archived aerial images. Further research with newer data fusion techniques such as the convolutional neural network U-Net is called for.

The suggested adaptation of the pair-correlation function for objects of finite size and irregular shape proved to be a useful tool for investigating the spatial distribution of canopy gaps. In contrast to other approaches, it avoids pseudo hard- and soft-core effects, does not weight the effects by gap sizes and is able to describe the real interactions even at small scales. Tested on simulated patterns and applied to 35 canopy gap patterns of various nemoral temperate forests, the adapted pair-correlation function documented its practicability and usefulness. The re-implementation in C++ in form of the R package “`apcf`” considerably increased usability and performance facilitating the analysis of larger and more complex patterns and confidence envelopes with higher confidence levels. Being freely available on CRAN makes it easy for potential users to analyze their respective patterns of interest. More samples from old-growth forest remnants and both unmanaged and managed forests are needed to gain a better understanding of the influence of management on the spatial distribution of gaps. In this way, the methods and tools presented in this thesis provide a step towards developing reference values for close-to-nature forestry.

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A Summary

Canopy gap research in European beech-dominated forests has experienced a remarkable upswing in the last decades. It contributes to answering both fundamental ecological questions and to designing silvicultural interventions according to the widely accepted concept of close-to-nature forestry. Although close-to-nature forestry aims at mimicking the dynamics of unmanaged forests, reference values of canopy gaps in old-growth or even semi-natural forests are still scarce. Old-growth forest remnants are rare, and the mapping of canopy gaps is extremely labor-intensive. From a forest structure perspective, canopy gap patterns are mostly characterized by the gap fraction and the gap size distribution and sometimes by gap shape and gap age. Although frequently demanded, an adequate description of the spatial distribution of canopy gaps is often lacking.

The present thesis represents a step towards gaining the needed reference values by automatically mapping and analyzing canopy gap patterns. It contributes to the methodology of automated delineation of canopy gaps based on remote sensing data and suggests a method to describe the spatial distribution of gaps respecting their finite size and irregular shape.

Three different approaches to canopy gap mapping based on remote sensing data are presented. Canopy gaps were mapped with (i) an adaptive median in a moving window exclusively using digital aerial photogrammetry (DAP) height models, (ii) a data fusion approach employing a support vector machine (SVM) combining color, texture, DAP height and height quality information from aerial images, and (iii) a two-part relative height threshold using a standard airborne laser scanning (ALS) data product of the Hessian land surveying office.

All three canopy gap mapping approaches are fully automated and thus not influenced by per gap or per stand subjective judgments. Mapping canopy gaps based solely on either the color or height information obtained from aerial images did not provide satisfactory results. The data fusion approach using a SVM allowed for better canopy gap maps than height or color separately. ALS showed the capacity to map canopy gaps of all sizes reliably over large forest areas.

In order to obtain status-quo canopy gap maps for large areas, ALS data are very well suited. However, if the focus is on the dynamics of the canopy gaps, time series of aerial images are still the best data source. The most promising approach for automating canopy gap delineation based on aerial images are data fusion techniques combining many information layers, such as DAP heights, color and texture.

An adaptation of the pair-correlation function is suggested for analyzing the spatial distribution of canopy gaps. In contrast to conventional point pattern analysis, the adapted pair-correlation function represents objects by their outer boundary. The method was first implemented using the geodatabase PostGIS and later as the R package "`apcf`" in C++ using the libraries GEOS and GDAL directly.

The adapted pair-correlation function applied to 35 forest sites was able to describe a large diversity of spatial distributions of canopy gaps. However, more samples are needed to study the relationship between the spatial distribution of canopy gaps and for instance forest structure, time since abandonment and local disturbance regime. The second implementation of the adapted pair-correlation function considerably increased usability and performance, rendering it possible to analyze larger and more complex patterns and generate confidence envelopes with a higher confidence level.

It was shown that the adapted pair-correlation function, in contrast to other approaches, avoids pseudo hard- and soft-core effects, is able to describe the real interactions at small scales and the size of the effects are not weighted by the size of the objects. The adapted pair-correlation function proved to be a useful analytical tool for analyzing the spatial distribution of canopy gaps.

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List of publications on which I collaborated during the dissertation project.

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