FROM POINTS TO FORESTS

The potential of 3D point clouds to evaluate the structural complexity of differently managed beech forests

DISSERTATION

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Submitted by

Liane Carolin Neudam

born on the 18.10.1994 in Göttingen

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1. Referee

Prof. Dr. Christian Ammer

Silviculture and Forest Ecology of the Temperate Zones,
Faculty of Forest Sciences and Forest Ecology
Georg-August-University Göttingen

2. Referee

Prof. Dr. Dominik Seidel

Spatial Structures and Digitization of Forests,
Faculty of Forest Sciences and Forest Ecology
Georg-August-University Göttingen

Other members of the examination committee

Prof. Dr. Peter Annighöfer

Forest and Agroforestry Systems
TUM School of Life Sciences
Technical University of Munich

Prof. Dr. Andreas Schuldt

Forest Nature Conservation,
Faculty of Forest Sciences and Forest Ecology
Georg-August-University Göttingen

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"You can't manage
what you can't measure"

– Dr. Peter F. Drucker –

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List of abbreviations

3D	Three-dimensional
CV	Coefficient of variation
D_b	Box dimension
DBH	Diameter at breast height
GEDI	Global Ecosystem Dynamics Investigation
ISS	International Space Station
LiDAR	Light Detecting and Ranging
MAP	Mean annual precipitation (mm)
MAT	Mean annual temperature (°C)
MLS	Mobile laser scanning
NASA	National Aeronautics and Space Administration
SMI	Silvicultural Management Intensity
SSCI	Stand structural complexity index
TLS	Terrestrial laser scanning
UCI	Understory complexity index

Summary

Climate change is leading to global shifts that can create a particular challenge for the stability and vitality of forest ecosystems. In the temperate forests of Central Europe, the natural forest vegetation is dominated by European beech. Although beech is competitive and has a large site amplitude, it is unclear whether it can adapt to the consequences of climate change. Forestry science is confronted with the task of dealing with the challenges of climate change and preserving the forest ecosystem and its functions. The stability of a forest is closely linked to its structural complexity, which can be controlled by silvicultural measures. Quantifying the structural complexity of forests and their changes is the fundamental element for objectively evaluating forests or their management concepts. The aim of this dissertation is to contribute to this subject. The research is based on 3D point clouds from laser scans of beech forests in Germany with different management histories, whose structural complexity is quantified and compared using fractal analysis.

In a first study, the accuracy of the scanning approach for monitoring seasonal changes in structural complexity is investigated (chapter 2). Repeated measurements with the mobile laser scanner (MLS) show that the effects of foliage (leaves emergence vs. leaves dropping) and management (managed vs. formerly managed) on the structural complexity of the forest are quantifiable and can thus be monitored with the applied method.

Our second and central study focuses on the simulation of different silvicultural treatments on 3D point clouds of real forest stands. A special feature here is that each treatment type is simulated on each study stand so that only the treatments can be compared. The effect of the treatments on the change in structural complexity and on short-term economic gain is then investigated (chapter 3). Six different treatments are simulated in 19 different real beech forest stands, and each treatment has a different negative effect on the structural complexity of the stands right after harvesting. We found that no trade-off between the objectives of small structural changes in the stand and a high economic return is necessary.

The aim of the third study presented here is to evaluate the closeness to nature of the study stands by comparing them with primary forests as a natural reference (chapter 4). To this end, the scan data from beech forests with different management histories were compared with data from primary forests in terms of their structural complexity and stem form. Our results show that although near-natural managed beech forests do not have the same stem forms as primary forests, they can achieve the same structural complexity of the stands.

The methodology of laser scanning technology is characterized by high accuracy and is suitable as a tool to capture the smallest changes in the structural complexity of forests. Different management methods can be objectively evaluated and compared in terms of their structural complexity on the basis of laser scanning data. The present results show that laser scanning can also help in the selection of future management methods in order to investigate their effects on the structural complexity of a stand before implementation in practice. Thus, the presented methodology provides a detailed and efficient assessment of the structural complexity to evaluate the forest condition and possible management methods. It could provide an important instrument for the target-oriented development of climate-adapted forests.

Zusammenfassung

Der Klimawandel führt zu globalen Veränderungen, die besonders für die Stabilität und Vitalität von Waldökosystemen eine Herausforderung darstellen. In den gemäßigten Wäldern Mitteleuropas wird die natürliche Waldvegetation von der Rotbuche dominiert. Obwohl die Buche konkurrenzfähig ist und eine große Standortamplitude hat, ist unklar, ob sie sich an die Folgen des Klimawandels anpassen kann. Die Forstwissenschaft steht vor der Aufgabe sich den Herausforderungen des Klimawandels zu stellen und das Ökosystem Wald und seine Funktionen zu erhalten. Die Stabilität eines Waldes hängt eng mit seiner strukturellen Komplexität zusammen, die durch waldbauliche Maßnahmen gesteuert werden kann. Die strukturelle Komplexität von Wäldern und ihre Veränderungen zu quantifizieren ist die Grundlage um Wälder oder deren Managementkonzepte objektiv beurteilen zu können. Das Ziel der vorliegenden Dissertation ist es einen Beitrag zu dieser Thematik zu leisten. Als Forschungsgrundlage dienen 3D-Punktwolken aus Laserscans von Buchenwäldern in Deutschland mit unterschiedlicher Bewirtschaftungsgeschichte, deren strukturelle Komplexität mittels Fraktal Analyse quantifiziert und verglichen wird.

In einer ersten Studie wird die Genauigkeit des Scanning-Ansatzes für die Überwachung der saisonalen Veränderungen der strukturellen Komplexität untersucht (Kapitel 2). Wiederholte Messungen mit dem mobilen Laserscanner (MLS) zeigen, dass die Auswirkungen des Laubes (Blattaustrieb vs. -abfall) und der Bewirtschaftung (bewirtschaftet vs. ehemals bewirtschaftet) auf die strukturelle Komplexität des Waldes quantifizierbar sind und somit mit der angewandten Methode überwacht werden können.

Unsere zweite und zentrale Studie konzentriert sich auf die Simulation von verschiedenen waldbaulichen Behandlungen an 3D-Punktwolken von realen Waldbeständen. Eine Besonderheit hierbei ist, dass jede Behandlungsart an jedem Untersuchungsbestand simuliert durchgeführt wird, sodass ausschließlich die Behandlungen verglichen werden können. Anschließend wird die Wirkung der Behandlungen auf die Veränderung der strukturellen Komplexität und auf den kurzfristigen wirtschaftlichen Gewinn untersucht (Kapitel 3). Sechs verschiedene Behandlungen werden in 19 verschiedenen realen Buchenwaldbeständen simuliert, und jede Behandlung wirkt sich in unterschiedlichem Maße negativ auf die strukturelle Komplexität der Bestände direkt nach der Ernte aus. Wir konnten feststellen, dass kein Kompromiss zwischen den Zielen, kleine strukturelle Veränderungen im Bestand und einem hohen wirtschaftlichen Ertrag, erforderlich ist.

Ziel der hier vorgestellten dritten Studie ist es, durch den Vergleich mit Urwäldern, als natürliche Referenz, die Naturnähe der Untersuchungsbestände zu bewerten (Kapitel 4). Zu diesem Zweck wurden die Scandaten von Buchenwäldern mit unterschiedlicher Bewirtschaftungsgeschichte mit Daten von Urwäldern hinsichtlich ihrer strukturellen Komplexität und Stammform verglichen. Unsere Ergebnisse zeigen, dass naturnah bewirtschaftete Buchenwälder zwar nicht die gleichen Stammformen wie Urwälder aufweisen, aber die gleiche strukturelle Komplexität der Bestände erreichen können.

Die Methodik der Laserscanning-Technologie zeichnet sich durch eine hohe Genauigkeit aus und ist als Werkzeug geeignet, um kleinste Veränderungen in der strukturellen Komplexität von Wäldern zu erfassen. Verschiedene Managementmethoden können hinsichtlich ihrer strukturellen Komplexität auf Grundlage von Laserscandaten objektiv bewertet und verglichen werden. Die vorliegenden Ergebnisse zeigen, dass Laserscanning darüber hinaus auch bei der Wahl der zukünftigen Managementmethode helfen kann, um deren Auswirkungen auf die Strukturkomplexität eines Bestandes vor der Umsetzung in der Praxis zu untersuchen. Dadurch bietet die vorgestellte Methodik eine detaillierte und effiziente Erfassung der strukturellen Komplexität zur Beurteilung des Waldzustandes und möglicher Managementmethoden. Sie könnte ein wichtiges Instrument zur zielgerichteten Entwicklung von klimaangepassten Wäldern bieten.

Chapter 1

Introduction

1.1 The role of forests in climate change

Long-term changes in temperatures and weather patterns are referred to as climate change. Human combustion of fossil fuels is the main cause of climate change since the 19th century (United Nations, 2021). Changes in the Earth's climate can be observed worldwide, and some of the changes that have already begun, such as the ongoing rise in sea levels, are irreversible (Intergovernmental Panel on Climate Change, 2021). According to the Food and Agriculture Organization of the United Nations (FAO, 2020) forests cover 4.06 billion hectares globally, which is nearly one-third of the earth's terrestrial surface. The highest percentage of the world's forests are in the tropics, followed by the boreal, temperate and subtropical regions (FAO, 2020). Deforestation and forest degradation have led to global environmental impacts in recent decades and contributed to climate change through the release of carbon dioxide (Gullison et al., 2007) and biodiversity loss due to habitat destruction (Laurance et al., 2012). At the international level, various discussions, frameworks, and initiatives have been launched to monitor and address anthropogenic forest loss, like for example the Kyoto Protocol from the United Nations Framework Convention on Climate Change or the "Reducing Emissions from Deforestation and Forest Degradation" (REDD +) program (Gullison et al., 2007; DeVries et al., 2015).

For Central Europe, an increase in mean annual temperature of 2.5 to 3.5°C (Rowell and Jones, 2006), an increase in the frequency and intensity of summer heat waves (Schär et al., 2004; Fischer and Schär, 2009), and a regional decrease in summer precipitation of up to 25 % (Meinke et al., 2010), is predicted by the end of the 21st century (Schuldt et al., 2016). For forests, these changes will have particular impacts on water availability, affecting their growth, vitality, and stability (Bréda et al., 2006; Weber et al., 2013), which may lead to tree mortality (Allen et al., 2010; Anderegg et al., 2015; McDowell and Allen, 2015), or changes in tree species distribution (Delzon et al., 2013; Rigling et al., 2013). Against this background, forest management policies in Central Europe promote large-scale forest conversions, from forests in monocultures to species-rich and uneven-aged stands, which are sought to be ecologically and economically more beneficial (Seidel, 2011; e.g. Lindner et al., 2014; Ammer et al., 2018; Seliger et al., 2023). Species-rich (Bazzaz, 1975; Tews et al., 2004; Bayer et al., 2013) and uneven-aged (Commarmot et al., 2005; Schall et al., 2018; Stiers et al., 2020) stands are characterized by high structural complexity. Structural complexity of forests is defined as the dimensional, architectural, and distributional arrangements of plant material in a given space at a given point in time (sensu Seidel et al., 2020), and is closely related to forest resilience

(D’Amato et al., 2011; Hardiman et al., 2011; Ehbrecht et al., 2017), resistance (Knoke and Seifert, 2008), life form diversity (Lindenmayer et al., 2000; Neill and Puettmann, 2013), ecosystem stability (Messier et al., 2013), and microclimatic stability (Ehbrecht et al., 2017; Seidel et al., 2020). The structural complexity of forests can be managed through silvicultural treatments (Jung et al., 2012; Messier et al., 2015; Stiers et al., 2020; Neudam et al., 2023). To halt biodiversity loss in European forests and to increase the flexibility of making future management changes, structural complexity is specifically promoted (Franklin, 1988; Hunter and Hunter, 1999; Lindenmayer et al., 2000; Lindner et al., 2014).

1.1.1 European beech (*Fagus sylvatica* L.) forests

The natural forest vegetation in the temperate forests of Central Europe is dominated by European beech, with the largest areas in France, central and southern Germany, and in the mountains of southeastern Europe (Bohn et al., 2003; Brunet et al., 2010; Ellenberg and Leuschner, 2010; Schuldt et al., 2016; Caudullo et al., 2023). Since the Middle Ages, however, old-growth European beech forests have been converted to agricultural land and later to fast growing coniferous forests (Ammer et al., 2018). *Fagus sylvatica* L. prefers a temperate, mild, and humid climate. It thrives on base-rich and well-drained soils and cannot endure waterlogging or severe drought (Mayer, 1984; Bolte et al., 2007; Brunet et al., 2010; Ellenberg and Leuschner, 2010). The average height of beech trees is 30-40 m with a maximum stem diameter of 100-150 cm in closed stands and a maximum age of about 200-300 years, in exceptional cases up to 400 years (Korpel, 1995; Brunet et al., 2010; Peters, 2013). Due to the high crown plasticity of European beech, the trees are able to respond quickly to changes in light availability and can therefore rapidly close small gaps in the canopy through horizontal crown expansion (Wagner et al., 2011; Fichtner et al., 2013; Feldmann et al., 2018; Stiers et al., 2018). Therefore, it is usually very shady under a closed old beech stands, although advanced regeneration can persist even under these conditions (Korpel, 1995). European beech is able to dominate in old-growth stands under favorable climatic and edaphic conditions (Ellenberg, 1988; Meyer et al., 2003; Brunet et al., 2010) and would naturally cover nearly 66 % of the area of Germany (Bohn et al., 2003; Ammer et al., 2010; Schuldt et al., 2016).

Even though *Fagus sylvatica* L. is competitive (Bolte et al., 2007), it remains unclear to what extent beech is threatened by or able to adapt to increasing drought under the prediction of a changing climate (Jump et al., 2006; Herbette et al., 2010). Typical symptoms of drought-induced mortality are discoloration and defoliation of the crowns (Peñuelas and Boada, 2003;

Jump et al., 2006). Increased beech mortality in southern Germany could be observed especially after the intense drought years of 2018 and 2019 (Obladen et al., 2021), with 2018 also reported as the hottest and driest year in Germany since meteorological observations began in 1881 (Kaspar et al., 2020; Zscheischler and Fischer, 2020). In the time of climate change, the maintenance of stable beech forest ecosystems plays an important role (Diaci and Kozjek, 2005), especially as carbon sinks (Allen et al., 2010). Selected European beech forests were inscribed on UNESCO World Heritage list as „Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe“ (UNESCO, 2017). Furthermore, in view of the increasing degradation of pure coniferous stands, it serves as a substitute or admixed tree species (Ammer et al., 2002; Ammer et al., 2008; Balcar and Kacalek, 2008; Hobza et al., 2008). Lastly, the economic value of beech wood has increased in recent years (Knoke et al., 2006; BMEL, 2015; Baumbach et al., 2019), and in connection with the progress of near-natural forest management based on knowledge of site ecology and natural processes, it is gaining importance (Diaci and Kozjek, 2005; Bolte et al., 2007; Schütz et al., 2012).

1.1.2 Management of European beech forests in Germany

Silviculture is the management of the structure and composition of forests to achieve economic, ecological, and/or social objectives. The methods to achieve these objectives include the selection of tree species, site preparation, planting, tending, as well as thinning (Duncker et al., 2012). The scope for action is determined by site conditions, disturbance regimes and social requirements (Knoke et al., 2022). In addition, it allows to control intra- and interspecific competition and light conditions (Bolte et al., 2007; Ammer, 2017), which will play an increasingly important role in predicted climatic changes. The choice of the forest management method influences the short-, medium-, and long-term silvicultural interventions in forests (Duncker et al., 2012). The challenge is to deal with the observed and modeled climate trends and the associated uncertainties in sustainable forest management (Messier et al., 2013; Lindner et al., 2014; Mori et al., 2017).

A widely used system for managing beech forests to produce high quality timber is the uniform shelterwood system (Burschel et al., 1987; Matthews, 1991; Diaci and Kozjek, 2005; Ammer et al., 2011). Even-aged (one age class) forest management method, such as uniform shelterwood leads to less structural complexity due to minimal variation in tree dimensions and age (Diaci and Kozjek, 2005; Brunet et al., 2010). The age difference between the oldest and youngest trees is limited to 20 % of the rotation length (Raymond et al., 2009). In this system, the interventions of the forests are carried out in form of intermediate thinnings and a final felling of mature trees after a certain age or target diameter (for beech DBH < 55 cm) has been reached (Finkeldey and Ziehe, 2004; Schall et al., 2018; Aszalós et al., 2022).

Under the projections of a changing climate, forest management for structural complexity is a priority. Therefore, different approaches have been discussed to replace conventional even-aged management systems (e.g. Messier et al., 2015), and to promote the structural complexity while producing high-quality timber (e.g. Schütz et al., 2012). These include uneven-aged (continuous cover) and multi-aged forest management methods, represented by a variety of selection (single tree or group) and irregular shelterwood systems (Diaci and Kozjek, 2005). These systems are characterized by selection cuttings based on target diameter distribution with small- to medium-sized openings which in the development of a multi-layered structure (at least two age classes) growing in the same area (Raymond et al., 2009; Aszalós et al., 2022). The uneven-aged silvicultural systems (continuous cover forestry) are close-to nature, resembled natural disturbance and regeneration processes, optimized the growth and value of individual trees, and maintained the forest ecosystem and its processes (Schütz, 2001; Messier et al., 2015; Ammer et al., 2018).

1.2 3D point clouds and fractal analysis

To successfully manage a forest and predict its future growth, foresters and scientists are increasingly interested in understanding the spatial structure of forests (Knoke and Seifert, 2008; Puettmann, 2011; Messier et al., 2015; Ammer et al., 2018; Seidel et al., 2020). Over the last two decades, different approaches to quantify the complex and three-dimensional character of forest structure were developed. Following Zellweger et al. (2013), vertical and horizontal heterogeneity were assessed separately and then combined in models to quantify the attributes in an index value of structural complexity, as described in McElhinny et al. (2005). Detailed information about the structural complexity of forests, being defined as the spatial distribution of plant material in a given space at a given time (e.g. Seidel et al., 2020), is needed. Using techniques such as Light Detection and Ranging (LiDAR), also termed laser scanning, the three-dimensional structure of individual trees as well as forest stands can be directly captured. There are several LiDAR-based methods, such as airborne laser scanning (ALS), terrestrial laser scanning (TLS), or hand-held or vehicle-mounted mobile laser scanning (MLS). The scanner is permanently mounted on a tripod in the case of TLS or is moved during the scanning process as in the case of MLS, by being carried by hand or attached to a car or in the case of

ALS even to an aircraft. The scanning principle is based on laser distance measurements between the scanner and any object in its surrounding that reflects the laser beam. The reflected laser beams are registered by the scanner and the distance between the scanner and the scanned object is calculated. Subsequently, the obtained spatial information can be visualized as three-dimensional point clouds. In this thesis, data from TLS and MLS (hand-held) were used to capture the forest scene in an efficient and objective manner. A more detailed description of the technical details and settings of the scanners used, as well as the scanning method, can be found in the material and methods part of the studies in chapters 2.2, 3.2, and 4.2.

The detailed 3D data of forests can be used to quantify the structural complexity of forests by mathematically based fractal analysis. According to Mandelbrot (1977) many of the apparent irregularities in nature can be modeled by mathematical objects, some of which are very irregular or fractional, others of which include a random component (Cannon, 1984). And thus Mandelbrot (1977) introduced the concept of the fractal, a geometric shape that is characterized by self-similarity across spatial scales (Palmer, 1988). Using fractal analysis to assess structural complexity is a holistic approach to define the structure of a forest, using the distribution and density of biomass as a unifying characteristic (e.g. Zeide and Pfeifer, 1991; Kaye, 1994; Jonckheere et al., 2006; Seidel et al., 2018; Neudam et al., 2022). On this basis, several indices have been developed that can derive structural complexity from 3D forest data and quantify it as a single number. Some examples are the stand structural complexity index (SSCI; Ehbrecht et al., 2017) or the box-dimension (D_b; Seidel, 2018) as methods to capture the structural complexity of the whole stand, as well as the structural complexity of the understory expressed by the understory complexity index (UCI; Willim et al., 2019; Seidel et al., 2021), or the canopy structural complexity, expressed as rugosity (Hardiman et al., 2011; Atkins et al., 2018).

In this study, the following parameters were recorded and analyzed from point clouds:

- General parameters of the study area and the trees
  - Plot size
  - Tree height
  - Diameter at breast height (DBH)
  - Lean of the stem (see chapter 4)
  - Sweep of the stem (see chapter 4)
  - Length of the stem (see chapter 4)

- Structural complexity
  - Box-dimension (D_b; see chapters 2 & 3)
  - Stand Structural Complexity Index (SSCI; see chapters 2 & 4)
  - Space filling (see chapter 4)

1.3 General study hypotheses

For the management of forests, it is necessary to be able to compare and evaluate them. The laser scanning approach presented in the following studies was used to quantify forests in terms of their structural complexity. The goal of the present thesis was to explore the possibilities offered by laser scanning in the field of forestry and forest science. The following hypotheses served as the basis for this work:

(I) Laser scanning technology is sensitive enough to quantify changes within one year in the structural complexity of European beech forests to allow efficient and objective monitoring of forests for example with respect to climate change.

(II) With the help of math-based fractal analysis, it is possible to simulate silvicultural treatments on real forest data in order to quantify their effects on structural complexity even before they are implemented in practice.

(III) The laser scanning approach provides a way to evaluate different management concepts, which offers an advantage in making decisions for future treatment.

The main part of this thesis consists of three studies (cumulative dissertation) and deals with the evaluation of the method of laser scanning for quantifying the structural complexity of forests and a selection of possible applications. For this purpose, the methodology was first tested by trying different scanning methods and quantifying the sensitivity of the method (study 1). Subsequently, different silvicultural treatments were simulated for the obtained 3D point clouds of the study stands to evaluate their impact in terms of structural change and net revenue generated (study 2). With the assumption that the laser scanning approach is sensitive enough to quantify structural changes in order to compare forest stands and silvicultural concepts, different concepts were evaluated in a further study (study 3).

For a more detailed overview, the hypotheses of the individual research studies are listed briefly below:

Study 1: Exploring the potential of mobile laser scanning to quantify forest structural complexity (chapter 2)

1) The scanning schemes affect the assessment of structural complexity based on the box-dimension from mobile laser scanning.
2) Repeated measurements on the same site and with the same measurement protocol lead to consistent results.
3) The scanning approach can be used to monitor changes in structural complexity due to the phenology (leaf-effect).
4) The scanning approach is sensitive enough to distinguish sites from each other that underwent different measurement regimes.

Study 2: Simulation of silvicultural treatments based on real 3D forest data from mobile laser scanning point clouds (chapter 3)

1) Different silvicultural treatments have varying effects on the forest stand structural complexity, here quantified based on the box-dimension obtained from mobile laser scanning.
2) This effect is influenced by the previous management (formerly managed vs. managed) of the stand.
3) Trade-offs exist between the effects of different treatments on structure and economic return when a forest owner strives for low changes in structural complexity and high net revenue.

Study 3: Stem shape and structural complexity change in beech forests along a management gradient (chapter 4)

1) Forest management targeted towards natural forest development can result in structures that resemble structures of primary forests, here assessed based on overall structural complexity and patterns of vertical space-filling.
2) Management intensity affects the shape of the trees growing in a stand, here assessed via lean, sweep, diameter, and length of branch-free stem.

1.4 Concept and design of the study

The basis for the present study was provided by the collaborative research project *Adaption strategies of beech forests to changing environmental conditions with different management intensities* ("NaWi") as part of support for achieving the climate goals of the Federal Government and was supported by the Fachagentur Nachwachsende Rohstoffe e.V. (FNR). Based on a resolution made by the German federal parliament, the collaborative research project was financially funded by the Federal Ministry for Environment, Nature Conservation, and Nuclear Safety (BMU) and the Federal Ministry of Food and Agriculture (BMEL) through the "Waldklimafonds".

The aim of the collaborative project, which was launched in February 2020, was to investigate the processes of adaption strategies of old European beech forests with varying management intensity to climate change. Forest structure, material fluxes in trees and soil, as well as essential tree physiological characteristics were analyzed and evaluated along a gradient of management intensity and site quality in different subprojects. The cooperating partners in the six subprojects were the Universities of Göttingen, Freiburg and Constance, as well as the Natural Resources Research Laboratory, a group of independent environmental consultants. The objective of the present subproject was to quantify the stand structure of beech forests. In order to determine the structural complexity of a stand, both mobile and terrestrial laser scanners were used. On the basis of three-dimensional point clouds, it was thus possible to map the spatial arrangement of objects (plant material) within the scanned study stand in detail. By evaluating the horizontal and vertical distribution of the plant material, the structural complexity of the forests could be analyzed.

1.4.1 Study sites and objects

For this collaborative project, old beech forests (main tree species *Fagus sylvatica* L.) with different management intensity were selected in the temperate climate zone (see Table 1.1). To allow for the test of consistency and generality of forest management effects across geographic regions, the study plots were established in four different regions of Germany. In detail, the study sites were located near Allstedt (Saxony-Anhalt), near Göttingen (Lower Saxony), near Lübeck (Schleswig-Holstein), and near Oppershofen (Hesse; see Figure 1.1).

Table 1.1 Main geographic characteristics of the four study sites.

	Allstedt	Göttingen	Lübeck	Oppershofen
Coordinates	51°22’ N/ 11°24’-11°25’ E	51°31’-51°33’N/ 10°01’-10°02’ E	53°38’-53°46’ N/ 10°33’-10°51’ E	50°25’ N/ 8°46’E
Geology	Late Permian and early Triassic	Sand and limestone Triassic	Young moraine landscape	Miocene clays and basalt
Soil type	Umbrisols and rendzic leptosols	Umbrisols with loess and rendzic leptosols	(Pseudogleyic) luvisols	Deep loess-haplic luvisols
Altitude (a.s.l.)	268 – 316 m	341 – 455 m	46 – 70 m	267 – 269 m
Annual mean temperature	9.81 °C	9.80 °C	9.60 °C	10.89 °C
Annual mean precipitation	466 mm	595 mm	655 mm	560 mm
Mean tree age (2021)	115	137	130	142
Natural forest vegetation	*Luzulo-Fagetum*	*Hordelymo-Fagetum*	*Asperulo-Fagetum*	*Asperulo-Fagetum*
No. of plot	2	8	7	2

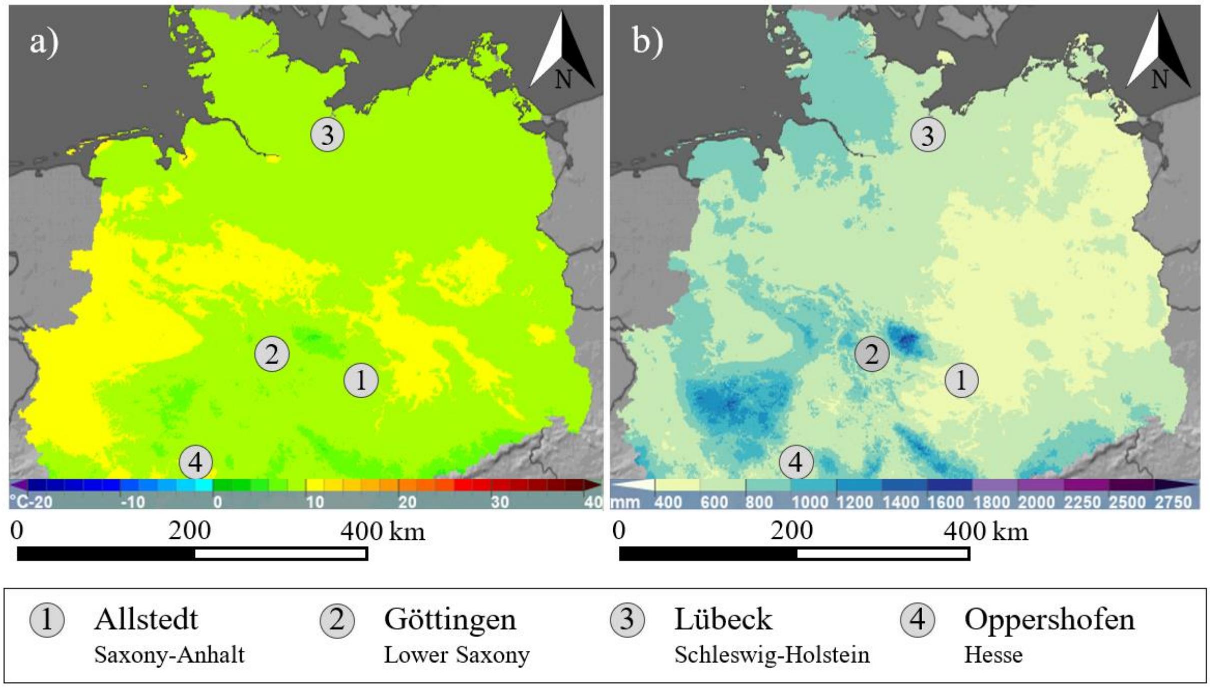

Figure 1.1 Geographic location of the four study areas in Germany with their mean annual temperature (a) and mean annual precipitation (b) from 1991-2020.

For each study site, a pair of plots was selected that differed in terms of management intensity. More precisely, the difference in management intensity can be explained by the management history (previous management system) of the plots, as one plot has been managed to the present day and the other plot was formerly managed but is no longer managed. For a more in-depth analysis of management intensity to test consistency and generality, five additional plots were selected for the study site in Lübeck and six for the study site in Göttingen (see Figure 1.2). In the formerly managed stands, forest interventions ceased between 1983 and 1995, except for one plot near Lübeck. This study area (LG1) is enclosed by moats and is located near the former border between the German Democratic Republic and the Federal Republic of Germany. Due to the difficult accessibility of this area, no forestry interventions have taken place on this area since the 1920's. The management of the managed stands followed a nature-oriented approach with single-tree selection harvest based on a target diameter breast height of 70 cm for mature beech trees.

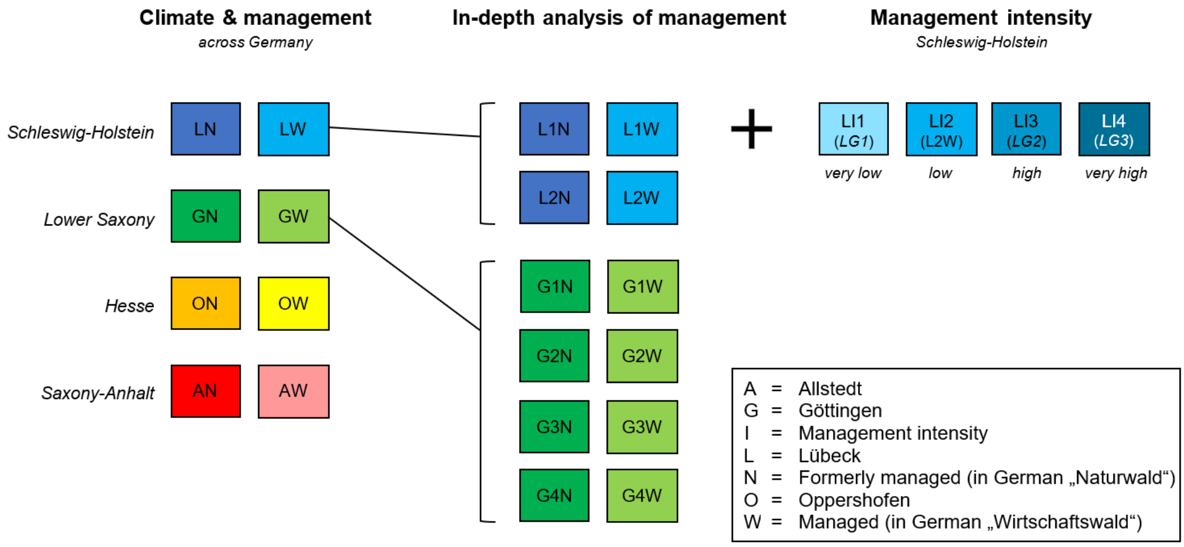

Figure 1.2 Plot design of the collaborative research project.

All selected plots were pure beech or beech-dominated stands with other tree species contributing less than 20 % basal area. By the time data were collected for this work, the age of the dominant trees ranged from 91 to 148 years. All study plots were scanned several times. Scans with the terrestrial laser scanner were taken during vegetation period in July 2020 and September 2021, with all trees densely foliated. The 19 study plots were also scanned with the mobile scanner under defoliated conditions in April 2020 and February 2021. In addition, 15 study plots were scanned monthly with the mobile scanner from March/ April 2020 to February 2021. Table 1.2 shows characteristics of the study stands from the segmented 3D point clouds of the trees based on the scan data. For further descriptions see chapters 2.2, 3.2, and 4.2.

For a comparison of the study plots with primary forests from Slovakia and Ukraine, data from another study of four additional plots were included (see chapter 4).

Table 1.2 Detailed characteristics of the study plots from the segmented 3D point clouds of the trees based on the scan data.

Study area	Managment history	Plot name	Mean diameter at breast height (cm)	Mean tree hight (m)	Stem density ($n\ ha^{-1}$)	Stand solid cubic meter ($m^3\ ha^{-1}$)	Stand basal area ($m^2\ ha^{-1}$)	Terrestrial laser scanning (month/year)	Mobile laser scanning (month/year)
Allstedt	Formerly managed	A1N	36	27	239	428	28	7/20 & 9/21	monthly 4/20 – 2/21
	Managed	A1W	26	22	360	279	22	7/20 & 9/21	monthly 4/20 – 2/21
Göttingen	Formerly managed	G1N	39	31	299	677	40	7/20 & 9/21	monthly 4/20 – 2/21
		G2N	30	24	317	389	26	7/20 & 9/21	monthly 4/20 – 2/21
		G3N	39	30	228	564	32	7/20 & 9/21	monthly 4/20 – 2/21
		G4N	34	28	294	587	34	7/20 & 9/21	monthly 4/20 – 2/21
	Managed	G1W	37	28	209	399	25	7/20 & 9/21	monthly 4/20 – 2/21
		G2W	31	23	265	423	26	7/20 & 9/21	monthly 4/20 – 2/21
		G3W	35	28	224	402	25	7/20 & 9/21	monthly 4/20 – 2/21
		G4W	35	30	267	529	30	7/20 & 9/21	monthly 4/20 – 2/21
Lübeck	Formerly managed	L1N	35	27	267	551	32	7/20 & 9/21	4/20 & 2/21
		L2N	42	31	181	580	31	7/20 & 9/21	4/20 & 2/21
		LG1	40	34	357	907	48	7/20 & 9/21	monthly 4/20 – 2/21
	Managed	L1W	43	30	173	484	28	7/20 & 9/21	4/20 & 2/21
		L2W	32	25	240	377	24	7/20 & 9/21	4/20 & 2/21
		LG2	38	29	217	556	31	7/20 & 9/21	monthly 4/20 – 2/21
		LG3	34	26	198	323	22	7/20 & 9/21	monthly 4/20 – 2/21
Oppershofen	Formerly managed	O1N	59	40	131	862	39	7/20 & 9/21	monthly 4/20 – 2/21
	Managed	O1W	35	27	189	404	23	7/20 & 9/21	monthly 4/20 – 2/21

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Chapter 2

Exploring the potential of mobile laser scanning to quantify forest structural complexity

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Exploring the potential of mobile laser scanning to quantify forest structural complexity

Liane Neudam[1], Peter Annighöfer[2] and Dominik Seidel[3]

[1] Department of Silviculture and Forest Ecology of the Temperate Zones, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

[2] Forest and Agroforest Systems, Technical University of Munich, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany

[3] Department of Spatial Structures and Digitization of Forests, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

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Abstract

Today, creating or maintaining forest structural complexity is a management paradigm in many countries due to the positive relationships between structural complexity and several forest functions and services. In this study, we tested whether the box-dimension (D_b), a holistic and objective measure to describe the structural complexity of trees or forests, can be used to quantify the structural complexity of 14 European beech (*Fagus sylvatica* L.) dominated forest plots by means of mobile laser scanning (MLS). The goal of this study was to explore the potential of this approach for quantifying the effect of leaves (summer vs. winter) and management (lately unmanaged vs. managed) on forest structural complexity. The findings suggest that repeated measurements on the same site and at the same time yielded consistent results if the measuring scheme is standardized. The results also showed that standardized measurement protocols allowed quantifying differences in forest structural complexity due to season. The highest stand structural complexity was found in leaf-on condition during summer, with the complexity being significantly higher than in winter condition. Also, in case of our beech-dominated plots, managed forests were more complex in structure than formerly managed but now unmanaged forests. This study illustrates the potential of MLS for monitoring the changes in forest structural complexity and allows correcting stand structural information for seasonality.

2.1 Introduction

The world's forests are likely to see a continued and increased pressure from human use (Ammer et al., 2018). At the same time, they are facing changing environmental conditions due to climate change in an unprecedented extent (Krankina et al., 1997; Dale et al., 2001; Millar et al., 2007; Lawler, 2009; Seidl et al., 2011). Precipitation and temperature patterns are changing and result in changes of forest species composition, health and structure (Millar et al., 2007; Lawler, 2009; Seidl et al., 2011). Only recently, it was shown that the structural complexity of unmanaged forests strongly depends on precipitation (Ehbrecht et al., 2021), with the structural complexity of a forest stand being defined as all dimensional, architectural, and distributional patterns of plant individuals and their organs in a given forest space at a given point in time (McElhinny et al., 2005; Seidel et al., 2020). The structural complexity is a characteristic that is often associated with aspired features of a forest, such as increased resilience (D'Amato et al., 2011; Hardiman et al., 2011; Ehbrecht et al., 2017), resistance (Knoke and Seifert, 2008), diversity of lifeforms (Lindenmayer et al., 2000; Neill and Puettmann, 2013), ecosystem stability (Messier et al., 2013) or microclimatic stability (Seidel et al., 2020), and it has become an important paradigm for forest management (Messier et al., 2013). In managed forests, structural complexity can be controlled by the silvicultural practices applied (Jung et al., 2012; Messier et al., 2015; Stiers et al., 2020) and hence management for complexity has been promoted as a tool to halt ecosystem simplification and the loss of biodiversity in managed forests of the temperate zones (Franklin, 1988; Hunter and Hunter, 1999; Lindenmayer et al., 2000).

Against this background, monitoring of structural complexity on landscape scale is a task of increasing importance. The ultimate goal is to monitor such changes at landscape scale from airborne sensors (e.g. Zellweger et al., 2013) or even at global scale through spaceborne remote sensing technologies, e.g. NASA's global ecosystem dynamic investigation (e.g. Rishmawi et al., 2021). However, ground-truthing remains an important task for such endeavors. Additionally, high-resolution (cm-scale) three-dimensional (3D) information on the forest structure from under the canopy is currently only available from close-range remote sensing approaches like laser scanning or below-canopy photogrammetry. This is particularly true when the focus is on the derivation of measures of structural complexity. In the past, indices of structural complexity were often composed of various measures that address the vertical and horizontal heterogeneity separately and that are later combined in models (e.g. Zellweger et al., 2013) with the aim to pooling attributes in a single index value of structural complexity, as nicely reviewed by earlier works (McElhinny et al., 2005). These approaches are fundamentally different from attempts to directly derive a measure of structural complexity from spatial data. The structural complexity index (SCI) by Zenner and Hibbs (2000) was one of the first of such integrating measures, relying on the height of all trees in a plot and relating the area of the surface created through the tree tops (rugged surface) to the surface area at the forest floor (flat surface). Naturally, measuring the height and position of every tree in a stand is time-consuming and it does not provide direct information on the inner forest strata. Recently, there has been a fast development in approaches that deliver objective and quantitative measures of the position of almost (occlusion effects) all plant elements in a forest. From such approaches, may they be based on light detection and ranging (LiDAR) or structure-from-motion (SFM), the three-dimensional structure of individual trees as well as forest stands became directly accessible (Dassot et al., 2011; Bauwens et al., 2016; Calders et al., 2018; Iglhaut et al., 2019). The remaining task, the integration of the spatial data into tangible indices, has been addressed in the last years. For example, canopy structural complexity, expressed as rugosity (Hardiman et al., 2011; Atkins et al., 2018), overall stand structural complexity, expressed as stand structural complexity index (SSCI; Ehbrecht et al., 2017) or box-dimension (D_b; Seidel, 2018), as well as understory structural complexity, expressed by the understory complexity index (UCI; Willim et al., 2019; Seidel et al., 2021) were all derived from 3D forest data and all integrate thousands to millions of measurements of spatial structures into a single number. While some of the new indices fundamentally rely on the use of specific instruments or measurement schemes, the box-dimension can be determined using data from any kind of measurement device or scheme, as long as it results in a 3D point cloud of the object or scene of interest (Seidel, 2018).

Being based on the pioneering work of Mandelbrot (1977), the box-dimension obtained from 3D data was discovered to be a meaningful measure of plant and forest structure in several studies (Seidel, 2018; 2019b; Seidel et al., 2019a; Arseniou et al., 2021; Dorji et al., 2021; Saarinen et al., 2021). Addressing the structural complexity of trees or forests by means of fractal analysis holds potential for simplifications, since the nested, self-similar structures of vegetation are considered a source for simplicity (Mandelbrot, 1977; Sugihara and May, 1990). The pattern of repetition of structures across scales and the distribution and density of the plant material are addressed as one single unifying characteristic (Zeide and Pfeifer, 1991; Kaye, 1994; Jonckheere et al., 2006; Seidel, 2018). This makes the box-dimension approach widely applicable and particularly interesting for large-area investigations or monitoring tasks.

Here, we were interested in (1) whether the complexity assessment based on the box-dimension from mobile laser scanning is affected by different scanning schemes, (2) whether repeated measurements on the same site and with the same measurement protocol yield consistent results and (3) whether the approach can be used to monitor changes in structural complexity due to the phenology (leaf-effect). Finally, (4) to assess the sensitivity of the approach in distinguishing sites that underwent different management regimes, we compared the complexity derived from MLS in managed forests, as well as in forests where management has been abandoned some decades ago.

2.2 Material and Methods

2.2.1 Study sites

We selected 14 forest stands at four different locations in Germany, namely Göttingen (Lower Saxony), Allstedt (Saxony-Anhalt), Oppershofen (Hesse) and Lübeck (Schleswig-Holstein; Figure 2.1 and Table 2.1), covering a gradient in precipitation. The mean annual precipitation between the years 2010 and 2020 ranged from approximately 466.23 mm in Allstedt to 655.33 mm in Lübeck. The mean annual temperature was comparable between the different sites (Table 2.1). All plots were located in pure stands of European beech (*Fagus sylvatica* L.) or in beech-dominated stands with 10 to 15 other broadleaved and coniferous tree species contributing less than 20 % basal area in any case. The age of the trees was between 91 and 148 years at the time of the measurement and the forest stands can be differentiated in terms of their management intensity. We selected seven managed and seven formerly managed (now unmanaged) forests. The management of the formerly managed forests was ceased since 26 to 100 years.

2.2.2 Sampling design

EFFECT OF DIFFERENT SCANNING SCHEMES AND REPRODUCIBILITY

The mobile laser scanning was conducted using a ZEB-Horizon (GeoSLAM Ltd., Nottingham, UK) mobile 3D laser scanner. The device was carried in hand and held towards the direction of walking, facing away from the person carrying it. The recording principle of the Horizon scanner is based on individual laser distance measurements based on the time-of-flight (TOF) principle. With each measurement, the distance between the scanner and each surrounding object at a maximum distance of 100 m was recorded with a range noise of about ± 30 mm. The wavelength of the laser is 903 nm and the scan rate is 300,000 points per second.

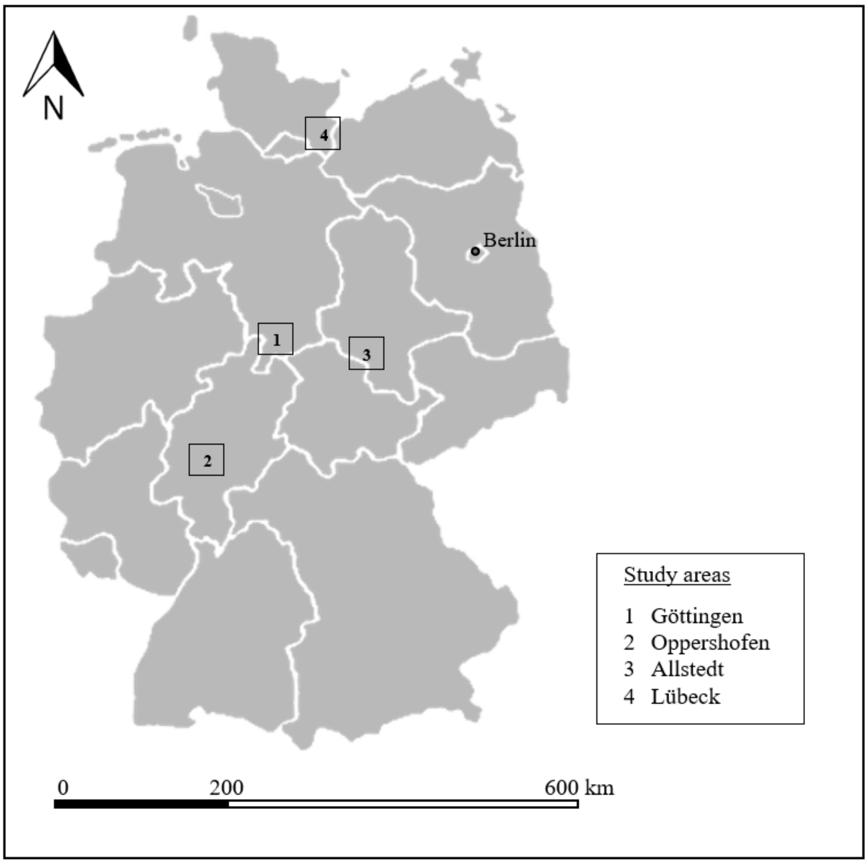

Figure 2.1 Geographic locations of the study areas located in Germany.

In order to capture each study site, we first marked the four corner trees of each of the rectangular study plots with a marking tape for a better orientation. After defining a starting point at a random plot corner and marking it temporarily (e.g. by placing a backpack at the position) the scanner was placed on the ground to initiate scanning (self-orientation). Once initiated, the scanner was picked up and the operator (always the same person) walked across the study plot several times in a specific manner while scanning the surroundings. Each scan process was finished after returning to the starting point marker. A complete scan took about 15 minutes at normal walking speed (~3 km*h^{-1}) depending on terrain and plot size.

To assess the effects of different scanning schemes on the data obtained for the same site, we scanned one exemplary plot (G4N, see Table 2.1) repeatedly within the course of one hour using five different walking schemes (trajectories). While we used the same starting point (corner of the plot) for all measurements, for the first (standard) measuring scheme we surrounded the four corner trees and thus the entire study area, followed by a diagonal crossing through the area and finally a zig-zag across the plot for better coverage (compare “standard scheme”, Figure 2.2). The second scheme was characterized by a walk from the starting point to the middle of the plot and then counterclockwise circular in concentric circles of increasing radius from the middle to the edge of the plot. At the edge, we first walked back to the middle of the plot and then to the starting point to finish the scan (compare Figure 2.2; scheme I). For the second measuring scheme, we walked in a zig-zag pattern with respect to one direction (Figure 2.2, scheme II). The same was done in scheme III (Figure 2.2, scheme III) but with zig-zags aligned to a direction perpendicular to scheme II. For the fourth scheme, we used the procedure from the standard scheme as previously described but with the opposing walking direction. First, we walked diagonally across the area, then followed a zig-zag line and finally surrounded the entire study area until we got back to the starting point (compare Figure 2.2, scheme IV).

Table 2.1 Detailed information about the climatic and geographic conditions of the study areas and the average age of the studied stands. MAP = mean annual precipitation (2010-2020); MAT = Mean annual temperature (2010-2020).

Study Area	Plot Name	Plot Size (ha)	MAP (mm)	MAT (°C)	Mean tree age (2021)	Management Type	Unmanaged since (years)
Göttingen	G1N	0.43	595.19	9.80	142	Formerly managed	38
	G1W	1.09	595.19	9.80	123	Managed	
	G2N	0.71	595.19	9.80	161	Formerly managed	26
	G2W	0.46	595.19	9.80	148	Managed	
	G3N	1.11	595.19	9.80	136	Formerly managed	26
	G3W	0.73	595.19	9.80	128	Managed	
	G4N	0.23	595.19	9.80	132	Formerly managed	26
	G4W	0.83	595.19	9.80	129	Managed	
Oppershofen	O1N	1.45	559.80	10.89	162	Formerly managed	33
	O1W	0.62	559.80	10.89	123	Managed	
Allstedt	A1N	0.37	466.23	9.81	140	Formerly managed	26
	A1W	0.7	466.23	9.81	91	Managed	
Lübeck	LG1	0.62	655.33	9.60	127	Formerly managed	100
	LG2	0.85	655.33	9.60	126	Managed	

In addition to the different scanning schemes, a set of scans was carried out within shorter intervals to quantify the reproducibility of the data acquired using mobile laser scanning in forests. For this purpose, one plot in Göttingen (G1N, see Table 2.1) was scanned in varying time intervals, more precisely several times a day, again after 24 hours, and again after one week according to the pattern described in Table 2.2. The results (D_b-values) of these repeated scans were compared with each other to assess whether the approach delivers consistent data.

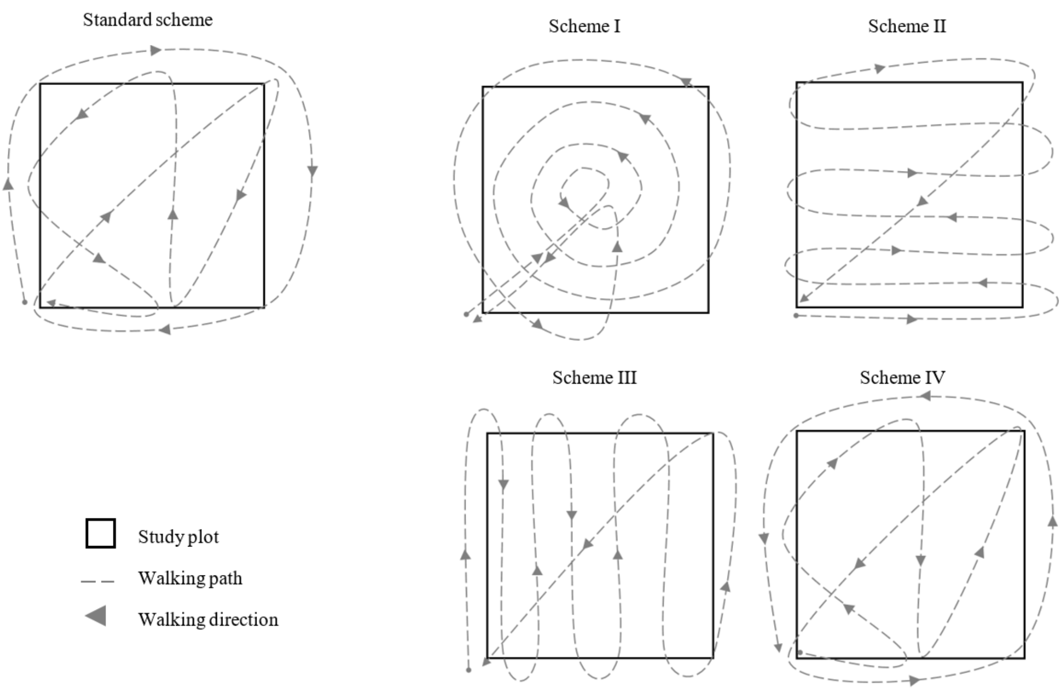

Figure 2.2 Measuring schemes from the standard design for quantifying the reproducibility and the seasonal changes in forest structural complexity (Standard scheme) and from the scans made through the course of one hour with four further different walking paths to quantify the differences between the repeated measurements at the same site (Scheme I – IV).

Table 2.2 Date and time of the measurements made on plot G4N to assess the reliability of the MLS approach.

Scan Number	Date	Time	Time period (hours)
1	June 10th 2021	9:00	0
2	June 10th 2021	9:30	0.5
3	June 10th 2021	10:00	1
4	June 10th 2021	12:00	3
5	June 10th 2021	15:00	6
6	June 10th 2021	18:00	9
7	June 10th 2021	21:00	12
8	June 11th 2021	9:00	24
9	June 16th 2021	9:00	144

ASSESSMENT OF SEASONALITY AND MANAGEMENT EFFECT

To quantify the seasonal changes in forest structural complexity (summer vs. winter), scans were collected several times in leaf-off and leaf-on condition, respectively, between March 2020 and February 2021. We ensured to scan only during dry and calm weather conditions to avoid effects of wind or precipitation on the data quality. We split the scan data into two groups, presumable leaf-on (May to October) and presumable leaf-off (November to April), based on the mean of the climatological classification of the phenology for beech of the years 1992 to 2020 provided by the DWD (Deutscher Wetterdienst, 2021).

2.2.3 Point Cloud Processing

The raw data captured by the scanner was transferred to a computer using the onboard data logger and USB exchange portal. Each mobile scan was then processed with the GeoSLAM software provided by the manufacturer of the Horizon (GeoSLAM Ltd., UK). This processing is based on the simultaneous localization and mapping (SLAM) procedure described in detail in earlier works (e.g. Bosse et al., 2012). Then the data was post-processed as described in Dorji et al. (2021) to create a point cloud of each plot. In brief, we used a laz-file for each scan and the associated trajectory-file (walking path) for orientation and cut the same plot area every time, using the first scan made on each site as a reference in the Open Source CloudCompare software (CloudCompare, v2.10.1, https://www.danielgm.net/cc/). Subsequently, each scan point cloud was subsampled to a 1 cm resolution (down sampling for homogenous point cloud density) and cleaned for outlier points using the noise filter (0.1 m distance).

For the comparison of the derived structural information of the same plots but at different moments in time or from different measurement schemes, it was necessary to use exactly the same area of the plots every time. We focused on a 45 by 45 m area in the center of each plot's point cloud, an area with greatest probability of high data quality due to the highest density of walk-throughs with the scanner in this central part. To ensure that the area was exactly the same in each of the repeated scans, the subsequent scans of a plot were spatially co-registered to one another using the reference scan (first scan made on each site, see above) for all other scans on the respective site. To do so, each subsequent scan was assigned to the first scan roughly by hand (translation and rotation by hand) and subsequently with the registration tool from CloudCompare (iterative closest point; ICP) for fine registration (error always less than 0.1 m). Hence, for each plot, a 3D point cloud with 45 x 45 m extent was created for further analysis.

Each plot's 3D point cloud was converted into a voxel model of 20 cm resolution to reduce effects of spatially heterogeneous data density and to enable efficient computing of the large datasets. Afterwards, a terrain-normalisation was conducted for the 20 cm voxel data by correcting each voxel in the voxel model with the underlying terrain height obtained from the digital terrain models as described in Stiers et al. (2020) and Juchheim et al. (2017). The normalized and spatially homogenized data was then used to determine the structural complexity of the forest stands based on the box-dimension (D_b, Mandelbrot 1977) using the algorithm introduced by Seidel (2018) and published recently as supplementary material in Arseniou et al. (2021).

2.2.4 Statistical analysis

We used parametric and non-parametric tests to analyse the data, depending on whether parametric assumptions were met. For small sample sizes it was necessary to use the Shapiro-Wilk-test as normality-test. We tested the homogeneity of variance by using Levine's test. In case normal distribution and homogeneity of variance could not be assumed, we used the non-parametric Friedman's ANOVA test for dependent variables with repeated measurements and the post-hoc test for Friedman's ANOVA. This was done to test for differences in D_b between the seasonal change of leaf-off and leaf-on conditions, between the management type of managed and formerly managed and between the managed forests of leaves emergence and leaves dropping. If the data met the requirements for parametric tests, we used the repeated measures ANOVA to test for differences between the dependent variables. This way, we tested for differences in D_b between the leaves emergence and the leaves dropping for the formerly managed forests. For all statistical tests, we used a significance level of $p < 0.05$. The statistical analyses were implemented with the software environment R, version 3.6.3 (R Core Team 2020, Vienna, Austria).

2.3 Results

2.3.1 Effects of different measurement schemes and reproducibility

The variation in D_b between the highest and the lowest value observed among the scans made on the same site within a single day, with 24 hours distance and one week later was 0.007 units of D_b, always following the same measurement protocol. For the same site on the same day but with different measurement schemes, the range in D_b was significantly larger and made up 0.02 units of D_b. Finally, for the monthly monitoring of the seasonal pattern on one site the range in D_b was found to be 0.04 units of D_b. This corresponds to a coefficient of variation of only 0.0009 for repeated measurements of D_b on the same site using the same measurement protocol. Based on a mean D_b of 2.55 for this plot, the observed range in D_b due to repeated measurements corresponds to a difference of 0.28 %. The effect of different measurement schemes was larger, accounting to a notable 17.8 % of the change observed due to the seasonal changes (summer to winter: 0.04 units of D_b). At the same time, if different measurement schemes are conducted, they might result in sampling-related difference in box-dimension that accounted for almost 60 % of the changes observed due to the seasonal changes in structure (Table 2.3).

Table 2.3 Range in D_b observed among the scans made on the same site with varying measurement schemes (* see Figure 2.2, Chapter 2.2.1; light grey column) within a single day, 24 hours later and after a week (intermediate grey column) and across the seasons (dark grey column). Check marks (✓) indicates that the respective scan in this line was used.

Measurement scheme*	Date	D_b	Comparison of measurement schemes	Comparison within one measurement scheme	Comparison across seasons
1	June 10th 2021	2.5534		✓	
1	June 10th 2021	2.5557		✓	
1	June 10th 2021	2.5558		✓	
1	June 10th 2021	2.5594		✓	
1	June 10th 2021	2.5586	✓	✓	
1	June 10th 2021	2.5560		✓	
1	June 11th 2021	2.5578		✓	
1	June 16th 2021	2.5521		✓	
2	June 10th 2021	2.5583			
3	June 10th 2021	2.5827	✓		
4	June 10th 2021	2.5638	✓		
5	June 10th 2021	2.5627	✓		
1	March 23rd 2020	2.5660			✓
1	May 12th 2020	2.5765			✓
1	June 17th 2020	2.5803			✓
1	August 12th 2020	2.5785			✓
1	October 22nd 2020	2.6067			✓
1	November 15th 2020	2.5801			✓
1	December 19th 2020	2.5811			✓
1	January 20th 2021	2.5675			✓
1	February 23rd 2021	2.5819			✓
Range of D_b			0.0244	0.0073	0.0407
Mean D_b same protocol				2.5561	
Relative D_b deviation with respect to mean D_b using same protocol				0.28 %	
Relative D_b deviation with respect to observed seasonal range			59.90 %	17.80 %	

The highest D_b was found on the managed study plot in Göttingen in August with 2.66 units of D_b and under fully leaved condition of the forest. The lowest D_b was observed with 2.37 units of D_b on the formerly managed forest stand in Oppershofen in February, with all leaves (Figure 2.3).

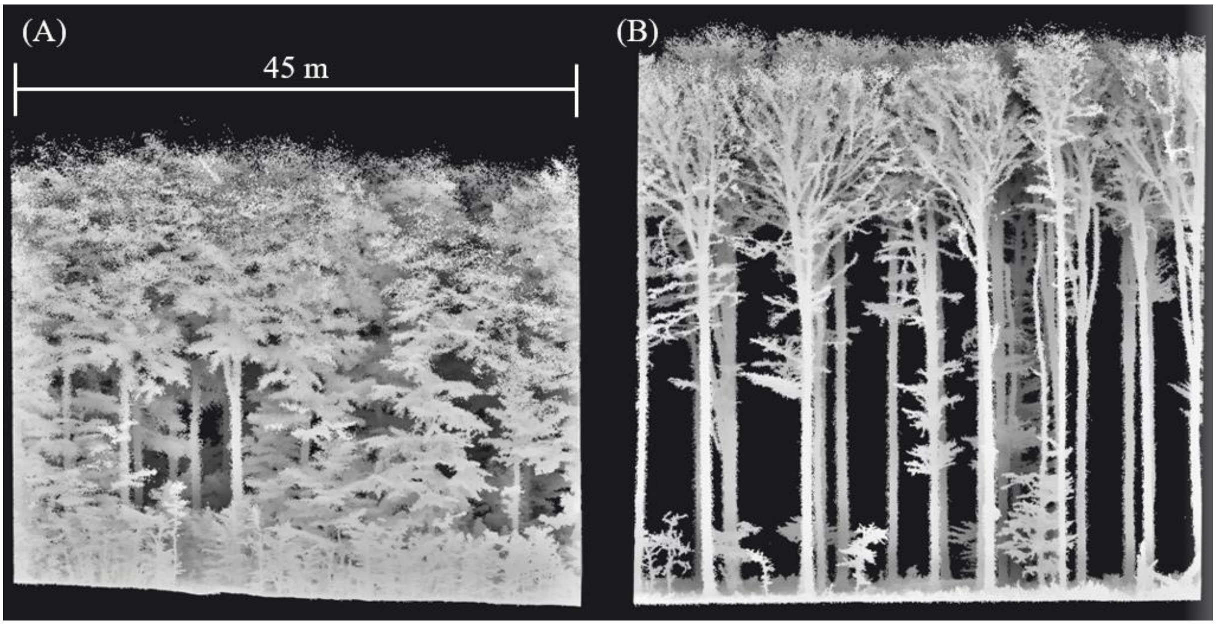

Figure 2.3 Point clouds (45 x 45 m plot area) from the mobile laser scanning in Cloud Compare. (**A**) From one uneven-aged managed study plot in Göttingen during August with an age of the most dominant trees of 148 years and (**B**) from the even-aged formerly managed forest stand in Oppershofen in February, during full defoliation with a tree age of 162 years, which is unmanaged since 1988. Figures are in scale.

2.3.2 Seasonal change and management effects

The stand structural complexity, assessed via the D_b, was found to vary significantly between summer and winter. Figure 2.4 illustrates the differences in stand structural complexity for each plot between leaf-on and leaf-off condition separately for the managed and unmanaged (formerly managed) sites. Data gaps are due to failed SLAM-processing of acquired scans in GeoSlam.

Each plot showed a decrease in structural complexity from the leaf-on to the leaf-off month (compare Table 2.4). Furthermore, the managed forest stands showed a higher D_b than the formerly managed ones on 13 out of 14 sites, except on one plot in Göttingen.

If all plots were considered together, D_b was found to be significantly higher during full foliation in summer than in leaf-off winter condition ($p < 0.025$, Figure 2.5A) and the difference in means was 0.02 units of D_b. A significant difference was also found if all plots were pooled to compared the differences in box-dimension between the managed and unmanaged (but formerly managed) plots (Figure 2.5B).

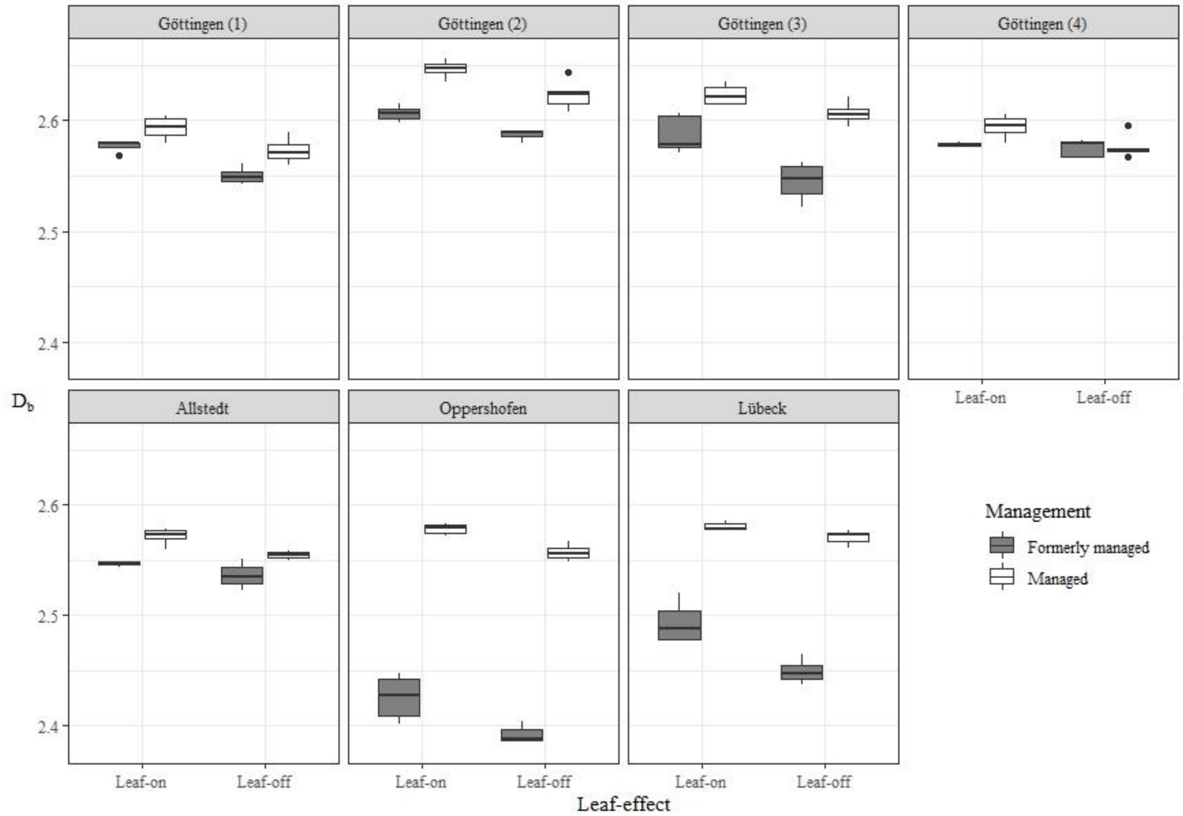

Figure 2.4 Box-Whisker plots of stand structural complexity, expressed as box-dimension (D_b), in leaf-on and leaf-off conditions for all 14 study plots and shown separately for the managed and unmanaged sites in each area. We omitted testing for significant differences for individual plots with regard to the leaf-effect and the management due to small sample sizes.

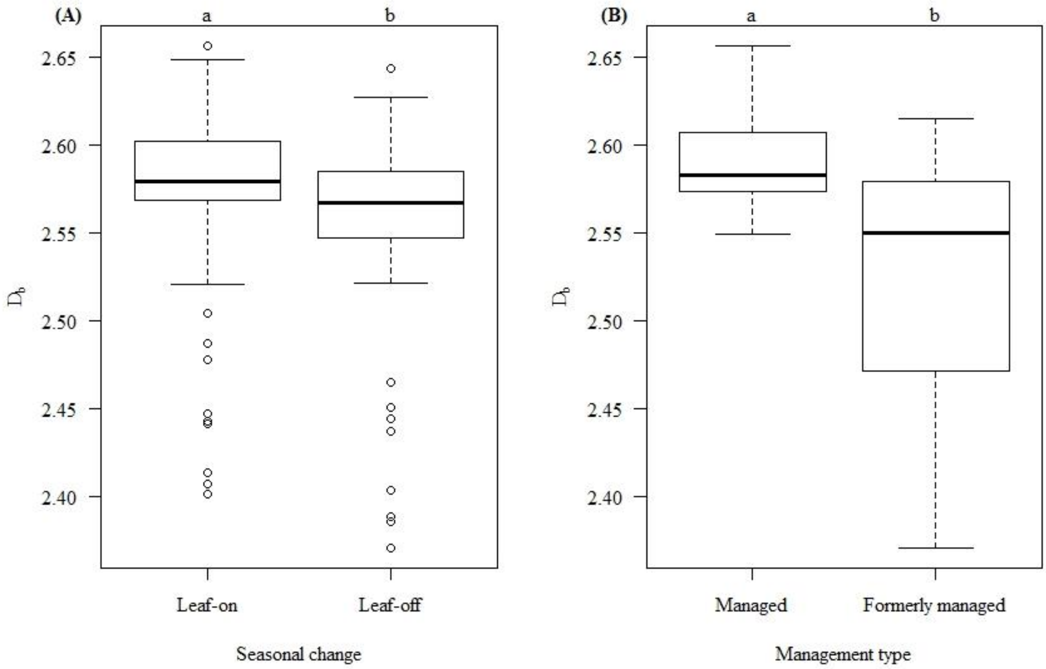

Figure 2.5 Box-Whisker plot of the pooled box-dimension (D_b) of all plots for the seasonal change between leaf-on (summer) and leaf-off (winter) conditions (**A**) and the pooled box-dimension (D_b) over different management types (**B**). Black horizontal lines indicate the median (n = 64 for "Leaf-on" and n = 55 for "Leaf-off"; n = 63 for "Managed", n = 56 for "Formerly managed"). Different lowercase letters indicate significant differences among the conditions at the level of $p < 0.05$.

Table 2.4 Data acquisition months for the TLS and MLS. Missing data is due to failed SLAM processing of the data after scanning.

Study Area	Plot Name	Month and year of TLS measurements	Month and year of MLS measurements leaf-off	Month and year of MLS measurements leaf-on
Allstedt	A1N	July 20	Nov 20, Dez 20, Feb 21	May 20, Jun 20, Sep 20
	A1W	July 20	Mar 20, Feb 21	May 20, Jun 20, Jul 20, Aug 20, Sep 20
Göttingen	G1N	July 20	Mar 20, Nov 20, Dez 20, Feb 21	May 20, Jun 20, Jul 20, Aug 20
	G1W	July 20	Mar 20, Nov 20, Dez 20, Feb 21	May 20, Jun 20, Jul 20, Sep 20
	G2N	July 20	Mar 20, Nov 20, Dez 20, Jan 21	Jul 20, Oct 20
	G2W	July 20	Mar 20, Nov 20, Dez 20, Jan 21, Feb 21	May 20, Jul 20, Aug 20, Oct 20
	G3N	July 20	Mar 20, Nov 20, Dez 20, Feb 21	May 20, Jun 20, Jul 20, Aug 20, Sep 20
	G3W	July 20	Mar 20, Nov 20, Dez 20, Feb 21	May 20, Jun 20, Jul 20, Aug 20, Sep 20, Oct 20
	G4N	July 20	Mar 20, Nov 20, Dez 20, Jan 21, Feb 21	May 20, Jun 20, Aug 20
	G4W	July 20	Mar 20, Nov 20, Dez 20, Jan 21, Feb 21	May 20, Jun 20, Jul 20, Aug 20, Sep 20, Oct 20
Lübeck	LG1	July 20	Apr 20, Nov 20, Dez 20, Feb 21	May 20, Jun 20, Jul 20, Aug 20, Sep 20
	LG2	July 20	Nov 20, Dez 20, Feb 21	May 20, Jun 20, Jul 20, Sep 20, Oct 20
Oppershofen	O1N	July 20	Mar 20, Nov 20, Dez 20, Feb 21	May 20, Jun 20, Jul 20, Aug 20, Sep 20, Oct 20
	O1W	July 20	Apr 20, Nov 20, Dez 20, Feb 21	May 20, Jun 20, Jul 20, Aug 20, Sep 20, Oct 20

The results showed an increase in structural complexity during spring (difference in D_b between April and May) and a decrease during fall (difference in D_b between October and November). The effect of leaves emergence on structural complexity was higher than that of leaves dropping during fall and this difference was significant for the formerly managed plots and not significant for the managed forest, even though a trend was clearly visible ($p = 0.051$,Figure 2.6).

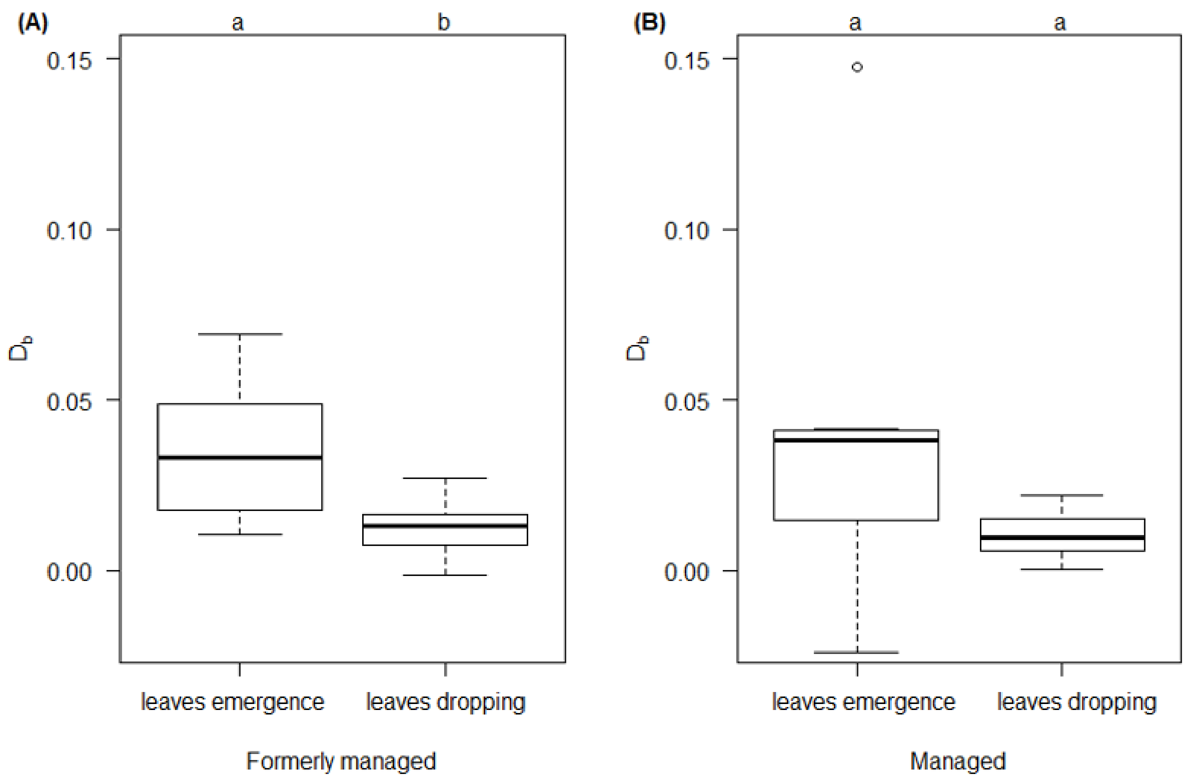

Figure 2.6 Box-Whisker plot of the difference in box-dimension (D_b) resulting from the foliation during spring (leaves emergence) and the defoliation during fall (leaves dropping) over the two different management types. Black horizontal lines indicate the median (Formerly managed (**A**): n = 6 for “leaves emergence” and n = 7 for “leaves dropping”; Managed (**B**): n = 7 for “leaves emergence” and n = 7 for “leaves dropping”). lowercase letters indicate significant differences among the conditions at the level of $p < 0.05$.

2.4 Discussion

2.4.1 Effect of different measurements schemes, reproducibility & assessment of seasonal changes

In this study, we measured the structural complexity of beech-dominated forests, based on the box-dimension (D_b), to explore the potential of MLS for providing efficient, reliable and meaningful data on forest structural complexity, e.g. throughout seasonal changes or due to different forest management. The D_b, as an holistic approach to stand-level complexity, can help quantifying the change in complexity within a year because it is sensitive to all changes in the amount and distribution of plant material in the investigated space (Seidel et al., 2019a; Arseniou et al., 2021). Therefore, the approach might, for example, be helpful to monitor changes due to reduced forest vitality or altered management approaches. The D_b is also an objective measure of structural complexity that is solely mathematically with no prior knowledge on the forest needed. It can theoretically range from one (single linear object = one tree with no branches) to 2.72, which is the dimensionality of the Menger sponge, a mathematical object with the greatest surface to volume ratio (Menger, 1926; Seidel et al., 2019a). Prior studies that have quantified the complexity for *individual trees* in terms of D_b consistently reported values lower than 2.2 in both foliated and defoliated condition (Seidel, 2018; Dorji et al., 2019; Seidel et al., 2019a; Stiers et al., 2020; Saarinen et al., 2021). This can be expected for individual trees (cf. Dorji et al., 2021), since self-shading would result in great inefficiency of values approaching the 2.72 benchmark (Seidel et al., 2019a). When it comes to entire forest stands, as in our study, higher values are to be expected due to niche partitioning and vertical layering in a forest consisting of several trees that are potentially of different size or species. D_b values greater than 2 have been reported by earlier studies for foliated beech-dominated forests (Seidel et al., 2019b; Seidel et al., 2020; Stiers et al., 2020) as well as for coniferous forest in many cases (Seidel et al., 2020). In our study, the D_b of the point clouds from mobile laser scanning in both conditions, leaf-on and leaf-off, were always greater than 2 across all study plots.

To further evaluate the reliability of MLS-based quantifications of the structural complexity, we compared the results obtained from different measurement schemes during MLS data acquisition as well as different temporal distances. Since the possible variation in D_b associated with the application of different measurement schemes (0.02 units) corresponds to about 59 % of the change in occurring throughout a year (0.04 units) we argue that one should avoid changes in the measurement scheme if temporal pattern of forest structures are to be assessed. To allow such temporal (seasonal) monitoring the sampling intensity must be higher than that in our study (~ 20 walking minutes per hectare). One could easily increase the sample intensity, e.g. by increasing the walking time and trajectory length to further reduce occlusion in the point cloud in areas not fully sampled. With the same scanning scheme applied in winter and summer, we still have a possible variation of about 17 % in the observed differences over time that is solely attributed to the data acquisition process. This might be due the remaining effect of wind during measurement, or, which we assume the more likely explanation, small changes in the walking path resulting in slightly different point clouds for the same forest. This again indicates that a higher sampling rate, in terms of walking time in the stand, must be recommended for plots of the size presented here (~1 ha). Given a successfully capturing of the entire plot comparisons, a more solid monitoring of changes in structural complexity would be possible and alterations in the walking trajectory will have a decreasing importance. This can hardly be investigated systematically, since identifying an optimal sampling density for all kinds of forests is impossible. We estimate that measuring times of at least 30 min, walking in a slow pace (<4 km*h^{-1}) might be a first guideline for a successful capturing of a ha-sized plot. In our case, using the same MLS measurement scheme was definitely crucial to assess the effect of seasonality on the structural complexity, acknowledging an uncertainty of around 17 % in the observed differences between seasons. This however, might partly be related to the fact that the observed seasonal changes of complexity were generally small on our plots, as could be expected, since none of the sites underwent a mortality event or alterations due to management activity. Therefore, differences in complexity arose almost solely from foliation and defoliation (leaf effect). While this was our intention, it might also indicate that more significant changes, as a result of large-scale diebacks, management or other disturbances, might be more easily captured with the presented approach. In literature, we see inconsistent findings when it comes to the effect of leaves on the structural complexity. Leaves may significantly affect the box-dimension of a single tree (Arseniou et al., 2021) or may not, as indicated by Guzmán et al. (2020). We hypothesize this is due to the fact that the trees in Arseniou et al. (2021) were isolated trees growing without competition and they developed a large crown with leaves-bearing branches already at the bottom of the stem. In the study by Guzmán et al. (2020) trees were growing in forest environments, with longer branch free boles. Therefore, the leaf-effect might be smaller for such forest grown trees due to smaller crown ratios. In our study, we could show that significant differences between leaf-on and leaf-off condition exist for real world forest stands and that they can be quantified using MLS despite a small overall annual amplitude. We support the findings by Guzmán et al. (2020), indicating that leaves-bearing trees produce more scattered point clouds than leaf-off trees, thereby increasing the point dispersion in a forest scene and therefore the overall complexity of the stand. We showed that a data-based quantification of structural complexity at a fine resolution and in a holistic manner is possible by using MLS with little effort.

2.4.2 Effects of different management regimes

The forest stands studied here were all beech-dominated but differed in their management regime. The formerly managed forests have not been managed for 26 to 100 years. With an age of 91 and 148 years all the forests studied are in the optimum phase, after the main growth stage and before the decay phase (Scherzinger, 1996; Stiers et al., 2018). In unmanaged stands or forests that are managed according to the even-aged management concept, this phase is characterized by the emergence of less structured and single-layered "vault-like" beech forests (German: "Hallenwälder", Stiers et al., 2018). This structure is caused by the natural reduction in tree numbers due to competition, which affects suppressed and less dominant trees most (Scherzinger, 1996; Boncina, 2000; Meyer, 2005; Feldmann et al., 2018). It is little surprising that the formerly managed and now unmanaged forests that were mostly single-layered in vertical structure when management was ceased, still reflect these structure that are rather low in complexity. Using a space-for-time substitution, Stiers et al. (2018) already showed that the cessation of management in this phase "halts" the development of structural complexity for quite some time. In contrast, the managed beech forests in our study, which have been managed as single-tree selection systems (uneven-aged forestry) showed a significantly higher stand structural complexity than their counterparts on all study sites.

The traditional even-aged system of forest management in Germany is constantly being replaced in the last decades by finer grained regeneration systems based on the final harvest of single trees (target diameter harvest), or groups of trees only. Thus, the creation of larger gaps was restricted to few cases aiming at promoting tree regeneration, resulting in uneven-aged forests (Puettmann et al., 2015; Schall et al., 2018). The inter-mixed developmental phases by the single tree selection approach leads to increased structural heterogeneity, which is reflected in a high variation in neighboring trees of different ages and sizes (Schall et al., 2018). It is assumed that the management practices, such as single-tree or group-selection, imitate gap dynamics and natural regeneration processes in the decay phase and have a positive effect on the stand structure complexity (Commarmot et al., 2005; Stiers et al., 2018). Our data supports this, as we observed a higher structural complexity in our managed forests. Stands managed for complexity by following the guidelines of continuous-cover-forestry were shown to develop a structural complexity that can even reach the level of primary beech forest in terms of the box-dimension in some cases (Stiers et al., 2020).

The higher D_b in our managed plots indicates a more homogeneous vertical and horizontal distribution of plant material in these forests. Consequently, the effect of leaves emergence in the managed forests was greater than in the formerly managed forests. If leaves emerge across many vertical layers, their contribution to the overall complexity will also be greater. Stiers et al. (2020) and Willim et al. (2019) showed this effect for managed beech forests. A greater effect on structural complexity observed as a result of leaves emergence, when compare to leaves fall, might partly be explained by the persistence of dead leaves on the trees until spring, since this delays the effect of leaves loss. In addition, the growth of twigs, branches and the stems during the course of the year might also result in a slightly increased overall complexity during fall, when compare to the conditions before the start of the growing season.

2.4.3 Methodological considerations

The box-dimension quantifies structures holistically, that is without distinguishing between individual objects, solely in terms of the spatial point distribution in the point cloud and the amount of material present (distribution and density). Additional attributes, like the health status of trees, woody debris on the forest ground, number of microhabitats or species diversity are not explicitly addressed but may be important aspects of complexity. In our study, we hence focused on structural complexity in its strictest mathematical sense. We cannot make statements regarding those other aspects of complexity.

While differences among the study sites are not in the focus of the analysis presented here, it is worth mentioning that slopes might positively affect the structural complexity of forests. Sloped sites naturally have a more pronounced vertical layering and even after a terrain normalization these effects can still be apparent. However, slope angles were rather low on all our plots and we could not see any relationship between slope angle and plot complexity (data not shown).

2.5 Conclusion

In this study, we demonstrated the use of the highly efficient mobile laser scanning technology, more precisely hand-held laser scanning, to produce detailed 3D data of forests that can be used to quantify forest structural complexity by means of fractal analysis. The approach was successfully used to quantify the effect of leaves emergence and leaves fall on structural complexity in beech-dominated forests. Additionally, we could show that structural differences that result from different management regimes could successfully be measured. Our study also clearly showed that, despite its wide applicability, MLS requires a standardized scanning procedure (walking scheme) to generate repeatable measurements of D_b. This limitation can likely be overcome if a greater sampling density is applied to avoid occlusion effects as much as possible. We conclude that the presented approach can be used for monitoring structural complexity in forest stands in an objective and efficient manner, with little training needed for field operators. It provides math-based quantifications of complexity that might be useful for certification procedures, monitoring protocols or any other evidence-based assessment of forest structural complexity. This can put management for complexity on solid ground, since status and direction of development in terms of structural complexity can be obtained objectively for any given forest.

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DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTION

LN and DS contributed to conception and design of the study. LN performed the statistical analysis. LN, PA and DS wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Chapter 3

Simulation of silvicultural treatments based on real 3D forest data from mobile laser scanning point clouds

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Simulation of silvicultural treatments based on real 3D forest data from mobile laser scanning point clouds

Liane C. Neudam[1], Jasper M. Fuchs[2], Ezekiel Mjema[3], Alina Johannmeier[3], Christian Ammer[1,4], Peter Annighöfer[5], Carola Paul[2,4] and Dominik Seidel[3,4]

[1] Department of Silviculture and Forest Ecology of the Temperate Zones, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

[2] Department of Forest Economics and Sustainable Land-use planning, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

[3] Department of Spatial Structures and Digitization of Forests, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

[4] Centre of Biodiversity and Sustainable Land Use, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

[5] Forest and Agroforest Systems, Technical University of Munich, Freising, Germany

Keywords: Forest structural complexity, Silviculture, Beech forest, Fagus sylvatica, Ecology and economics

Abstract

Forest management has a direct influence on the structure and stability of forests. In this study, we used the 3D data from mobile laser scanning in real forest stands dominated by European beech (Fagus sylvatica L.) to simulate different silvicultural treatments and assess their impact on the structural complexity and short-term economic return. For the structural assessment, we used the box-dimension (D_b), a holistic measure of structural complexity in forest. The expected net revenues of the silvicultural treatments were used as a proxy for short-term economic gain. We simulated six different treatments in 19 different real-world forest stands. The results showed that each treatment had a negative impact on the structural complexity of the stands but with varying severity. The treatments with the smallest effect on stand structural complexity showed the highest net revenue, indicating no trade-offs if a forest owner strives for small stand structural changes and high economic return. The approach used here allows quantifying the structural and economic consequences of different treatments in forest stands prior to the actual application in the real world. This holds large potential for decision making according to the forest owner's objective.

3.1 Introduction

Forests provide many different functions and services. Both national and international policy guidelines suggest to facilitate multi-purpose forestry, which means providing several ecosystem services simultaneously (Simons et al., 2021). There is some evidence that structurally complex forests promote high above- and below-ground multifunctionality (e.g. aboveground biomass, litterfall productivity and soil organic carbon stock) (Sanaei et al., 2021) which in turn may result in multiple ecosystem services (Mori et al., 2017). However, structurally complex forests are thought to have additional advantages, such as lower vulnerability to climatic changes (D'Amato et al., 2011), and higher diversity of some taxa (Dove and Keeton, 2015), although this does not seem to be a general rule (Sabatini et al., 2016). In the long-term, increasing forest structural diversity may also increase expected economic return (Parkatti and Tahvonen, 2020) and resilience to disturbance (Knoke et al., 2022).

The structure of managed forests is shaped by silvicultural interventions (Jung et al., 2012; Messier et al., 2015; Stiers et al., 2020). It is therefore important to know how different silvicultural approaches also change stand structural complexity, with structural complexity being defined as the dimensional, architectural, and distributional pattern of plant material in a given space at a given time (sensu Seidel et al., 2020). If, for example, a managed and well structured forest should be affected as little as possible, other management practices need to be applied from the very beginning compared to a case where structure is less relevant (Hunter and Hunter, 1999; Lindenmayer et al., 2000). In this context, it is helpful to be able to estimate which structural changes are associated with which silvicultural approach before an actual intervention, so that the forest owner can estimate the effects of alternative interventions on structure and economic success in advance.

So far, mostly two-dimensional approaches were used to access forest structural complexity, e.g. through stem distribution pattern (Clark and Evans, 1954; Füldner, 1995), diameter distributions curves (Westphal et al., 2006), basal area (Smith, 1992), or combinations of all those patterns (Seidel et al., 2018). However, such assessments have clear disadvantages, as they ignore the natural structural variability of the most complex part of a tree, the crown. A three-dimensional (3D) assessment of the structural complexity offers the potential to monitor and quantify the consequences of silvicultural interventions on structural complexity in greater detail and includes the forest canopy. Various approaches exist to capture the detailed 3D structure of individual trees or entire forest stands based on close-range remote sensing technologies such as structure from motion or laser scanning (Dassot et al., 2011; Hardiman et al., 2011; Bauwens et al., 2016; Ehbrecht et al., 2017; Atkins et al., 2018; Calders et al., 2018; Seidel, 2018; Iglhaut et al., 2019; Willim et al., 2019; Seidel et al., 2021). Based on laser scanning data, the box-dimension from fractal analysis proved to be a useful measure to quantify the structure of plants and forests (Seidel, 2018; Seidel et al., 2019b; Seidel et al., 2019a; Guzmán et al., 2020; Arseniou et al., 2021; Dorji et al., 2021; Saarinen et al., 2021). The approach is widely applicable because it addresses the pattern of repetition of structures across scales and the distribution and density of plant material as one single unifying characteristic (Zeide and Pfeifer, 1991; Kaye, 1994; Jonckheere et al., 2006; Seidel, 2018; Neudam et al., 2022). The box-dimension is therefore an ideal measure to objectively quantify and monitor structural complexity in forests and yields valuable insights into the complexity and its changes due to forest management measures (Seidel et al., 2020; Neudam et al., 2022).

While for some forest owners maintaining or even enhancing structural complexity of a stand may be the primary management objective, others might primarily be interested in the economic output. Forest management decisions can be interpreted as investments into the biophysical and economic yield of the future stand or forest generation (Koster and Fuchs, 2022). However, the short-term profitability also plays a key role. In forest enterprise realities, liquidity and financing of forest management activities are drivers of economic sustainability (von Arnim et al., 2021). On top of this, climate change increases uncertainty concerning future forest developments, making short-term profitability of silvicultural treatments even more relevant. Therefore, management for complexity should not disregard economic aspects, particularly short-term profits, which can be key drivers of management decisions.

Against this background, the simulation of different silvicultural treatments based on 3D laser scanning data of real-world forests can become a promising new tool to quantify the effects of different management regimes on the structural complexity of a given forest before silvicultural measures are applied. Here, we were interested in (I) how the effects of different silvicultural treatments on forest stand structural complexity differed, quantified based on the box-dimension obtained from mobile laser scanning. We also wanted to know (II) whether this effect is influenced by the previous management (formerly managed vs. managed) of the stand. Finally, (III) we tested whether trade-offs between the effects of different treatments on structure and economic return exist if a forest owner strives for low changes in structural complexity and high net revenue.

3.2 Material and Methods

3.2.1 Study sites

For this study, we chose 19 pure European beech (*Fagus sylvatica* L.) or beech-dominated forest stands in Germany. Eight of them can be found near Göttingen (Lower Saxony), seven plots near Lübeck (Schleswig-Holstein), two plots near Oppershofen (Hesse) and two plots near Allstedt (Saxony-Anhalt; Figure 3.1). The age of the dominant trees was between 92 and 162 years. Thus, all forest stands studied can be assigned to the optimum phase, after the main growth stage and before the decay phase (Scherzinger, 1996; Stiers et al., 2018; Neudam et al., 2022). The study plots differ in management intensity. While ten stands are managed since decades, in nine stands management was abandoned around 30 years ago. In one case, however, management was ceased in 1920 (Figure 3.1).

3.2.2 Mobile laser scanning

Each study plot was scanned using a ZEB Horizon mobile laser scanner (GeoSlam Ltd., Nottingham, UK) in February 2021. Using the time-of-flight principle and simultaneous localization and mapping (SLAM) the hand-held scanner captured the forest in all three dimensions with a resolution of about 3 cm while being carried through the forest stands. After scanning in the field following a standardized measurement scheme (see Figure 3.2), each plot was processed in GeoSlam Hub software (GeoSlam Ltd., Nottingham, UK) for the actual SLAM calculation and exported as laz-file. We then used the open source CloudCompare software (www.danielgm.net) for further selection of the exact study area. The resulting point cloud was then noise filtered, subsampled to a minimum point distance of 1 cm and exported as xyz-file for further processing. The exact study area of the captured forest scenes in the plots ranged from 9 953.97 m² to 21 934.42 m² (mean ± standard deviation: 15 271.04 m² ± 3 544.77 m²).

3.2.3 Single tree extraction

Each point cloud was imported to LiDAR360 software (GreenValley International Ltd., California, USA) for classification into ground, versus vegetation points, using the ‘classify ground points’ tool. Then, based on the ground points, terrain normalization of the point cloud was conducted using the ‘normalize by ground points’ tool, resulting in a slope-corrected, perfectly horizontal point cloud.

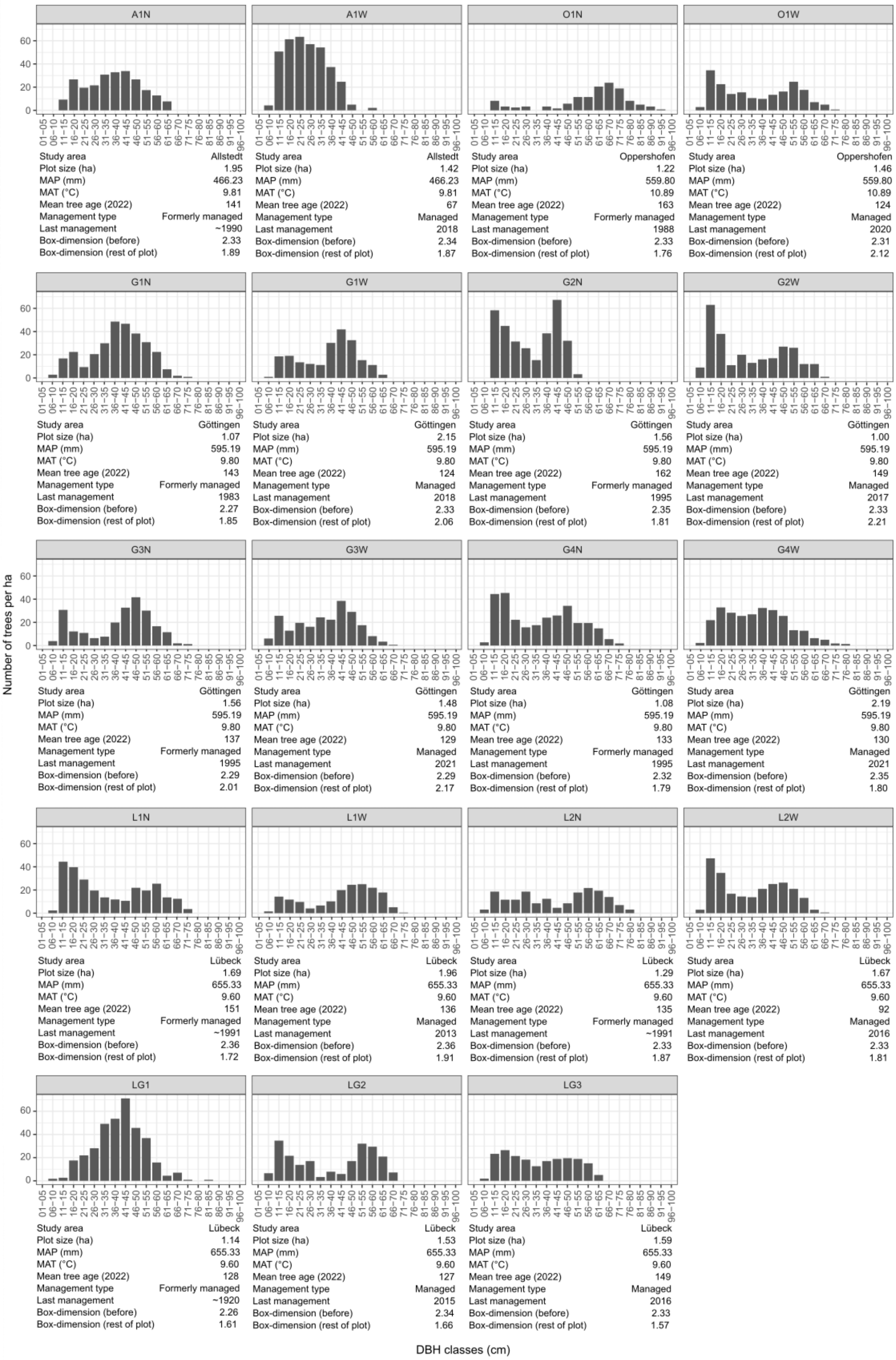

Figure 3.1 Diameter distributions, climatic and geographic conditions of the study areas, average age of the study stands and their structural complexity (box-dimension before = structural complexity prior to simulated silvicultural interventions; box-dimension rest of plot = structural complexity of the understory and ground). MAP = mean annual precipitation (2010-2020); MAT = Mean annual temperature (2010-2020).

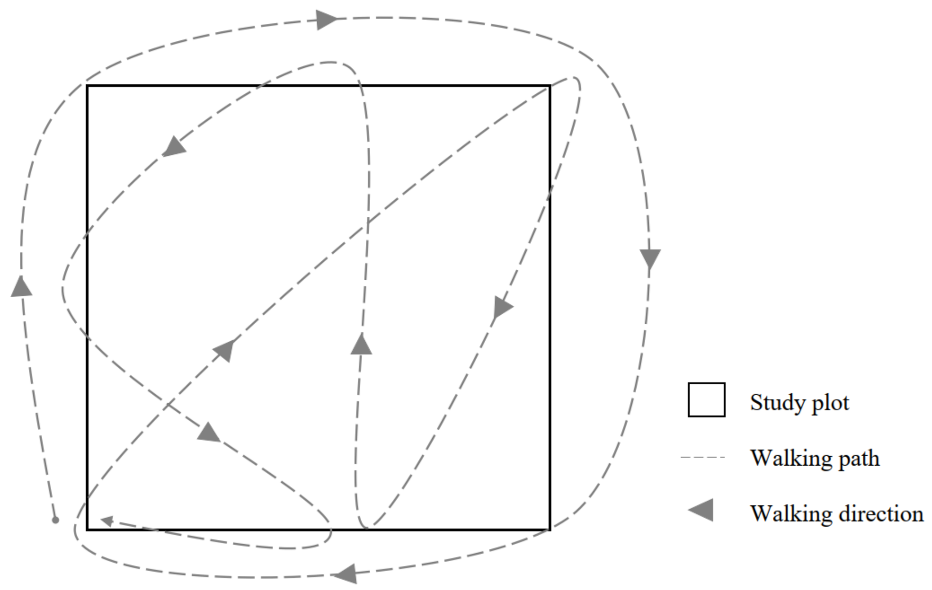

Figure 3.2 Standardized measurement scheme applied to all plots indicating the trajectory (walking path) within the plot margins and the walking direction. After defining a starting point at a random plot edge and marking it temporarily (e.g. by placing a backpack or a cap on the position) the scanner was placed on the ground to initiate (self-orientation). Once initiated, the scanner was picked up and the operator (always the same person) walked across the study plot several times in a specific manner while scanning the surroundings. On every plot, we first surrounded the corners and thus the entire study area, followed by a diagonal crossing through the area and finally a zig-zag across the plot for better coverage (adapted after Neudam et al., 2022).

Based on the points not classified as ground, the 'automatic tree segmentation' process was conducted to obtain point clouds of individual trees from a fully automatic segmentation of the point cloud. Each identified tree was stored separately, together with an extra file we named 'rest of plot', in which all understory vegetation and ground layer was included that was not classified as a tree. For each tree, LiDAR360 provides additional information stored in a list of all trees per plot, containing each tree's position, height, and diameter at breast height (DBH). We used this list to contrast the DBH measurements with tree height, identifying outliers based on an expected realistic range of values for the height-to-diameter ratio (h/d ratio) between 0.5 and 1.5. While the tree height was confirmed to align perfectly (r^2 of 0.99) between the LiDAR360 and a reference method for tree height measurements in laser scanning data (see Seidel et al., 2011), which we applied to a subsample of 300 trees from our data, the DBH showed outliers in most plots (e. g. diameters greater than 1 m). Therefore, the diameters of trees provided by LiDAR360 with an h/d-ratio outside the above range were replaced with the diameter modelled based on the height-to-diameter relationship for this particular plot. To obtain the height-to-diameter relationship we determined the best-fit power function ($DBH = a * height^b$) without the data of the trees falling out of the realistic range in h/d ratio.

3.2.4 Silvicultural simulations with real world data

In a next step, all trees belonging to a forest plot were combined to resemble the forest virtually, based on the real tree positions and tree shapes. We did not include the data classified as ‘rest of plot’. We applied a set of six different virtual silvicultural treatments to each forest plot’s point cloud (n = 19), modelling real world silvicultural interventions in the 3D representation of the stands. To do so, we used the list of tree positions including the diameters as basic information. Note that each stand was virtually treated with *each* of the six silvicultural treatments in separate modelling runs. Every modelling run followed the guideline that 20 % of the stand basal area were to be harvested, minus the last tree’s basal area that, if harvested, would have resulted in more than 20 %. Therefore, the actually removed basal area in each run was always greater than 19 % and smaller or equal to 20 % of the initial basal area. In the following, each silvicultural intervention applied is briefly described and visualized in Figure 3.3. Figure 3.4 shows the 3D point cloud of one plot (L1N) before the treatments and each treatment as well as an exemplary ‘rest of plot’-point cloud.

STRIP CUT

During *strip cuts*, trees were harvested from East to West according to their position only. This was done until 20 % of the stand basal area were removed. Harvesting from East to West is a common approach in stands dominated by conifers in mountain areas in Germany due to predominantly westerly winds, thereby avoiding the risk of wind throw due to exposed edges next to the harvested strip.

GAP CUT

The *gap cut* procedure was based on the identification of a diameter threshold, separating small from large trees. Due to the fact that the investigated stands differed in their diameter distributions (see Figure 3.1), a single fixed diameter threshold could not be applied. Therefore, the diameter threshold was set to be the 85 %-quantile of the diameter distribution of each individual plot, with trees of DBH greater than that being considered “large”. In a next step, the number of gaps to be created in a plot was determined based on the area of the plot and the initial assumption that two gaps of 1 000 m² (circular, with a 17.84 m radius) per hectare would result in the targeted amount of basal area to be removed. The final number of gaps was corrected (increased) if not enough trees could be harvested by creating two gaps only. Trees were harvested if they were located with their stem base within an intended gap area, after a manual placement of the gaps for equal distribution on the plots (without overlap). In each gap, trees were removed so that each gap contributed equally to the 20 % basal area removal on the total plot, proceeding from the inside to the outside of the gap.

SHELTER CUT

During shelter cuts, we only considered harvesting large trees as defined in the *gap cut* procedure (trees with diameter greater than 85 % diameter quantile). Then, among the group of large trees, the shelter trees were retained and then successively trees were removed according to their size, from the thickest to the thinnest tree, until 20 % of basal area were virtually harvested.

GROUP CUT

To resemble the group selection treatment, we picked large trees (for definition of “large tree” see *gap cut*) across the plot manually, one after another, for each tree removing the tree itself and all large trees in a circular distance of 17.84 m distance (1 000 m² area) around the tree. Smaller trees in this search radius were omitted and remained in the stand. This procedure was conducted for as many large trees as necessary to reach the final basal area threshold of 20 % of the initial plot basal area.

RANDOM CUT

The *random cut* treatment was based on the random removal of trees as long as the harvested total basal area was less or equal to 20 % of the plot basal area. This approach was conducted ten times per plot (see *random cut* (1-10) in Figure 3.3) in order to provide a solid database for an evaluation of this approach when compared to others.

MINIMUM COMPLEXITY CUT OR $D_b$min CUT

The concept of the “*Minimum complexity cut*” or *$D_b$min cut* was to remove only the least complex tree individuals. Therefore, the box-dimension of each segmented tree individual was determined using the algorithm introduced in Seidel (2018). Subsequently, trees were removed beginning with the least complex individual, followed by the second least complex and so on, until 20 % of the basal area was removed. Due to the positive relationship between a tree’s extensions and its complexity (cf. Seidel et al., 2019c) this procedure resulted in the removal of predominantly small trees or trees with reduced vitality (cf. Heidenreich and Seidel, 2022).

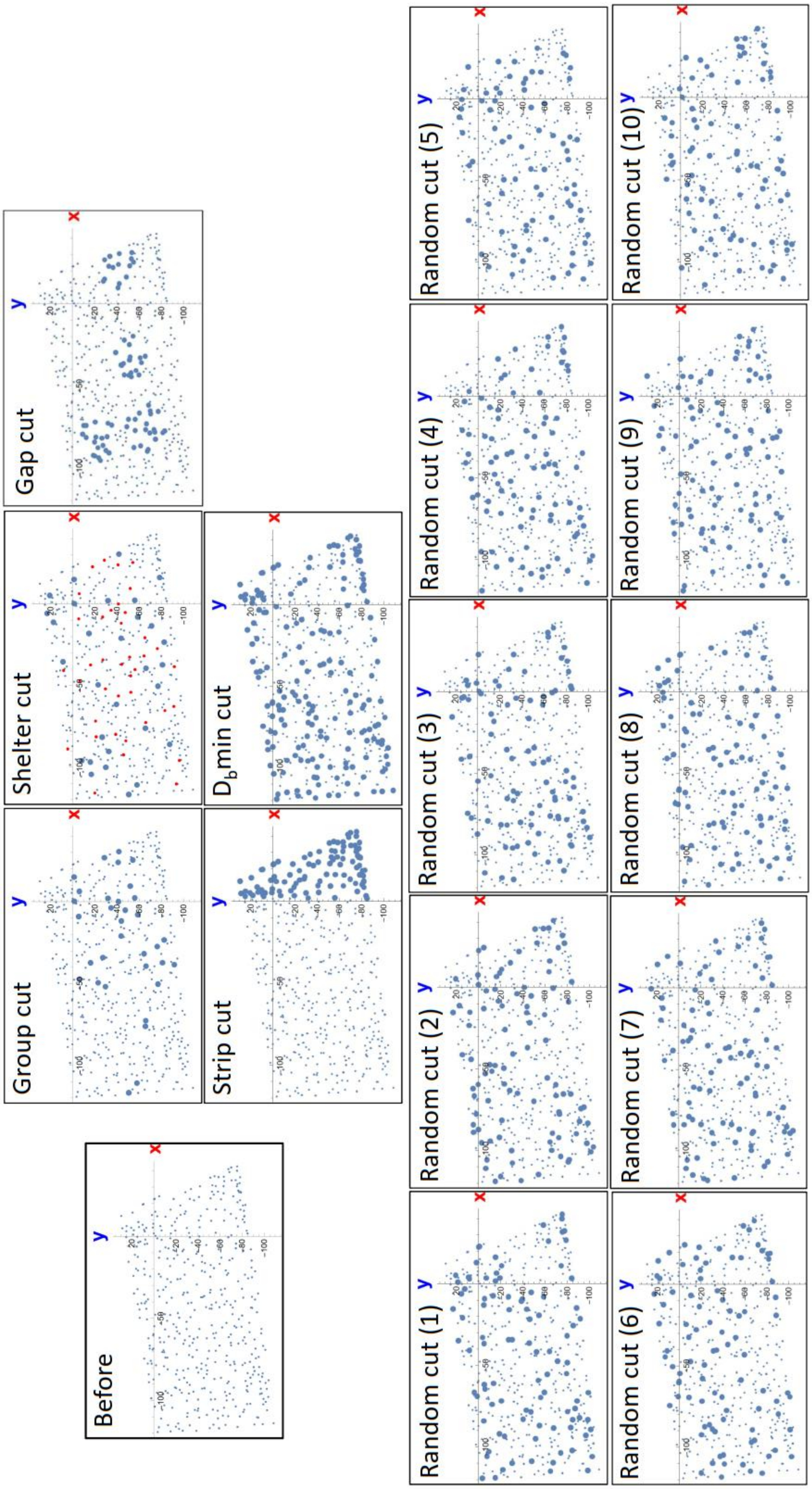

Figure 3.3 Visual overview of the virtual silvicultural treatments as applied to an exemplary plot (L1N). For each treatment, all trees in the plot are shown as small dots and the harvested trees as larger dots. For shelter cut, red dots indicate retained shelter trees.

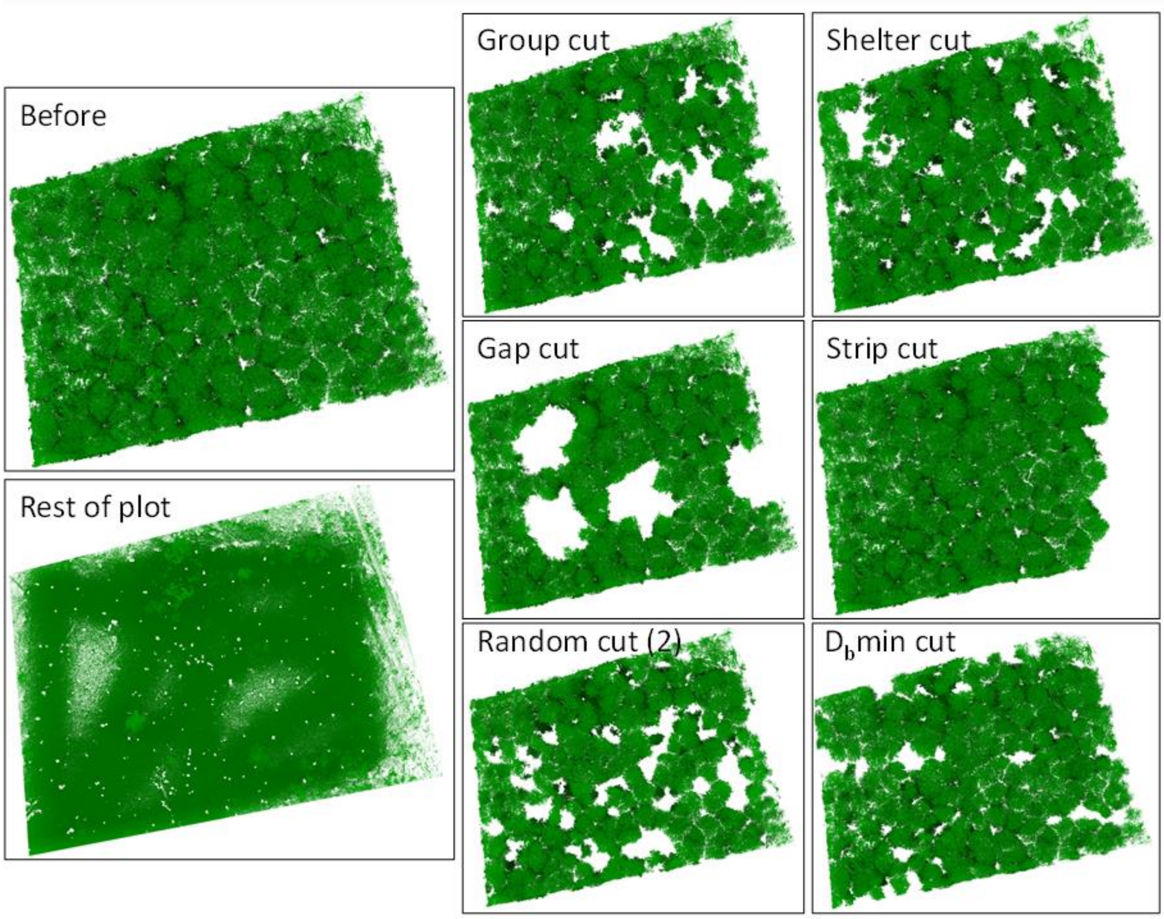

Figure 3.4 2D representation (top view) of the 3D point cloud of exemplary plot L1N before the treatments, and after applying group cut, shelter cut, gap cut, strip cut and D_b min cut, as well as after one of the ten random cuts. For comprehensiveness, the 'rest of plot' data, containing all shrubs, ground, downed wood which were not classified as trees by LiDAR360 is also displayed.

3.2.5 Distribution of structural complexity on the plots after treatment

After applying the six different virtual silvicultural treatments, the remaining plots were further examined. To assess how the structural complexity was distributed on the plot after treatment, four squares with a side length of 30 m were randomly cut out on each plot and the box-dimension was calculated for each of them. Since the area of the study plots after the treatment *strip cut* was considerably reduced, the results were corrected for the new area. For this purpose, the size of the original area was used in the random selection of the four squares so that the treatment *strip cut* could subsequently be compared with the others. Then, the coefficient of variation (CV) was calculated from the mean and standard deviation of the four squares for each plot after the treatments. For the treatment *random cut*, the CV was first calculated for all ten random treatments and afterwards the mean of all ten CV-values was calculated.

3.2.6 Statistical analysis

To test for differences of the mean stand structural complexity, expressed as D_b, before and after treatment, we analysed the data using parametric and non-parametric tests, depending on whether normal distribution was confirmed by the Shapiro-Wilk-test. When the data met the requirements for parametric tests, we used a One-way-ANOVA to test for differences followed by a pairwise-t-test for posthoc comparison. In cases where the parametric assumptions were not met, we used the non-parametric Kruskal-Wallis-test and the Wilcoxon rank sum test with the Bonferroni p-value adjustment method for posthoc comparison. The same procedure was used to assess differences in mean values of structural complexity between stands of different management history (formerly managed vs. managed).

Differences in the mean values of structural complexity of the treatment *random cut* before and after the tree extraction were evaluated using the non-parametric Kruskal-Wallis-test, because parametric assumptions such as normal distribution (Shapiro-Wilk-test for normality) were not met. For posthoc comparisons between the management history, we also used the Wilcoxon rank sum test with the Bonferroni p-value adjustment method.

We analysed the coefficient of variation of the remaining structural complexity after treatments for each plot, also using the non-parametric Kruskal-Wallis-test, because parametric assumptions like normal distribution (Shapiro-Wilk-test for normality) were not met either. For posthoc comparisons between the treatments, again Wilcoxon rank sum test with the Bonferroni p-value adjustment method was used.

All statistical analyses for this study were carried out in the R software language, version 4.1.2 (R Core Team 2021). Statistical significance was assessed at $p < 0.05$.

3.2.7 Economic consequences of simulated silvicultural treatments

We used two indicators to compare the short-term economic consequences of the different silvicultural treatments: First, the direct net revenues of timber harvesting and second, the net economic gain associated with each simulated silvicultural treatment considering its impact on the subsequent 5-year growth period.

Net revenues reflect the revenues from selling the harvested trees at the forest road minus the costs for harvesting and hauling. Both revenues and costs depend on the quadratic mean diameter (QMD) of the extracted stems. This reflects the usually higher share of sawn wood assortments with increasing diameters and decreasing harvesting costs per m^3 for thicker trees, due to economies of scales (von Bodelschwingh, 2018). These functional relationships are taken into account in the wood revenue and harvest cost models by von Bodelschwingh (2018) as implemented in the R package woodValuationDE (Fuchs et al., 2022). The models were fitted for different harvest situations. We assumed a moderate quality of the stands, standard access conditions for harvesting (i.e. slopes < 36 %, no moist sites) and a diameter-dependent selection of fully-mechanized or semi-mechanized tree harvesting (i.e. using a harvester or chainsaw, respectively). Given this harvest situation, the revenues for the saleable wood s [€/m^3] were calculated as:

$$s = 1.11 \cdot 10^{-8} \cdot QMD^4 - 5.63 \cdot 10^{-5} \cdot QMD^3 + 6.081 \cdot 10^{-3} \cdot QMD^2 + 0.112 \cdot QMD + 43.4$$

with the quadratic mean diameter QMD [cm]. The harvest costs h [€/m^3] were calculated as:

$$h = \begin{cases} 38267 \cdot QMD^{-2.913} + 17.4, & if \;\; 38267 \cdot QMD^{-2.913} + 17.4 < 60 \\ 60, & otherwise \end{cases}.$$

For the virtual treatments on our plots, the resulting net revenues for the volume over bark ranged from 19.2 €/m^3 to 36.3 €/m^3 with a median of 28.9 €/m^3.

von Bodelschwingh (2018) derived the function parameters based on the Hessian assortment tables by Offer and Staupendahl (2018) and sales data from the public forest enterprise of the Federal State of Hesse (Germany) from 2010-2015. Given the proximity of Hesse to the study sites and similarities in species distributions and markets, we consider the data representative for our study sites. The volume of the extracted trees, needed as input for the woodValuationDE function was calculated by using taper functions based on Kublin (2003) as implemented the R package rBDAT (Version 0.9.8) (Vonderach et al., 2021).

We extended the consideration of the value of the harvested trees by quantifying the short-term economic gains and losses incorporating the subsequent 5-year planning period, a typical interval for growth predictions. The “short-term net economic gain” ponders two economic considerations of harvesting and thinning: First, we calculated the 5-year interest on the net revenues from harvesting. The interest mimics the fact that the net revenues gained from timber harvesting can be invested in other projects, such as planting or pruning, or could be invested externally. To reflect these alternatives and the scarcity of capital, we assumed a discount rate of 1.5% as estimated by Möhring (2001) for internal interest rates in Central German forest management. The economic gain from interest needs to be contrasted to the potential loss in the increment of the net monetary value of the remaining growing stock compared to a scenario in which the stand had not been treated. Therefore, as a second component, we quantified the harvest-induced loss in incremental change in net value of the growing stock over the subsequent 5-year growth period. This increment in net value largely follows the volume increment but also accounts for diameter-dependent changes in wood assortments and prices. For growth predictions of both the non-harvest scenario and the different silvicultural treatments we used the yield tables by Albert et al. (2022). We adjusted the growth to the actual stand density using respective correction factors (Albert et al., 2022). The net value of the growing stock in the next 5 years without and with simulated silvicultural treatments was derived as net revenues of a hypothetical harvest of all remaining trees using the woodValuationDE functions. The harvest-induced loss in incremental change in the net value of the growing stock was then calculated as the increment in value of the growing stock in the five years under a "non-intervention" scenario minus the predicted future value increment following each virtual silvicultural treatment. As the absolute increment in the value of the growing stock decreases due to silvicultural intervention this difference resulted in a positive value, interpreted as a loss.

The overall short-term net economic gain of the following five-year period is the difference between the interest gained on the net revenues from harvesting and the loss in increment in the net value of the growing stock.

3.3 Results

3.3.1 Effect of different simulated silvicultural treatments

The stand structural complexity, assessed via D_b, was found to vary significantly before and after each treatment (Figure 3.5). The ten *random cut* treatments were combined into one by showing the average.

Each treatment resulted in a decrease in stand structural complexity in the simulation. The treatments *group cut* and *shelter cut* showed the lowest change in structural complexity, followed by *gap cut*, the pooled *random cuts* and the *minimum complexity cut*. The highest change in D_b (before vs. after) showed the *strip cut* treatment.

To test whether the change in structural complexity was dependent on the simulated treatment, we standardized the initial values of all forests by setting the D_b of all stands to 100 % before treatment and calculated this for the treatment *random cut* (Figure 3.6).

We found that the range in structural complexity of the *random cuts*, assessed as D_b in percent of the structural complexity before the treatment, could neither be explained by the complexity before the harvest nor by the coefficient of variation of the diameters of the plots.

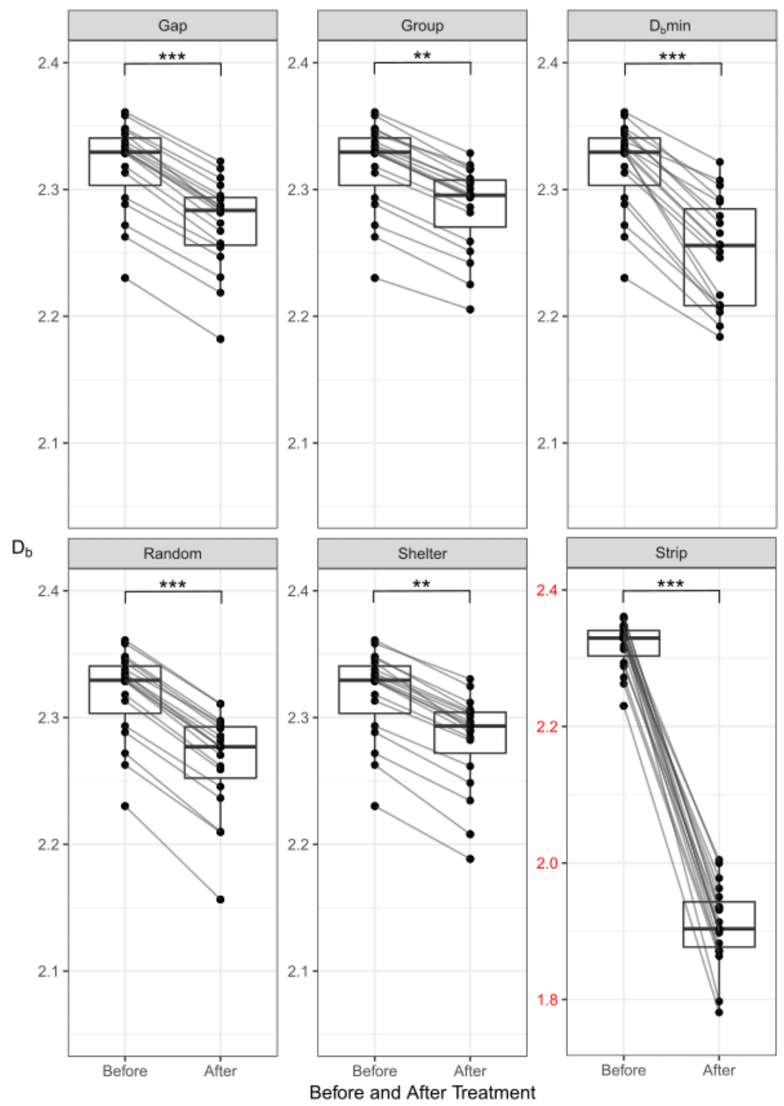

Figure 3.5 Box-Whisker plots of stand structural complexity, expressed as box-dimension (D_b), before and after the treatment for all 19 study plots and each of the six treatments. The ten different random cuts were averaged per plot and averaged to one value. The differences in the scale needed to illustrate the strip cut treatment are marked in red. Black horizontal lines indicate the median and stars indicate significant differences among the conditions at the level of $p<0.05$ (*), $p<0.01$ (**) and $p<0.001$ (***).

The variation of structural complexity across plots after applying the treatment indicated that *strip cut* and *gap cut* were significantly different from the other treatments (Figure 3.7). They showed the largest differences in the distribution of structural complexity. The treatment *minimum complexity cut* ($D_b$min) shows the least difference in the distribution of structural complexity after treatment, followed closely by the treatments *group cut*, *random cut* and *shelter cut*.

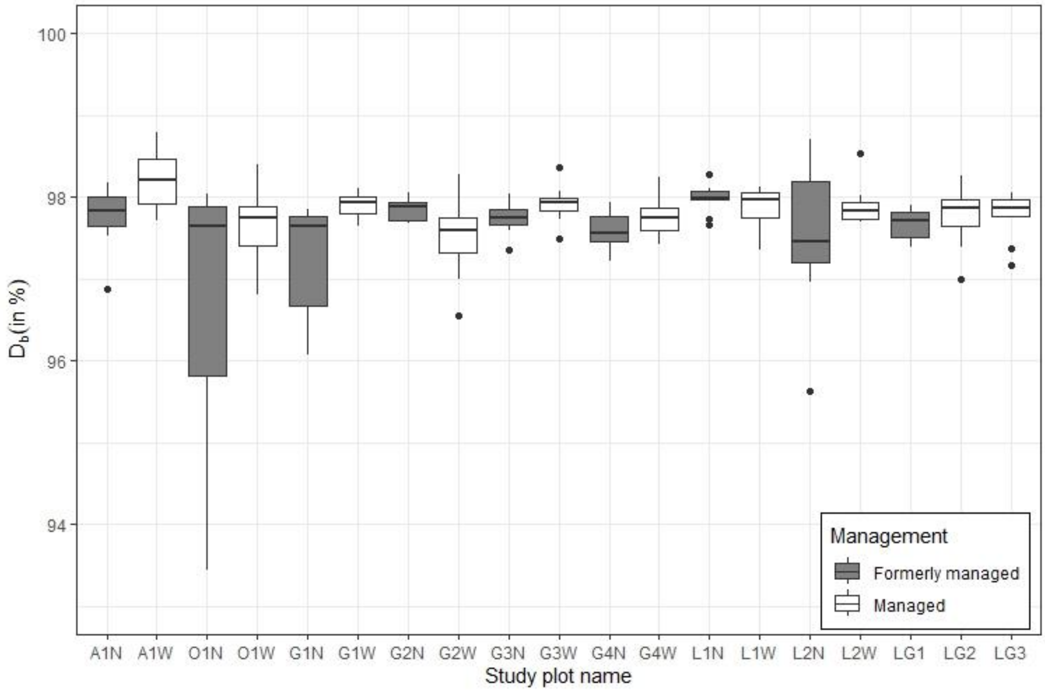

Figure 3.6 Box-Whisker plots of the structural complexity, expressed as box-dimension (D_b), after the ten simulations of the treatment random cut in percent of the structural complexity before the treatment for all 19 study plots and shown separately for the management status.

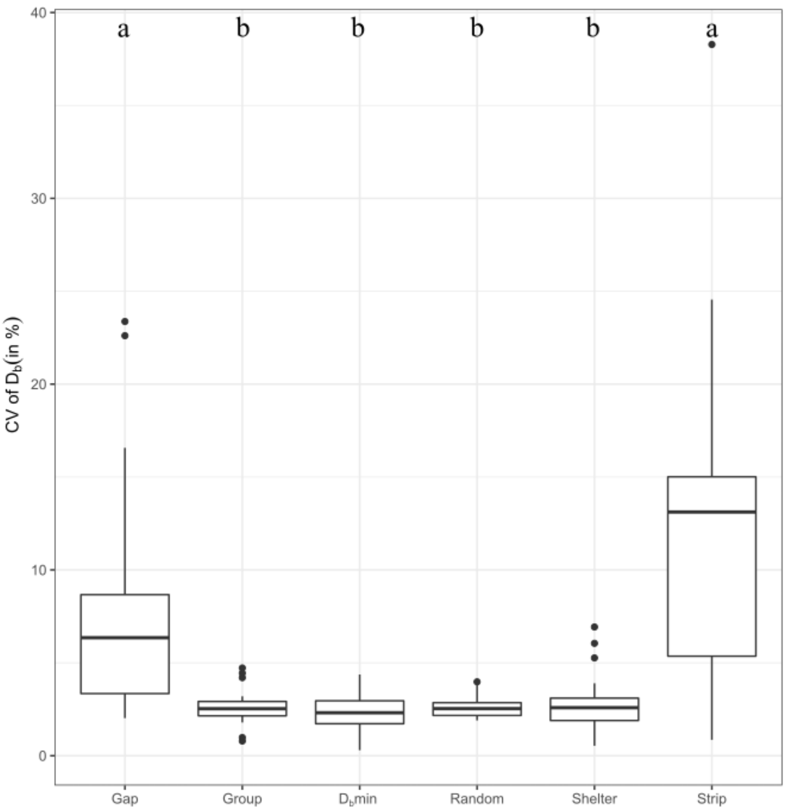

Figure 3.7 Box-Whisker plots of the coefficient of variation of the remaining structural complexity, expressed as box-dimension (D_b), for all 19 study plots after the treatments. The ten different treatments random cut were averaged per plot and combined as one. Black horizontal lines indicate the median. Different lowercase letters indicate significant differences among the conditions at the level of $p < 0.05$.

3.3.2 Effect of the previous management history

The currently still managed stands showed lower differences (median) in stand structural complexity before and after the treatment (Delta D_b) than the formerly managed ones across all treatments, except for the treatment *gap cut* (Figure 3.8). However, the differences were not statistically significant.

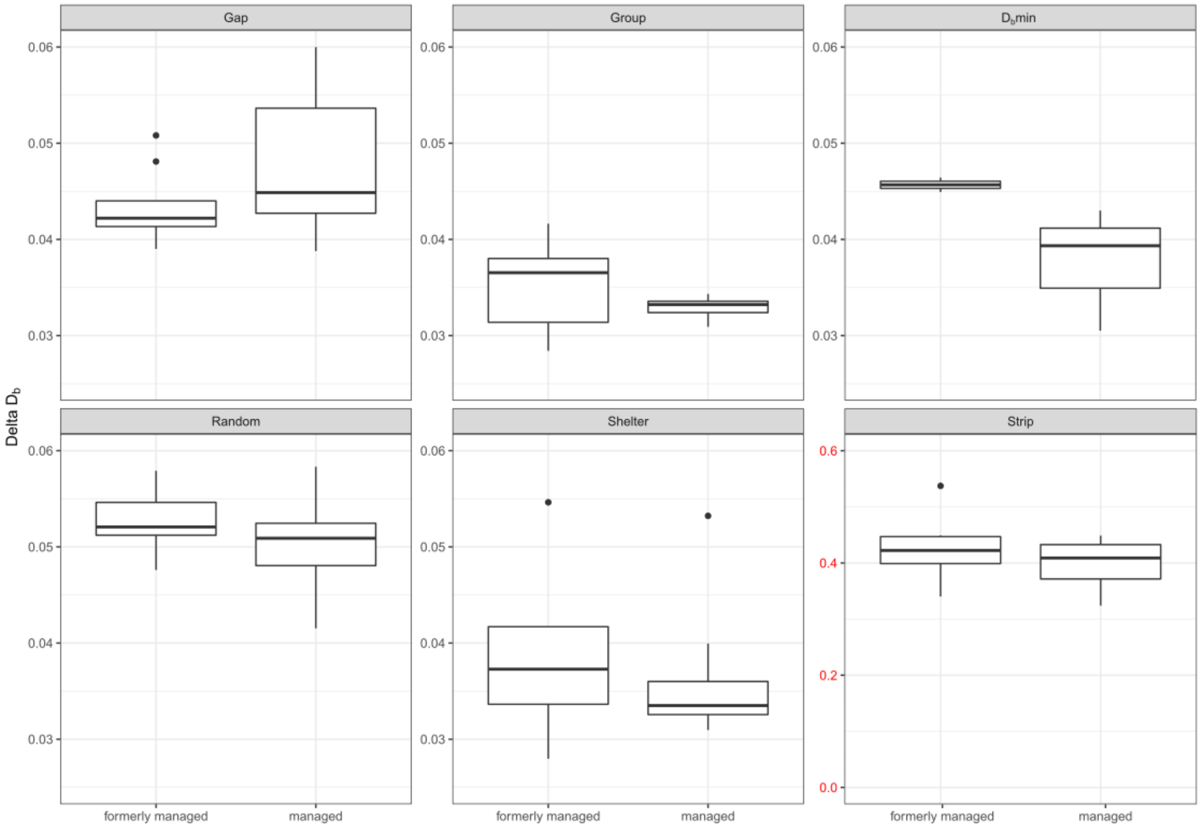

Figure 3.8 Box-Whisker plots showing the difference in box-dimension (Delta D_b) resulting from structural complexity before and after the treatment in all 19 study plots, between stands of different management history. The ten different treatments random cut were averaged per plot and combined as one. The differences in the scale for the strip cut treatment are marked in red. Black horizontal lines indicate the median. None of the differences in mean were significant.

3.3.3 Quantification of structural and economic effects of the simulated treatments

The different simulated treatments were evaluated in terms of their economic and structural impacts. While treatment effects on structural complexity was quantified by the D_b, net revenues of the removed trees served as a proxy for the short-term economic profits from the treatments. For D_b we found the smallest changes for the treatments *group cut* and *shelter cut* which did not differ from each other but from all other treatments (Figure 3.9). Interestingly, the latter were all significantly different from each other.

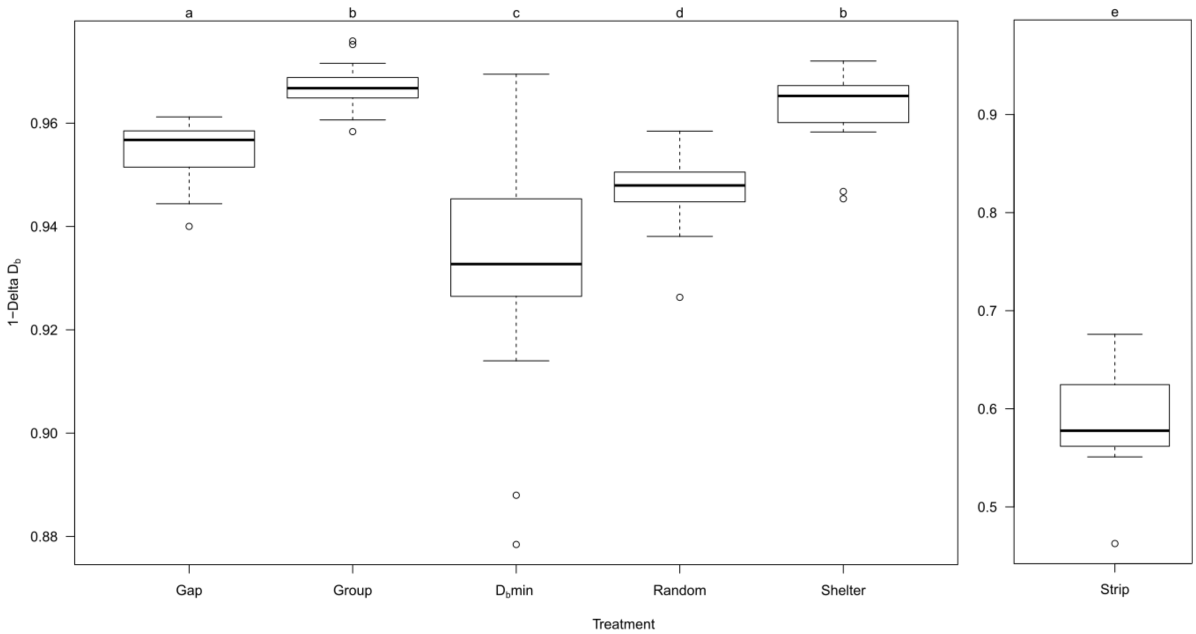

Figure 3.9 Box-Whisker plots of the difference in box-dimension (Delta D_b) resulting from the structural complexity before and after treatment in all 19 study plots. The 10 different treatments *random cut* were again averaged per plot. The treatment *strip cut* has a different scale. Black horizontal lines indicate the median. Different lowercase letters indicate significant differences among the conditions at the level of $p < 0.05$.

The net revenue of the treatment *minimum complexity cut* was lowest and differed significantly from the treatments *group cut* and *shelter cut*. No other significant differences between treatments were observed (Figure 3.10a). The differences between the economic consequences of the silvicultural treatments even decrease when analyzing our predicted short-term net economic gain (Figure 3.10b) instead of the direct net revenues. The income from harvesting can be invested in other projects (gain in income from interest in Figure 3.12, Supplementary material). However, this economic gain results in opportunity cost, as it reduces the increment in net value of the growing stock in all but two plots, both treated with a *minimum complexity cut* (loss in value increment in Figure 3.12, Supplementary material). Under our assumption of an interest rate of 1.5 %, the *group cut* has the highest median for the resulting net economic gain (Figure 3.10b). However, the ranking of the treatments along the short-term net economic gain depends on the assumed interest rate, i.e. the owner's individual scarcity of capital, as shown in the sensitivity analysis in Figure 3.13, Supplementary material. At the low end, assuming an interest rate of 0 %, i.e. weighing current and future values equally, would favor the *minimum complexity* and *strip cut* regarding the economic consequences in the simulated 5-year period. Giving more weight to the future value increment of the stand than to immediate income, i.e. under an interest rate of 3 or 5 %, favors the *group* and *shelter cut*, reflecting the ranking of the direct net revenues (Figure 3.13, Supplementary material).

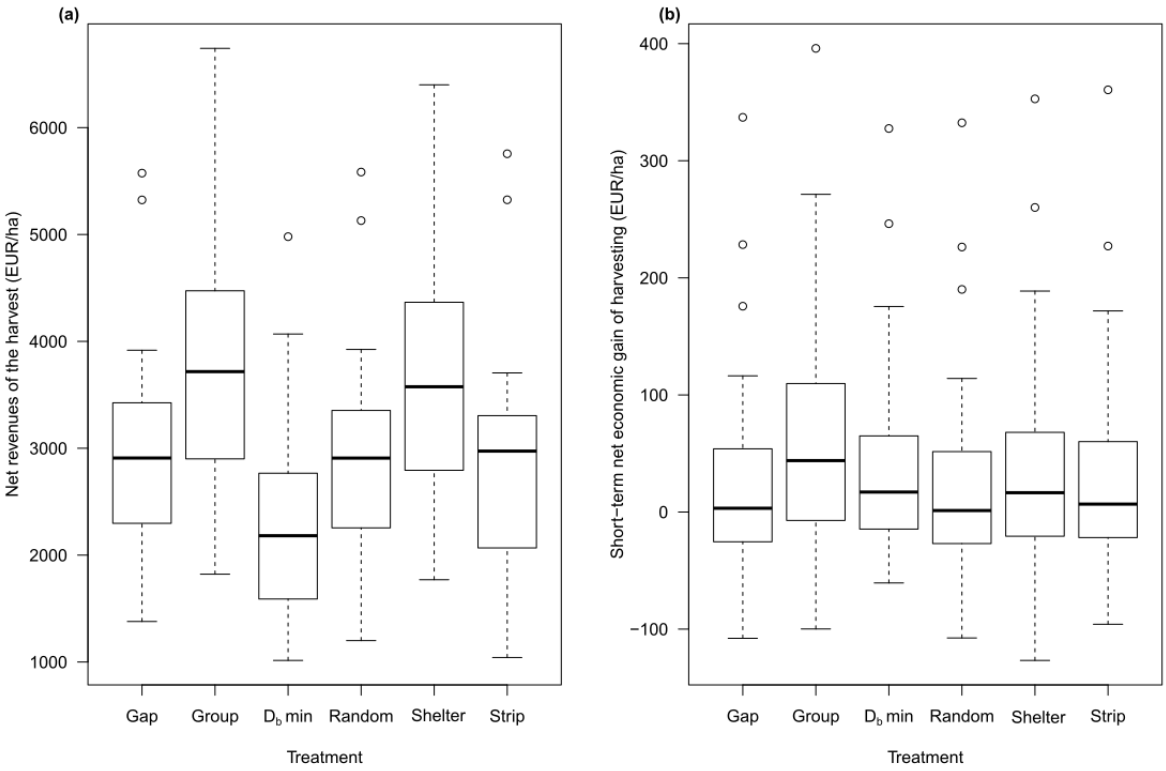

Figure 3.10 Box-Whisker plots of net revenues in €/ha at the time of harvesting (a) and short-term net economic gain of harvesting in €/ha at the end of the following 5-year period (b) of the simulated silvicultural treatments for all 19 study plots. The 10 different treatments random cut were averaged per plot and combined as one. Black horizontal lines indicate the median.

When combining the results of stand structural changes and the economic assessment it becomes apparent that the treatments *group cut* and *shelter cut* perform positively in both the change in structural complexity and in net revenues (Figure 3.11). In contrast, *strip cut* seems to have a strong negative effect on the structural complexity and a medium effect on economic indicators. The treatment *minimum complexity cut* generated the lowest net revenues compared to all other treatments. For the two treatments *random cut* and *gap cut* both complexity and economic indicators range between the results for *group cut* and *shelter cut* on the one hand, and *minimum complexity cut* on the other hand. However, the differences between the treatments *gap cut* and *random cut*, but also between *group cut* and *shelter cut* are small.

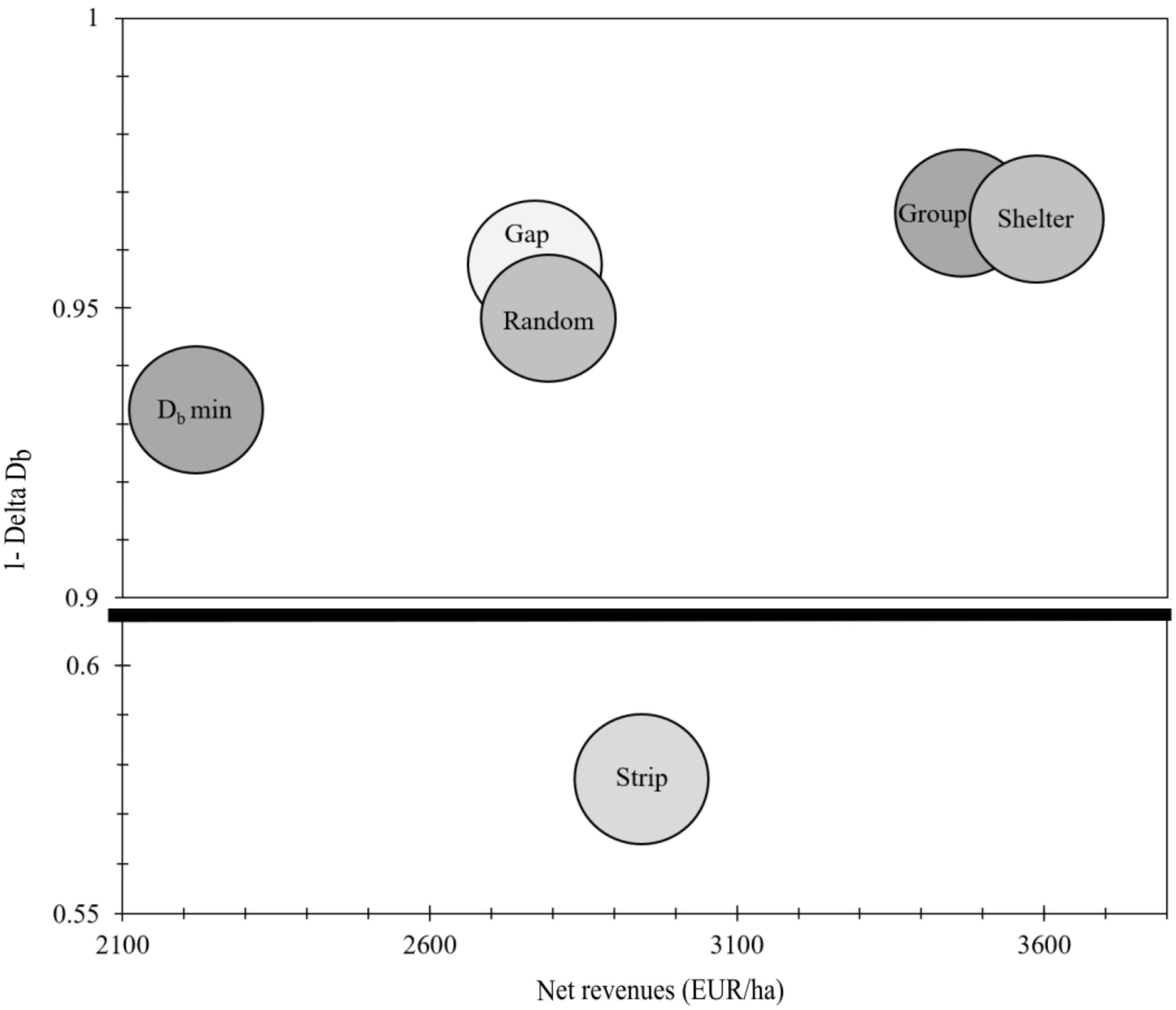

Figure 3.11 Combining the results of the change in structural complexity (Delta D_b) and net revenue (see Fig. 3.9 and 3.10a) of the different simulated treatments. The ten different random cut simulations were averaged per plot as before. The scale is compressed in the range from 0.6 to 0.9 on the y-axis for better illustration.

3.4 Discussion

3.4.1 Effect of different simulated silvicultural treatments

In practice, it is impossible to test different silvicultural treatments in the exact same stand and compare their effects on the structural complexity or any other measure. A tree that is cut down in one treatment cannot be reused for another treatment. In this study, we used real forest data from beech-dominated forests and simulated different silvicultural treatments. To quantify the effect of different treatments on stand structural complexity of the forests, we used the box-dimension, based on 3D laser point clouds. Seidel et al. (2019a) and Arseniou et al. (2021) have shown that the D_b is a holistic approach to structural complexity, which is sensitive enough to capture all changes in the amount and distribution of plant material. According to previous studies, the D_b is an objective measure that is solely mathematically and enables the comparison of different forests (Seidel et al., 2019b; Seidel et al., 2020; Stiers et al., 2020). Thus, D_b could be helpful to capture and compare the changes in stand structure due to different silvicultural treatments. It is worth mentioning that it is possible that for example selected animal species might benefit from open structures created by tree removal, while the box-dimension would be negatively affected by such "holes" in the stand. This would contradict the idea of considering a high D_b as something generally good. However, we argue that while such relationships might exist, it was shown that natural forests (primary forests) possess a higher box-dimension then managed forests (e.g. Stiers et al., 2018; Camarretta et al., 2021), indicating that a high box-dimension is beneficial to diversity, or other positive characteristics associated with primary forests.

The first focus of our study was to determine the strength of the effect of different silvicultural treatments on forest complexity right after harvest. As one would expect, all treatments had negative effect on the structural complexity but with varying degree. The small changes in complexity observed for the treatments *group cut* and *shelter cut* could be explained by the spatial layout of tree removal. Here, the distributed pattern resulted in structural changes all over the stand, which is in contrast to the more aggregated effects of tree removal in the treatment *group cut* or *shelter cut*, leaving large parts of the stand unchanged. Earlier studies have shown that selection of single large trees or groups best imitates gap dynamics and natural regeneration processes as known from primary beech forests (Meyer et al., 2003; Commarmot et al., 2005; Brunet et al., 2010; Nagel et al., 2013). Treatments that result in canopy openings of varying sizes appear to maintain a multi-layered forest and avoid single-layered structures (Stiers et al., 2018). The random removal of trees ten times per plot showed incidental results which suggested that neither the diameter distribution of the trees before the treatment nor management history of the stands had a significant influence on the degree of change in structural complexity during the *random cut* procedure. In case of a perfect forest plantation, with all trees being exactly the same, the *random cut* of a given basal area would only quantify the effects of the spatial layout of the positions of the harvested individuals on the structural complexity of the forest. The amount of complexity removed would always be the same in the ten *random cuts*, but the trees would be taken randomly from varying positions. As soon as the structural complexity differs between the tree individuals in a forest, as it is the case in our data and likely in every real forest, the repeated *random cuts* quantify the effect of both, the individual's complexity as well as its spatial position in the stand. Therefore, we argue that repeating the *random cuts* ten times was certainly helpful to provides us an average effect of the random approach, but it should not be used further to draw conclusions on the stand characteristics, simply because the effect of spatial distribution and individual tree complexity cannot be separated.

Treatments that showed the highest variability in their structural complexity after tree removal were *strip cut* and *gap cut*. Thus, these alternatives led to significantly more heterogeneous stand structures as compared to the other treatments. *Strip cut* and *gap cut* therefore seem to be suitable measures when increased stand structural heterogeneity is wanted to either promote biodiversity of various taxa (Heidrich et al., 2020) or to favor the regeneration of light-demanding tree species (Coates, 2000).

3.4.2 Effect of the previous management history

Forest structure is an important characteristic of forest ecosystems that influences biodiversity, productivity, stability and resilience (Nagel et al., 2013; Ehbrecht et al., 2017; Feldmann et al., 2018; Stiers et al., 2018). Natural forests are considered to have the highest structural complexity (Scherzinger, 1996; Nagel et al., 2013; Feldmann et al., 2018; Stiers et al., 2018). However, the formerly managed forests in our study had a lower structural complexity than the managed forests, which seems to contradict the above. We explain our findings with the fact that we used forests with different management history. The short period of non-use of the "formerly managed" stands investigated here (27-102 years), could explain why they possess a lower structural complexity than the managed forests. It was shown in earlier studies that formerly managed beech forests are predominantly single-layered, have "vault-like" structures and are rather low in complexity (Stiers et al., 2018; Neudam et al., 2022). The structure of the formerly managed but recently unmanaged beech forests was caused by the natural reduction in stand density due to self-thinning, which affects suppressed and less dominant trees most (Scherzinger, 1996; Boncina, 2000; Meyer, 2005; Feldmann et al., 2018). Stiers et al. (2018) showed that terminating management in the optimum phase "halts" the development of structural complexity for quite some time. In contrast, managed beech forests usually have multi-layered structures (Schall et al., 2018; Stiers et al., 2018; Neudam et al., 2022). This is due to the fact that the basal area of managed forests is usually lower than in unmanaged stands of the same age, which allows for regeneration establishment and growth (Schall et al., 2018). Single tree or group harvest approaches result in high structural complexity, reflected in a high variation of neighboring trees of different ages and sizes (Schall et al., 2018). The fact that the virtual treatments had a greater impact on the structural complexity of the formerly managed stands is likely associated with their more single-layered structure, which apparently was more sensitive to tree removal. In these stands, tree removal often results in actual gaps in the entire vertical extent of the forest, while in the managed, multi-layered stands, tree removal in the overstory still left behind trees in the understory or vice versa.

3.4.3 Quantification of structural and economic effects of the simulated treatments

In this study, different silvicultural treatments were simulated and their effect on changes in structural complexity were quantified. The selection of a silvicultural treatment depends on the forest owner's objective. Here we considered the aspect of structural complexity, quantified by the box-dimension, and short-term profitability, measured as the net revenues of the different treatments. It is important to keep in mind that the effect of the various treatments on the current structure was examined here, but not the effect that the intervention will have in the long term. For example, a given treatment may lead to a strong reduction in structural complexity but facilitate processes such as revitalization of suppressed trees or tree regeneration which may increase the structural complexity in the near future. Important further ecosystem services as well as long-term economic consequences of silvicultural treatments on future yields and the future forest generation are therefore disregarded.

Nevertheless, we may conclude that we did not find a severe trade-off between maintaining a high level of structural complexity and gaining net revenues from the silvicultural treatment. The two treatments with the lowest change in structural complexity were also those providing high net revenues. The net revenues describe the economic consequences of harvesting only at one point in time, disregarding any future consequences. They thus do not adequately reflect the key drivers of economic harvest decisions, the scarcity of capital and growing space (Koster and Fuchs, 2022). Our short-term net economic gain illustrates that forest owners have to balance the possible alternative investments of the revenues gained by harvesting the trees, i.e. the reduced scarcity of capital, and the allocation of growing space to promising trees and its consequences for the stand's future value increment. While the remaining trees, for which more growing space is available, might compensate for at least parts of the growth of harvested trees (e.g., Pretzsch, 2005; Albert et al., 2022), we found a loss in value increment in mostly all simulations. Only in two stands when harvesting mainly thin trees (*minimum complexity cut*), the treatment promoted the growth of valuable neighbors in a magnitude that the future value increment increased. However, with an increasing level of capital scarcity, i.e. a higher interest rate, the reduction in capital scarcity compensated for increasing parts of these losses (Figure

3.13, Supplementary material). Forest owners following these assumptions prefer current revenues over future value increments. The short-term net economic gain still does not account for the long-term nature of forest management (cf. Koster and Fuchs, 2022). For instance, the treatments *gap* and *group cut* may be favorable compared to even-aged stand management when aiming at structured, stable, and thus economically favorable (Knoke et al., 2022), future tree generations. Assessing these long-term effects would require more profound forest growth simulations rather than our simplified short-term growth predictions. However, this would most likely not change the ranking of the treatments. For instance, considering the long-term consequences of economically favorable natural regeneration would probably support the *group cut* system, which is also favorable for gaining net revenues and maintaining a high structural diversity. Here we wanted to determine the treatment which has the lowest impact on structural complexity and highest net revenue and found that it is not necessary to compromise between the two objectives. Which treatment is most appropriate depends, of course, on the individual objectives of the forest owner.

3.4.4 Methodological considerations

In this study, silvicultural treatments were simulated and compared in their effects on stand structural complexity. The data were based on 3D point clouds from mobile laser scans. In assessing structural complexity, we calculated D_b, a mathematical approach at stand-level. This calculation evaluates the spatial point distribution and density of the point cloud instead of distinguishing between individual objects. Aspects such as the health status of the trees or the species diversity in the forest stand cannot be considered directly with this approach, even though are related to the structural complexity of a tree and forest as assessed with laser scanners (Ehbrecht et al., 2017; Juchheim et al., 2019; Heidenreich and Seidel, 2022).

The treatments simulated here were intended to resemble selected silvicultural treatments applied in forest practice. By removing always 20 % of the basal area of the stand, the different approaches could be compared in their effects on stand structural complexity. However, as mentioned above the development of stand structural complexity (and economic yield) beyond the time of removal and thus the long-term effect of the treatments could not be considered with our approach. Technically, our methodology can be applied to every forest for which detailed 3D data can be obtained, including e.g. mixed forests, tropical forest with very high complexity, or dense plantations. The greatest challenge in very dense or very young forests would currently be the automatic segmentation of the point cloud (particularly in leaf-on condition) which is needed to obtain the single tree data. However, continuous progress in the software available to perform the segmentation task can be expected, in particular through the use of deep learning approaches.

Covering beech-dominated forests from different sites in Germany, our stands differed regarding the tree age, the soil conditions and climatic characteristics. Although slope effects were accounted for in the D_b approach, we cannot rule out potential effects of differences in soil conditions, climate, etc.

3.5 Conclusion

With this study, we provide evidence that it is possible to precisely quantify the change in structural complexity through different silvicultural treatments. We found that any form of treatment has a negative effect on structural complexity at the time of harvest (here: virtual tree removal in the 3D forest model). However, the change in structure did not depend on the diameter distribution of the stands or their management history, but in fact only on the simulated silvicultural treatment. In brief, the effects of harvesting methods on forest structure depend on the form of treatment. We conclude that the silvicultural approach selected for an actual tree harvest should be selected carefully as it has specific effects on stand structural complexity and net revenue. If a (beech) forest owner seeks for minor changes in structural complexity, they could choose the silvicultural treatments along the following order of effect: *group cut* $<$ *shelter cut* $<$ *gap cut* $<$ pooled *random cuts* $<$ *minimum complexity cut* $<$ *strip cut*. This study may pave the way to methods that allows different simulations to be carried out on real forest data to determine the final tree harvest treatment that fits best to the objectives of a forest owner. For the first time, it was possible to compare the effects of real-world forest management scenarios applied to the exact same forest and their consequences for the structural complexity of the forest. This can never be done in real forests, as uncontrolled confounding factors would always inhibit a direct comparison of two neighboring stands. The methodology presented here could be used to optimize the forest management towards the forest owner’s targets, to test management scenarios with regard to their effect prior to the actual harvest, and to avoid unnecessary losses in structural complexity due to timber harvests.

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DATA AVAILABILITY

Data will be made available on request.

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3.8 Supplementary material

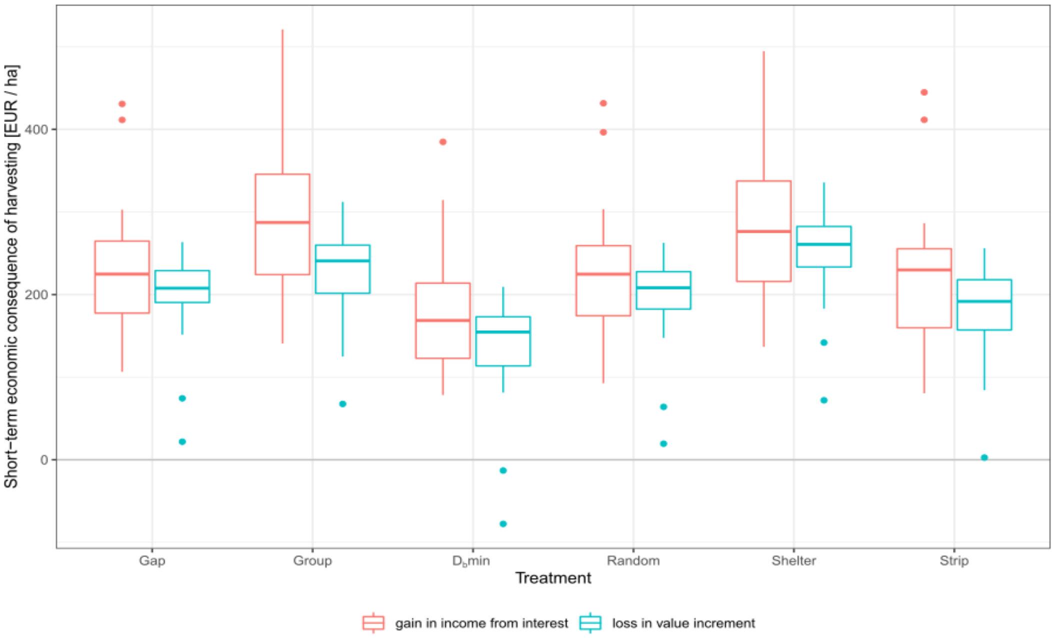

Figure 3.12 Short-term economic consequences in the 5-year period following the different simulated silvicultural treatments for all 19 study plots. The 10 different treatments random cut were averaged per plot and combined as one. Bold horizontal lines indicate the median. Income from interest refers to the 5-year interest on the net revenues of the harvest. Loss in value increment is the change in increment in the net value of the growing stock over the following 5 years between a non-intervention scenario and the different simulated silvicultural treatments. Negative losses therefore refer to an absolute increase in net value of the growing stock following the silvicultural treatment.

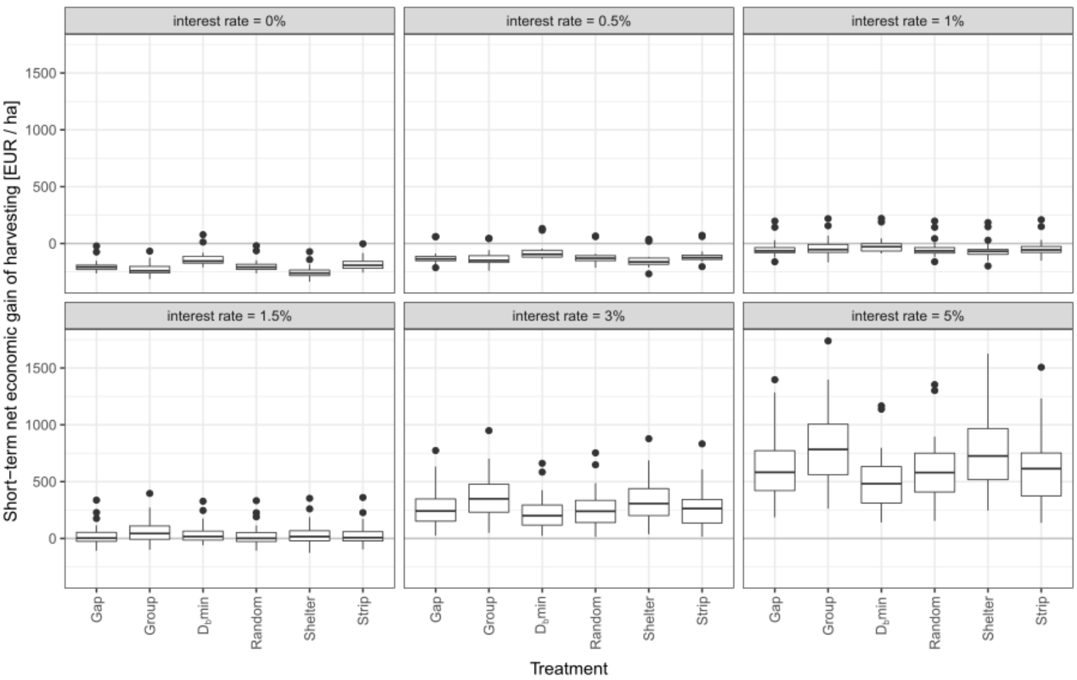

Figure 3.13 Effect of assumed interest rate on short-term net economic gain [€/ha] of the simulated silvicultural treatments at the end of the following 5-year period for all 19 study plots. The 10 different treatments random cut were averaged per plot and combined as one. Black horizontal lines indicate the median.

Chapter 4

Stem shape and structural complexity change in beech forests along a management gradient

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Stem shape and structural complexity change in beech forests along a management gradient

Liane C. Neudam[1,2], Kirsten Höwler[2] and Dominik Seidel[2,3]

[1] Department of Silviculture and Forest Ecology of the Temperate Zones, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

[2] Department of Spatial Structures and Digitization of Forests, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

3 Centre of Biodiversity and Sustainable Land Use, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

Keywords: European beech, structural complexity, laser scanning, stem shape, primary forest, close to nature management

Abstract

For about half a century, attempts have been made to manage forests as close to nature as possible. This management targeted the creation of structures that resemble those found in primary forests. Laser scanning provides the opportunity to quantify such structural “naturalness” and allows to evaluate which management practices come closest to forest structures found in primary forests. In this paper, European beech (*Fagus sylvatica* L.) forests with different management intensity were compared to primary forests in terms of their structural complexity and the shape of tree stems. For this purpose, data from mobile and terrestrial laser scans (MLS and TLS) of managed forests, of forests whose management has been abandoned, and of primary forests was used. We found that management intensity influenced the distribution of plant material in the forest stand and thus the structural complexity on stand level. Also, management affected the shape of the stems. Here, it is important to consider the management history of the forest stands and the forest development phase in which management was abandoned. The stem shapes of trees in primary forests were significantly different (larger stem diameters and longer branch free boles) from those of the other investigated forests. Nevertheless, our results showed that it is possible to achieve old-growth-like structures such as high standing volumes, a multi layered canopy, high number of large trees and high variation in tree size and age through targeted silvicultural treatments in order to accelerate the close-to-nature development of forests. The present study illustrates the possibility of using mobile and terrestrial laser scanning to objectively compare and evaluate the structural effects of different silvicultural concepts.

4.1 Introduction

During the Middle Ages, forests in Central Europe were extensively used for pasture and their litter was collected. In addition, wood was intensively used as a source of energy and building material (Knopf et al., 2015). The woodland regions were degraded by this centuries-long overuse (Zerbe and Wiegleb, 2009). In the second half of the 19^{th} century and the first half of the 20^{th} century, the focus laid on a rapid reconstruction of the forests. In this process, even-aged monocultures were mostly created to ensure constant wood production (Olsthoorn et al., 1999). However, the dense cultivation of the same tree species led to a higher risk of pest infestation (Mori et al., 2017) and storm damage (Dvořák et al., 2001). For more than 100 years now, attempts have been made to focus more on natural processes and structures in order to create stable and adaptable forests, promoting the model of plenter forest (in German: "Plenterwald") and other Continuous Cover Forestry (in German: "Dauerwald") concepts, during the period 1850-1950 (Gayer, 1886; Möller, 1935; Röhrig and Gussone, 1982; Heyder, 1986). It is assumed that primary forests (no human impact) have a particularly high stability, biodiversity, and adaptability due to their structural heterogeneity (Stiers et al., 2018; Seidel and Ammer, 2023). In view of this, there have been efforts to reproduce the dynamics and structures, which normally developed naturally over decades, by silvicultural management (Röhrig and Gussone, 1982; Heyder, 1986; Nagel et al., 2013). In this way, strongly anthropogenically formed forests are to be transformed into near-natural forest ecosystems with increased structural complexity (Zerbe and Wiegleb, 2009). According to Puettmann et al. (2015), the aesthetic and ecological drawbacks of conventional silvicultural management were supposed to be overcome by irregular size-class distributions and single-tree selection rather than clear cuttings.

In order to use forests in a near-natural way, detailed knowledge on the natural condition of the forests is required (Rademacher et al., 2001). Several definitions of the concept of naturalness can be found in the literature (Anderson, 1991; Scherzinger, 1996; Siipi, 2004). As an example, geobotany provides the first basis for assessing naturalness (Walentowski and Winter, 2007) with its concept of "potential natural vegetation" developed in the 1950s by Tüxen (1958). "Potential natural vegetation" refers to the final state of vegetation in a habitat without human influence and enables the vegetation-geographical characterization and differentiation of natural areas (Zerbe and Wiegleb, 2009). However, this approach has often been criticized for its static character which ignores biological uncertainties and natural temporal variations (Kowarik, 1987; Zerbe, 1998; Chiarucci et al., 2010). The most practicable, objective, and efficient approach to estimate the "degree of naturalness" of a given forest structure is likely a detailed assessment of its structural character in direct comparison to the structural characteristics of a primary forest (Stiers et al., 2020; Seidel and Ammer, 2023). This, however, is limited to forest dominated by the same tree species, as compositional effects on complexity might otherwise override management effects.

In Central Europe, European beech (*Fagus sylvatica* L.) is one of the most essential climax species in unmanaged forest ecosystems under the current climate conditions (Ellenberg and Leuschner, 2010). Only a small number of beech dominated primary forests remain today (Kucbel et al., 2012; Trotsiuk et al., 2012; Hobi et al., 2015; Glatthorn et al., 2018), which could serve us as indicators of natural forests. However, the development of concepts for near-natural forests requires a detailed understanding of the processes and structures in primary forests (Rademacher et al., 2004; Nagel et al., 2013; Feldmann et al., 2018). In Germany, primary forests do not exist anymore. However, conservation programs for old-growth forest communities were implemented, in which trees are left standing or management is entirely ceased (Schaber-Schoor, 2008; Meyer and Schmidt, 2011). An increasing number of forest areas was abandoned from forestry interventions for several decades (Bücking et al., 2000; Meyer, 2005; Meyer et al., 2007). In addition, more and more unmanaged forests are being designated as nature reserves or national parks (Meyer and Schmidt, 2011).

To describe forests in a quantitative manner, three-dimensional point clouds from laser scanning can be used, e.g., to investigate the horizontal and vertical distribution of plant material (Seidel et al., 2016). Furthermore, selected structural parameters allow quantifying the structural complexity of different forests and comparing them with each other (Dassot et al., 2011; Hardiman et al., 2011; Ehbrecht et al., 2017; Atkins et al., 2018; Calders et al., 2018). Consequently, it is feasible to use data from primary forests to evaluate their structural complexity and compare it to managed forests, if the dominant species is the same (here: European beech; Stiers et al., 2018). The method of laser scanning offers an objective characterization of the structures and can be used to quantify structural "naturalness". This in turn could serve as a control for near-natural silviculture and nature conservation concepts and form the basis for action or non-action.

In this study, we used 3D point clouds based on laser scans from beech forests in Germany with different management intensities and different management histories to compare their structural complexity and stem shape with data from temperate European beech primary forests. The primary forests are located in the Ukraine and Slovakia as the unmanaged natural reference forests to test the following hypothesis:

I) Forest management targeted towards natural forest development can result in structures that resemble structures of primary forests, here assessed based on overall structural complexity and patterns of vertical space-filling.
II) Management intensity affects the shape of the trees growing in a stand, here assessed via lean, sweep, diameter and length of branch-free stem.

4.2 Material and methods

4.2.1 Study sites and management intensity

We selected 19 forest stands in Germany, which were either pure European beech (*Fagus sylvatica* L.) or beech dominated stands. The forests are located near Göttingen (Lower Saxony), Lübeck (Schleswig-Holstein), Oppershofen (Hesse), and Allstedt (Saxony-Anhalt, see Figure 4.1). The stands range in age of the dominant trees from 93 to 163 years and differ in terms of their management history (Table 4.1). All stands were managed for decades but in nine stands forestry interventions were ceased between 28 and 100 years ago, these areas are described as "formerly managed" in the following. The areas that are still managed today are defined as "managed forests". In order to assess and evaluate these forests in terms of structural complexity, we added data from four study plots in temperate European beech primary forests in western Ukraine (Uholka) and eastern Slovakia (Rožok, see Figure 4.1), defined as "primary forests" in the following. The average age of the dominant trees in the two plots in Uholka was 350 years and in the two plots in Rožok 220 years (see Table 4.1 and Stiers et al., 2018 or Willim et al., 2019 for detailed information).

To compare the study stands in terms of their management intensity, we used the silvicultural management intensity indicator (SMI) according to Schall and Ammer (2013). Based on Schall and Ammer (2013), the SMI, a purely quantitative measure for ranking forest along a gradient of how intense the given stand has been managed so far. The index is calculated as average of *stand loss risk* and *stand density components* and ranges from zero to one. According to Schall and Ammer (2013), the *risk component* of silvicultural management intensity is defined as an age-dependent probability that a stand will be lost at a given age before reaching a certain reference age. As such, it combines the effect of tree species selection and stand age on the probability of survival due to natural risks (e.g. ageing, wind throw or biotic pathogens) at or before a reference age (Juchheim et al., 2017). The *stand density component* calculates the impacts of removals and regeneration techniques using the basal area in comparison to the maximum natural basal area of the site. To calculate the *risk component* of the SMI as a function of stand age for all study plots, the survival functions developed by Staupendahl and Zucchini (2010) for several tree species, including European beech, were used here. The survival functions are based on inventory data collected in Rhineland-Palatinate between 1994 and 2008. These results are considered representative for Central Europe, as the forests of Rhineland-Palatinate are mainly located in the submontane zone, but also have a considerable part in the low to mid montane and colline zone (Schall and Ammer, 2013). To calculate the *density component* of the SMI, the site index (measured as max. mean annual increment) from German yield tables of each stand was first estimated from the stand age, the mean height of the trees, and the basal area of the stand. The mean height of all trees and the basal area were obtained from the laser scans. Then, depending on the respective site index, the maximum natural basal area of the site could be derived from region specific German yield tables for European beech according to Schober (1967). The maximum natural basal area of the site was then compared with the basal area of the stand according to Schall and Ammer (2013). The amount of deadwood was not considered in the calculation of the density component due to the lack of information.

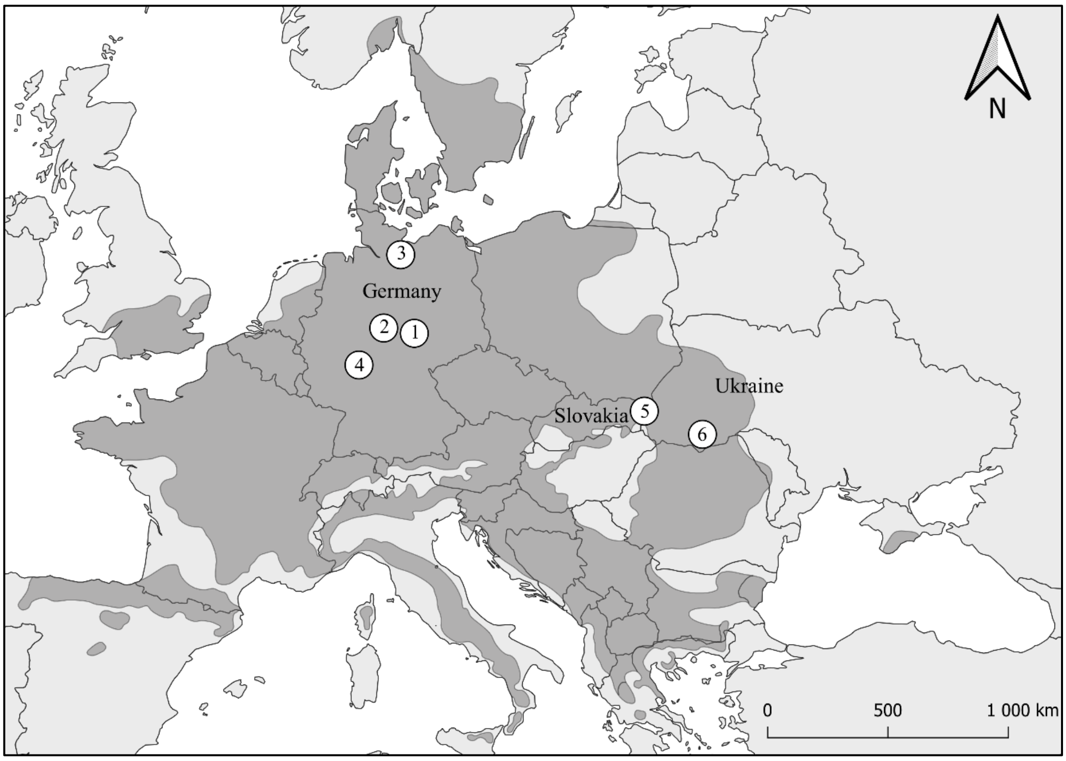

Figure 4.1 Location of the study areas and distribution range of *Fagus sylvatica* L. in Central Europe (dark grey area) according to Caudullo et al. (2023). Each number represent one study site (1 = Allstedt; 2 = Göttingen; 3 = Lübeck; 4 = Oppershofen; 5 = Rožok and 6 = Uholka).

Table 4.1 Detailed information about the climatic and geographic conditions of the study areas and the average age and height of the forest stands. MAT = mean annual temperature; MAP = mean annual precipitation. On all sites beech contributed at least 80 % to the total basal area (beech-dominated).

Country	Study Area	Elevation (m a.s.l.)	MAT (°C)	MAP (mm)	Management history	Plot name	Plot size (ha)	Mean tree age (2023)	Mean stand height (m)
Germany	Allstedt (1)	268-316	9.81	466	Formerly managed	A1N	1.95	142	35.50
					Managed	A1W	1.42	92	31.12
	Göttingen (2)	341-455	9.80	595	Formerly managed	G1N	1.07	144	37.16
						G2N	1.56	163	35.24
						G3N	1.56	138	38.63
						G4N	1.08	134	40.18
					Managed	G1W	2.15	125	35.78
						G2W	1.00	150	38.51
						G3W	1.48	130	36.97
						G4W	2.19	131	42.18
	Lübeck (3)	46-70	9.60	655	Formerly managed	L1N	1.69	152	42.32
						L2N	1.29	136	40.36
						LG1	1.14	129	44.81
					Managed	L1W	1.96	137	39.61
						L2W	1.67	93	36.72
						LG2	1.53	128	40.36
						LG3	1.59	150	33.60
	Oppershofen (4)	267-269	10.89	560	Formerly managed	O1N	1.22	164	46.81
					Managed	O1W	1.46	125	41.60
Slovakia	Rožok (5)	580-745	6-7	780	Primary forest	R1	0.47	~220	43.75
						R2	0.33	~220	44.85
Ukraine	Uholka (6)	700-840	7	1407	Primary forest	U1	0.28	~350	44.80
						U2	0.30	~350	45.50

4.2.2 Terrestrial and mobile laser scanning

For the primary forests in Uholka and Rožok, an area of 50 x 50 m (2500 m^2) was scanned with the Faro Focus 3D 120 terrestrial laser scanner (Faro Technologies Inc., Lake Mary, USA). The scanner was set up for each scan at breast height (1.30 m) and fixed on a tripod. The scan parameters were configured to encompass a horizontal field of view of 360° and a vertical field of view of 300°, with a scan rate of maximal 976,000 points per second. The terrestrial laser scanner sent invisible laser beams into the forest environment and identified those beams reflected from neighboring trees or other plant features with a maximum distance of up to 120 m using phase-difference technology. Each laser beam had a wavelength of 905 nm and an angular resolution of 0.19 mrad (0.011°). Depending on the density of understory vegetation, 60-80 scans per plot (2500 m^2) were made from different directions using a systematic sampling grid to minimize shadowing. Artificial checkerboard targets were arranged over the plot for spatial co-registration of the single-scans into a multi-scan point cloud with Faro Scene (Faro Technologies Inc., Lake Marry, USA). The scans from the primary forests plots were carried out during the vegetation period in August 2017 (see Stiers et al., 2018). This data was used to extract single tree point clouds.

In addition, a 2-hectare forest area was scanned in each primary forest based on an 82 m regular sampling grid of single scans using the FARO Focus 3D 120. This was done to ensure wider spatial coverage and independence of the individual scans (no overlap). In Rožok a total of 71 scans were made, while in Uholka 152 scans could be placed in the study area (see Stiers et al., 2018 for details).

For the comparison of the study plots with the primary forest plots in terms of their structural complexity, we used data from terrestrial laser scans gathered in July 2020 for the plots in Germany. Following Ehbrecht et al. (2016), nine scans per plot were taken to minimize occlusion effects within the plot with the terrestrial Faro Focus M70 laser scanner (Faro Technologies Inc., Lake Mary, USA). This terrestrial laser scanner works according to the same measuring principle with a wavelength of 1550 nm using an angular resolution of 0.19 mrad (0.011°) and a point measurement rate of 976,000 per second.

A ZEB Horizon mobile laser scanner (GeoSlam Ltd., Nottingham, UK) was used to compare the primary forest data with the study plots in terms of special arrangement of plant material in stand layers (space filling) and stem shapes. The hand-held scanner was taken through the forest stands and used simultaneous localization and mapping (SLAM) and the time-of-flight principle to record the forest in all three dimensions with a scan range noise of ± 30 mm. The distance between the scanner and each surrounding object at a maximum distance of 100 m was measured with a wavelength of 903 nm, and a scan rate of 300,000 points per second. The mobile laser scans of the study plots in Germany were collected in July 2020 and February 2021 (see Neudam et al., 2023).

4.2.3 Point cloud processing to quantify the structural complexity

To analyze the structural complexity, we used the single scans from terrestrial laser scanning taken in August 2017 for the primary forests and in July 2020 for the formerly managed and managed forests. For the single-scans, the predefined settings of the Faro Scene software (Faro

Technologies Inc., Lake Mary, FL, USA, and version 7.1.1.81) were used to filter out erroneous points, according to the software's standard settings (Dark Scan Points, Outliers). A height-normalization was used in order to account for uneven terrain for each point cloud by correcting the underlying terrain height previously obtained from digital terrain models. Each 3D point cloud was exported as an xyz-file for further processing (Stiers et al., 2020).

The normalized and spatially homogenized data were then utilized to calculate the structural complexity based on the stand structural complexity index (SSCI, Ehbrecht et al., 2017) using an algorithm written in Mathematica (Wolfram Research, Champaign, Illinois, USA). This well-established index, based on single-scans, quantifies the spatial arrangement of plant material in forests and has been shown to distinguish between different stand structures (Ehbrecht et al., 2017; Ehbrecht et al., 2021). For this, the forest scene is first divided into several vertical cross-sectional polygons from the perspective of the scanner (entire forest stand above breast height, 1.3 m). Based on this, the SSCI mathematically describes the relationship between the areas and perimeters of these cross-sectional polygons and thus quantifies the complexity of the stand. The range of values for the SSCI is typically between zero (no structures present) and around 15 for extremely complex structures (see Ehbrecht et al. 2021 for a global dataset). Structural complexity increases as the value increase. For further information on the equation and index creation see Ehbrecht et al. (2017; 2021).

4.2.4 Point cloud processing to quantify vertical space filling

To analyze vertical space filling as a proxy for vertical layering in the stands we used four combined multi-scan point clouds from the single scans of the primary forests and 15 mobile laser scans of the formerly managed and managed forests. The scans were acquired in the vegetation period, when all trees were fully foliated. The mobile scans were processed in the GeoSlam Hub software (GeoSlam Ltd., Nottingham, UK) for the actual SLAM calculation after being scanned in the field using a defined measuring scheme and exported as a laz-file. We then utilized the free and open-source software CloudCompare (www.danielgm.net) to narrow down the precise study area in the scanned point cloud of each plot. Following noise filtering and subsampling (down sampling for homogenous point cloud density of 1 cm and elimination of outlier points that have no neighbor within 10 cm distance),the resulting point cloud was exported as a xyz-file for additional processing (Neudam et al., 2022). When address in vertical layers, space filling can be used to determine the plant material density in predefined stand strata and therefore to describe the vertical arrangement of organic material in forests (Stiers et al., 2020), a measure closely related to a forests ecological functions and adaptability (see Figure 4.2; Seidel and Ammer, 2023). To calculate space filling, total plot volume was determined as ground area multiplied by median stand height. We isolated the upper 20 % of the stand height (outlier points of single emergent trees) and calculated the median for these horizontal values to identify the median height, which was utilized for future calculations. This avoided shading in the densely foliated data that might otherwise have led to underestimation of the upper canopy. We eliminated all voxels below one meter, before calculating relative space filling to avoid effects of the ground due to the scanning pattern. If these points, which represented mostly understory vegetation, had not been removed, space filling for the bottom stand layers would have been overrated. The space above the lowest voxel layers and the median stand height were used to compute space filling. The space occupied by voxels is calculated by counting all voxels and multiplying the number by the voxel volume (Stiers et al., 2020).

The plots were then vertically partitioned into 50 equally thick layers based on the median stand height, as described in Seidel et al. (2013) and Juchheim et al. (2017). Following that, we determined the space filling percentage of each layer as a fraction of the total using the 20 cm voxel representation of the stand. We utilized accumulation curves to illustrate the cumulative arrangement of space filling in the vertical layers of the scanned forest plots in order to investigate the vertical distribution of plant material (Stiers et al., 2020).

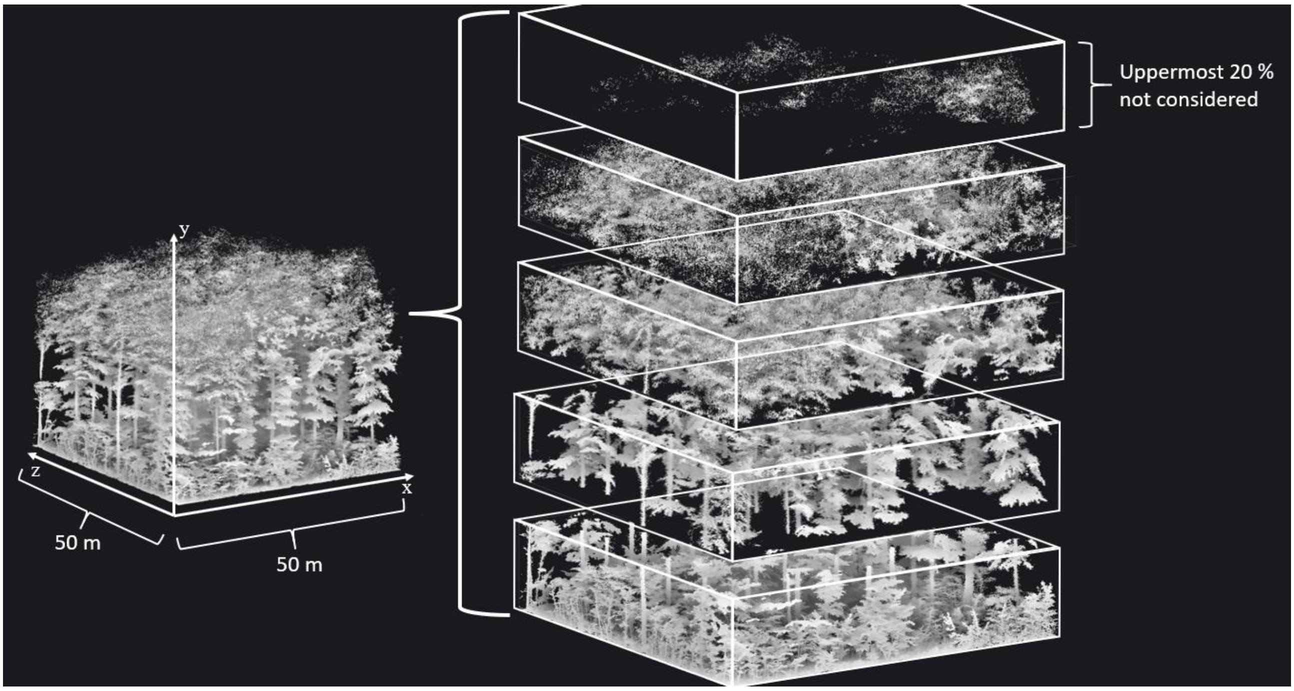

Figure 4.2 Schematic illustration of the determination of space filling in vertical layers with the scanned forest plot on the left and the same plot separated into exemplary layers for which the space filling was then calculated based on 20 cm voxels. This is for illustration only, as we used 50 layers during processing for a finer resolution.

The upper-most 20 % (here highest layer) was not considered due to potential occlusion effects still persisting in the 20 cm voxel model (cf. Mathes et al., 2023).

4.2.5 Point cloud processing for quantify of stem shape

In a next step, we aimed at analyzing simple structural metrics of individual trees. To obtain point clouds from the mobile laser scanning of the single trees for the formerly managed and managed forests we used the 'automatic tree segmentation' method from the LiDAR software (GreenValley International Ltd., California, USA). LiDAR 360 saved each individual tree independently with additional information about each tree's position, height, and diameter at breast height (DBH, see Neudam et al., 2023). For the primary forests, we used the single scans from the terrestrial laser scanning. For the quantification of stem shape, 10 trees per study plot were randomly selected from the dominant tree layer. Then, we manually removed all ground vegetation, elements from neighboring trees, and branches in the 3D point cloud of the trees using the CloudCompare software. The individual stems ranged in height from the root collar to the crown base height (see Figure 4.3). The point clouds of the stems were then exported as xyz-files for additional processing.

In the following, we used several measures to enable a detailed description of the shape of the stems. An algorithm that was coded in Mathematica (Wolfram Research, Champaign, Illinois, USA) was used to process all stem point clouds. Along the stem, horizontal layers of 10 cm thickness were extracted and each projected on a plain. Afterwards, a circle was fitted to the points of each layer based on QR decomposition in agreement with Seidel and Ammer (2014) and Höwler et al. (2017). The center of the circle was used as the location of the stem center at the corresponding height. The length of the stem was calculated as the difference between the upper- and lowermost point in the stem point cloud. Based on the horizontal distance between the centers of the upper- and lowermost circles, we estimated the overall lean of the stem sections. To determine a length-independent measurement of lean per meter, this number was multiplied by the length of the section as a whole. The ratio of the shortest distances between the centers of the lower- and uppermost circles to the total of the shortest distances between the centers of all succeeding circles along the vertical direction was found to represent the whole sweep of the stem. Total sweep was divided by the length of the stem section to get sweep per meter (see Figure 4.3 and for further information see Höwler et al., 2017).

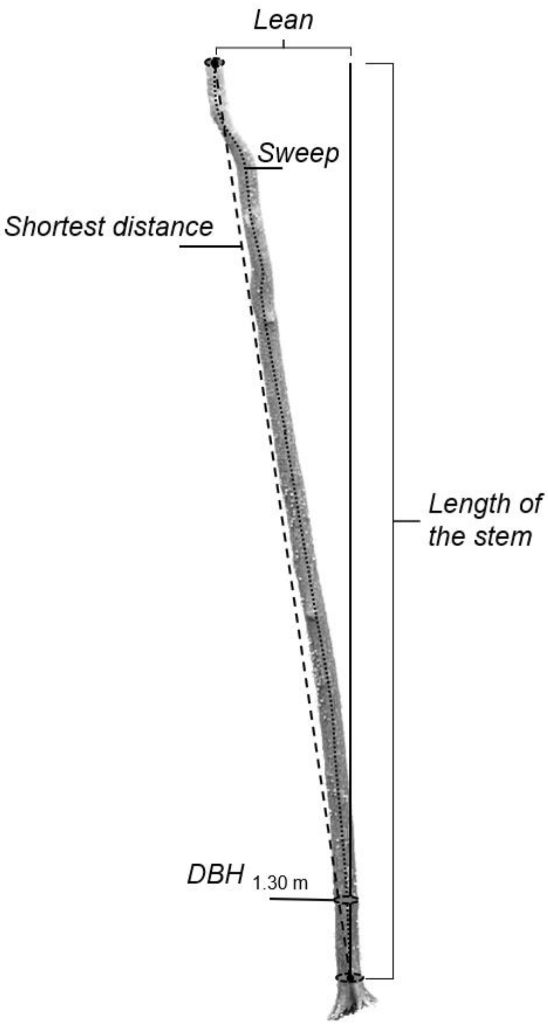

Figure 4.3 Three-dimensional point cloud from one of the isolated stems as an example with the different measures (adapted from Höwler et al., 2017).

4.2.6 Statistical analyses

For the statistical computing and graphics, we used the free software environment R (version 4.1.2; R Core Team, 2021). In evaluating the stand structural complexity and the stem shapes with respect to the management gradient, we used a smoothed regression line to illustrate the linear trend. For this purpose, the "loess" method of *geom_smooth()* function (formula = "y ~ x") was used in R, which allows to add the linear trend and confidence intervals around it. The significance level for all statistical tests was set to 5 %. To analyze the data, depending on their distribution (Shapiro-Wilk-test for normally distributed population) we used parametric and non-parametric tests to test for differences between the stands of the different management histories. If the data satisfied the criteria for parametric testing, a one-way ANOVA was performed to test for differences between the variables, followed by a pairwise *t*-test with the Bonferroni *p*-value adjustment procedure for post-hoc comparison. Using this method, we looked for differences in length and DBH of the stems between the stands of different management histories. When parametric assumptions were not met, we used the non-parametric Kruskal-Wallis-test and the Wilcoxon Rank Sum Test with Bonferroni *p*-value adjustment technique for post-hoc pairwise comparisons. This was done in order to compare the Lean and Sweep of the stems and the stand structural complexity index between the stands with varying management histories.

4.3 Results

4.3.1 Gradient of management intensity and structural complexity

Using the silvicultural management intensity indicator (SMI), it was possible to classify the stands in terms of their management intensity. The formerly managed forests showed a lower management intensity than the managed forests (Figure 4.4).

The stand structural complexity (SSCI) from terrestrial laser scanning was lowest for the formerly managed forests (mean ± standard deviation (sd): 4.51 ± 0.86) and increased with higher management intensity (mean ± sd: 5.68 ± 1.53, cf. Figure 4.5). The values of the primary forests ranged from 2.88 to 11.41 (mean ± sd: 5.77 ± 1.56).

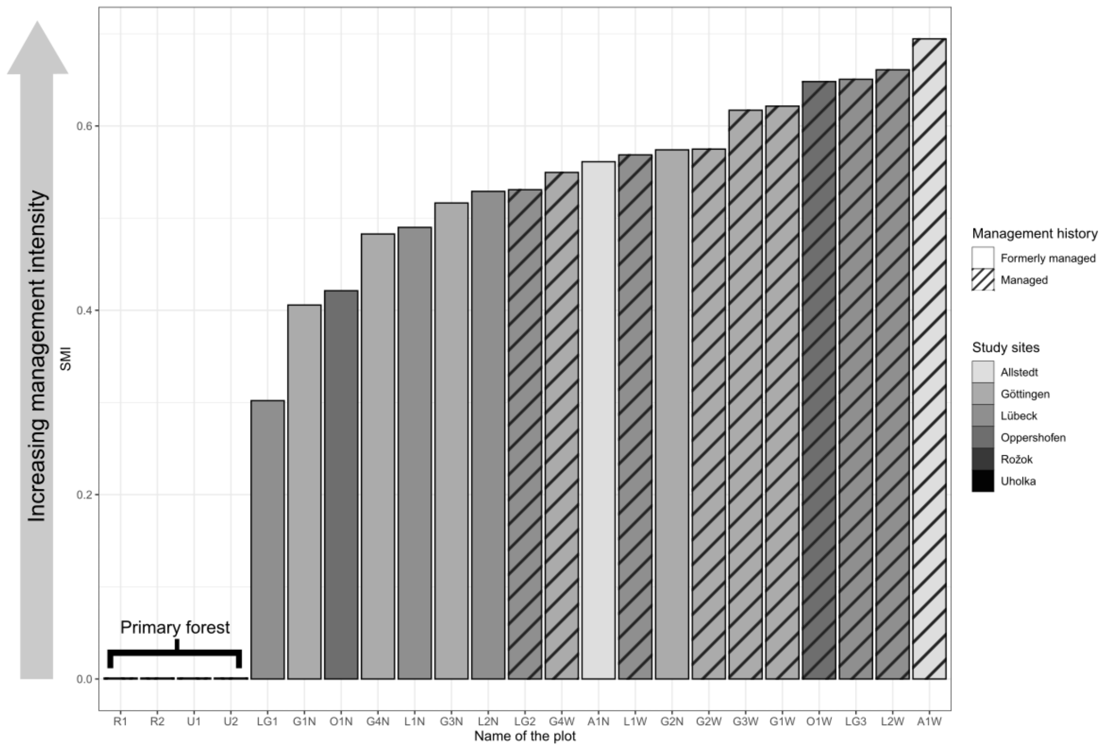

Figure 4.4 Ranking of study plots with increasing management intensity (from left to right). Indicator for silvicultural management intensity ("Silvicultural Management Intensity", SMI) according to Schall and Ammer (2013) for all study plots.

We found significant differences in stand structural complexity between the formerly managed and the managed forests stands as well as between the formerly managed and the primary forest stands, but not between the managed stands and the primary forests (see Figure 4.6). The stand structural complexity was lowest in the formerly managed forests (mean ± sd: 4.52 ± 1.24), highest in the primary forests (mean ± sd: 5.77 ± 1.56), and intermediate in the managed forests stands (mean ± sd: 5.66 ± 1.94).

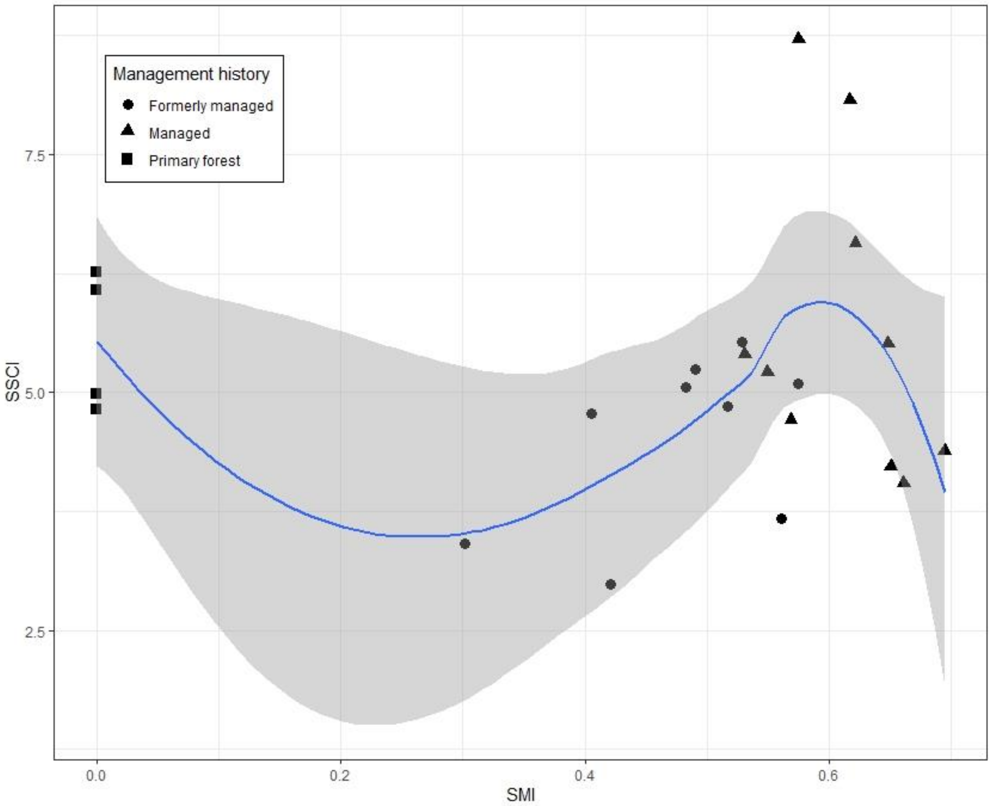

Figure 4.5 Scatter plot of structural complexity, expressed as "Stand Structural Complexity Index" (SSCI), of 23 European beech forests differing in their silvicultural management intensity (SMI). Increasing structural complexity results in an increased structural complexity index while increased management intensity results in an increased SMI. The symbols are the mean of the scans on each study plot. The squares are the primary forests (n= 4), discs show the formerly managed forests (n = 9), and the triangles are the managed forests (n = 10). The smooth local regression line is marked in blue and the confidence interval is highlighted by the grey area around it.

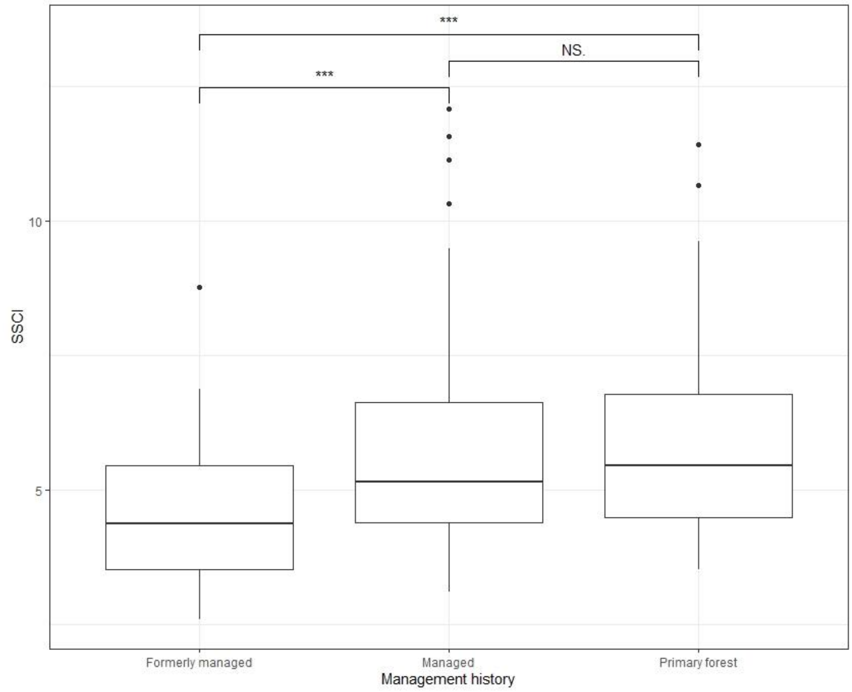

Figure 4.6 Box-Whisker plots of stand structural complexity, expressed as SSCI, for 23 study plots with different management history. Black horizontal lines indicate the median of the scans per plot (n = 81 for “Formerly managed”, n = 90 for “managed” and n = 223 for “Primary forest”). Stars indicate significant differences among the conditions at the level of $p > 0.05$ (NS.), $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.0001$ (***).

4.3.2 Vertical pattern of space filling

The space filling was used to calculate the percentage of filled volume in the layers and thus to describe the special arrangement of plant material for the formerly managed, the managed, and the primary forests stands. The accumulation curves of space filling showed the varying proportions in the defined stand layers for all study plots (Figure 4.7).

The studied forests showed different distributions in the stand layers. The assumption that each stand layer is evenly filled and the space filling is homogeneously distributed is exemplified by the angle bisector. The primary forests were located close to the angle bisector and thus had a particularly homogeneous distribution of plant material across the stand layers. Compared to the primary forests, the managed forests were further away from the bisecting line. The formerly managed forests were clearly below the bisector, which indicates a heterogeneous distribution of plant material across the stand layers.

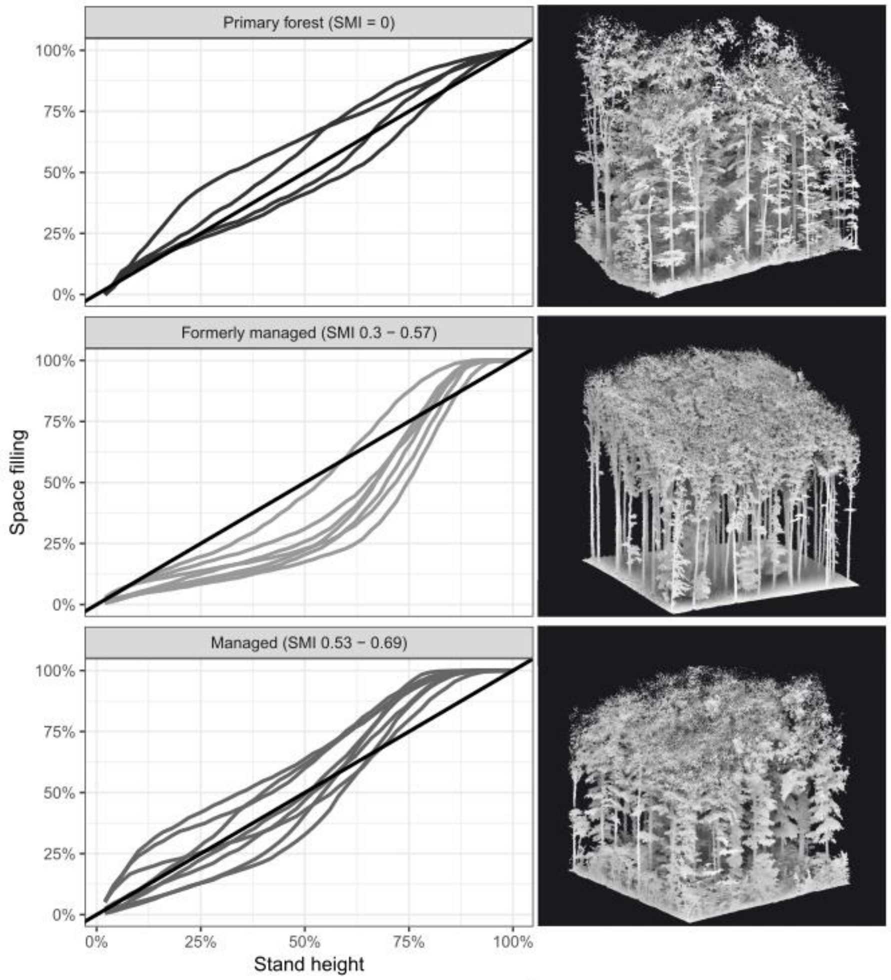

Figure 4.7 Cumulative relative space filling over relative stand height is represented by accumulation curves under full foliated conditions with exemplary point clouds for each management history. The 19 plots are divided according to their management history (Primary forests n = 4; formerly managed forests n = 7; managed forests n = 8) and the range of silvicultural management intensity indicator (SMI) is indicated. A homogeneously distributed voxel filling, in which each stand layer is evenly filled, is shown by the angle bisector.

4.3.3 Stem shape

In the following, the data from mobile laser scanning of the study plots is compared with TLS data from primary forests with regard to stem shape in relation to the management gradient. The results showed that the trees in the primary forests had a significantly higher diameter at breast height (DBH, mean ± sd: 76.82 ± 3.37) compared to the other study plots (mean ± sd: formerly managed = 56.53 ± 6.01; managed forests = 51.66 ± 5.13), with significantly higher values of sweep (mean ± sd: 0.09 ± 0.08) and lean (mean ± sd: 0.99 ± 0.002) and large stem lengths (mean ± sd: 20.72 ± 1.19, see Figure 4.8). The trees of the formerly managed forests had straighter stem shapes with long branch-free stem lengths and intermediate DBH. Trees of the managed forests, on the other hand, had short stem lengths with more curved and crooked stems and moderate DBH. However, the differences between the trees of the formerly managed forests and those of the managed forests were not significant ($p < 0.05$). Nevertheless, a change along the management gradient was detected (Figure 4.8).

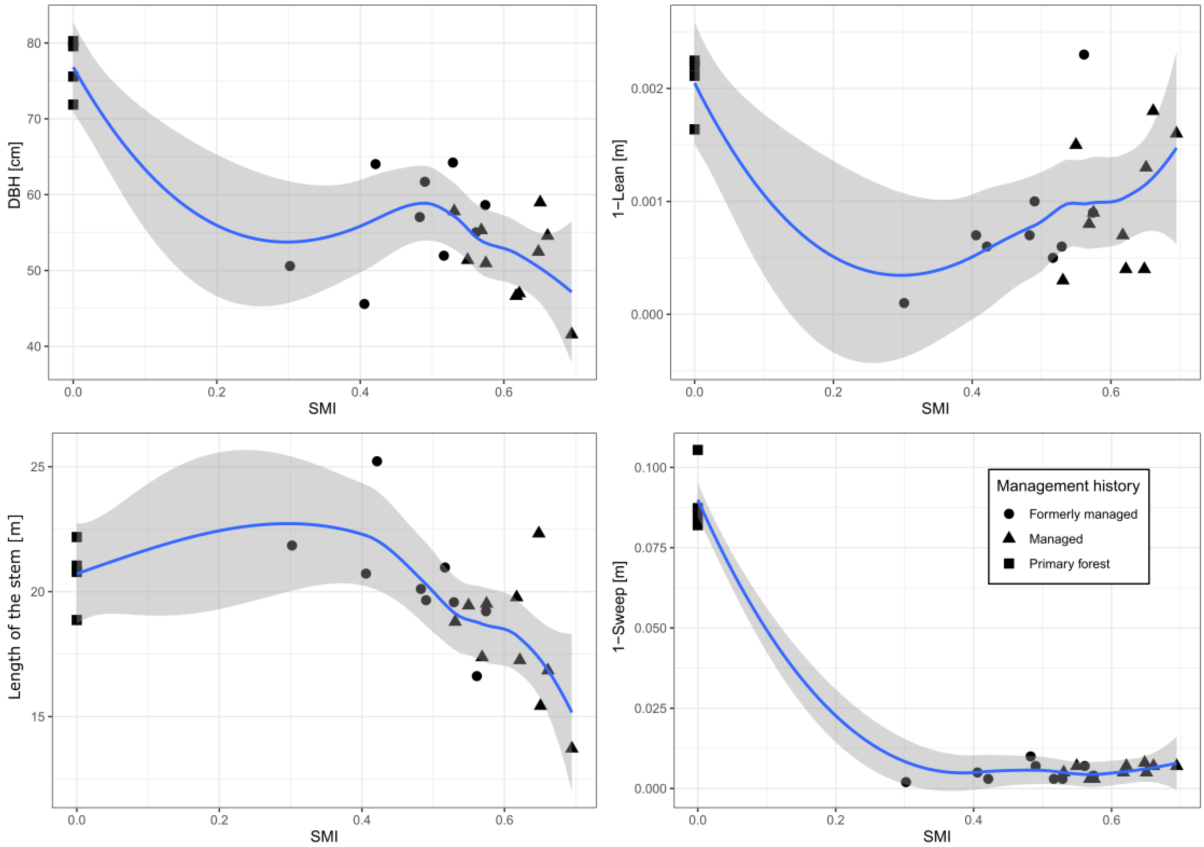

Figure 4.8 Scatter plots showing the shape of the stems of ten trees each from 23 European beech forests differing in their silvicultural management intensity (SMI). Markers indicate the mean of the ten stems for each study stand. The squares are the primary forests (n = 4), the dots show the formerly managed forests (n=9), and the triangles are the managed forests (n = 10). The smooth regression line is marked in blue and the confidence interval is highlighted by the grey area around it.

4.4 Discussion

4.4.1 Gradient of management intensity and structural complexity

Primary forests are characterized by a natural development with high structural complexity, without human influence (Brunet et al., 2010; Schütz et al., 2012; Trotsiuk et al., 2012). When investigating hypothesis (I: forest management can create structures that mimic structures observed in primary forest), we first ranked the study stands according to their management intensity using the silvicultural management intensity indicator. As the studied forests were selected solely based on their management history (primary forests: no management history; formerly managed: management was ceased at least 28 years ago; managed forests: still under management), it was surprising that the boundary between the formerly managed forests and the managed forests could be clearly drawn. Therefore, the investigated stands cannot be classified into only two management intensities. Consequently, instead of dividing the study areas into formerly managed and managed forests, they may be classified according to their management gradient. It is known that the structural complexity of forests is influenced by the intensity of management (Duncker et al., 2012; Puettmann et al., 2015; Ehbrecht et al., 2017; Stiers et al., 2020). Hence, not only the intensity of the forestry intervention is decisive for the comparison of managed forests with primary forests, but also the silvicultural treatment and the quantity of interventions. Silvicultural treatment methods, like shelterwood cutting or clear-cutting, result in large single-layered, evenly aged stands (Brunet et al., 2010). The formerly managed forests in this study showed such single-layered, even-aged structures (Figure 4.7). Since the last 40 years, treatments which led to single-layered structures and even-aged stands have increasingly been replaced by target diameter harvesting (Finkeldey and Ziehe, 2004; Schall et al., 2018). Repeated target diameter cuttings initiate the first phase in the creation of uneven-aged stands (Schall et al., 2018). The managed forests in this study contained such multi-layered, uneven-aged structures (Figure 4.7).

The comparison of the study plots with regard to their structural complexity revealed an increase with management intensity. Assuming that a higher intensity of a silvicultural treatment leads to fewer trees in the stand, this result is unexpected. Forestry interventions have the effect of lowering the structural complexity of forests at the time of tree removal (Neudam et al., 2023). However, the gaps created by tree removal can contribute to the development of additional stand layers. Intensive management interventions such as clear-cutting, where almost all stems are removed, can lead to higher species richness in the understory (Gossner et al., 2014) and promote shade-intolerant species (Coates, 2000). Also, natural regeneration is influenced by the dynamics of the overstory such as canopy openings and successive re-closure in European beech forests (Stiers et al., 2019). However, it should be noted that gaps above a size of 1000 m^2 lead to drastically changed conditions in the forest ecosystem (Yamamoto, 1992; Coates, 2000). The contribution of gaps in the total forest area of beech-dominated forests is given in the literature as 3-19 % (Nagel and Svoboda, 2008; Kenderes et al., 2009; Petritan et al., 2013; Feldmann et al., 2018). These gaps also occur in the course of natural processes of a beech forest due to the death of one or more trees (Drössler and von Lüpke, 2005; Bottero et al., 2011; Hobi et al., 2015). It can be assumed that the removal of individual trees or groups of trees resemble these "natural" processes in managed forests. The growth rate of the regenerating trees can be optimized through targeted canopy openings based on group, irregular, strip, or wedge shelterwoods and group-selection (Coates, 2000) and may emulate small-scale disturbance regimes and gap dynamics (Kuuluvainen et al., 2012; Zenner, 2016). This suggests that quantifying silvicultural management intensity alone is not sufficient to assess the naturalness of forest structures, as management can also promote natural dynamics and structures.

The absence of significant differences in structural complexity between the primary forests and the managed forests in our data is likely explained by the fact that the managed forests were managed according to a concept based on natural dynamics and structures. The applied silvicultural approach, i.e., variable density thinning, is intended to create and promote spatial heterogeneity that is characteristic for natural forests (Schütz et al., 2012). Close-to-nature forest management, for instance Continuous Cover Forestry, is distinguished by single-tree or group removal and leads to higher structural complexity in beech forests due to multi-layered and multi-aged stand structure (Brunet et al., 2010). Forests managed in this way can achieve structures almost as complex as primary forests (Stiers et al., 2020). For the investigated managed forests, management concepts based on natural structures and dynamics have had a positive effect on the structural complexity of the forests, accelerating the development of primary structures that would otherwise have taken a long time to develop (Stiers et al., 2018). The formerly managed forests were significantly different from the managed forests and primary forests in terms of structural complexity. About 40 years ago, the management in the managed forests was converted to near-natural and was abandoned in the formerly managed forests. In the managed forests, this included the removal of tree groups around the target trees and their subsequent removal as individual trees when the target diameter (55 cm DBH or larger for beech e.g. Finkeldey and Ziehe, 2004) was reached. Over decades, this led to a multi-layered stand structure in the managed forests (Schall et al., 2018; Stiers et al., 2020; Neudam et al., 2023) and thus to almost primary forest-like structures. It should be noted that the management of the formerly managed forests ended in the optimal phase, i.e., after the main growth phase and before the decay phase of the natural stand development, resulting in a persistent single-layered and even-aged stand structure that can only be enriched if adult trees die.

As a basic model of natural forest dynamics, Watt (1923; 1947) presented the concept of the forest cycle for deciduous forests. Here, the development phases *innovation, aggradation, early biostatic, late biostatic*, and *degradation* alternate continuously and asynchronously within the forest area, creating a changing mosaic of development phases (Watt, 1947; Emborg, 1998). The development cycle of a natural forest was also described by Leibundgut (1959) through various phases. These phases were classified by Korpel (1995) and Tabaku (2000) into growth, optimum, and breakdown (Kucbel et al., 2012; Stiers et al., 2018). Beech forests may reach an age of 200-300 years, in rare circumstances even 400 to 500 years (Korpel, 1995; Brunet et al., 2010; Trotsiuk et al., 2012). The dominant trees of the study stands were between 93 to 163 years old, which is probably still too young to initiate the decay phase with the death of trees. In comparison, according to Stiers et al. (2018) the primary forests in Rožok are between the optimal and decay phases, depending on their age, whereas Uholka has been in the decay phase for a long time. Without the removal of trees, no gaps have occurred in the managed stands so far. Due to the lack of light on the forest floor, no additional layers were able to develop, which led to these forests having a single-layered stand structure. Consequently, abandoning management will result in the persistence of structures for an unknown period of time in the absence of major disturbances. The formerly managed forests were abandoned from forestry decades ago and showed a lower structural complexity compared to the managed forests. This confirms the halted development of complex structures in the formerly managed forests. It might take hundreds of years for a previously managed or extensively disturbed forest to achieve multi-layered structures with a wide range of tree size and age (Trotsiuk et al., 2012). Our results also showed that there is a gap between the primary forests and the formerly managed forests in terms of their silvicultural management intensity indicator (see smoothed regression line in Figure 4.5). According to Rademacher et al. (2001) non-interventions must continue over several generations before primary structures can be achieved in beech forests. Thus, the method of abandonment is not a time-efficient way to achieve primary forest-like structures. In addition, the phase in which the forest is in its development should be taken into account. At some point, even forests abandoned from forestry interventions will return to primary forest-like structures, but the time is uncertain.

The distribution of plant material within the subdivided horizontal layers again revealed a difference between the studied forests. In near-natural temperate forests, where light is a limiting factor, it can be assumed that the plant material is vertically homogeneously distributed (Davi et al., 2008). It is to be expected that the plant material of primary forests is most homogeneously distributed compared to the other forests (Seidel and Ammer, 2023). The near-natural managed forests showed a homogeneous distribution of plant material within the stand, which is due to their multi-layered stand structure. The distribution of plant material in the formerly managed study stands is heterogeneous, which can be explained by the single-layered stand structure with a pronounced dominance of the upper canopy layer.

Consequently, forest management targeted towards natural forest development can result in structures resemble to those of primary forests (I). The analyzed stands showed that it is possible to resemble primary structures in managed forests under near-natural management. Such structures relate to an increased adaptive capacity and should therefore be promoted (Seidel and Ammer, 2023).

4.4.2 Management and shape of the stems

The shape of a tree's stem directly relates to the economic value of a tree (Knoke et al., 2006; Ammer, 2016), the abundance of microhabitats (Vuidot et al., 2011; Larrieu et al., 2022), physiological process in the tree, such as water conductance, as well as it's disposition to wind throw and other risks. Although the managed forests have structures similar to primary forests, the stem forms of the trees were significantly different from those of the primary forests. The stem form of the trees of the formerly managed forests also differed significantly from those of the primary forests. Accordingly, the second hypothesis, that management intensity affects the shape of the trees growing in a stand (II) could also be confirmed. The formerly managed forests had longer and straighter stem shapes, which is also due to the fact that they were abandoned by forestry interventions during the optimal phase. European beech trees show rapid height growth (Rozenbergar et al., 2007; Bottero et al., 2011) and reacts quickly to changes in light availability (Feldmann et al., 2018). The time span for the development of an understory layer is too short, as gaps in the canopy are quickly closed by horizontal crown expansion of neighboring beech trees (Feldmann et al., 2018). This leads to single-layered structures in the optimal phase of beech forests (Leibundgut, 1959; Scherzinger, 1996; Meyer, 2005). Due to the fact that the abandonment of forest interventions stopped the formerly managed forests in their development, they are still in the optimal phase. The trees of the primary forests, on the other hand, showed shorter and more curved stem shapes. This is due to the fact that beech trees lose their ability to form an upright stem when exposed to shade and competition for an extended length of time (Diaci and Kozjek, 2005; Rozenbergar et al., 2007; Bottero et al., 2011).

Despite the fact that the studied managed forests are similar to the primary forests in terms of structural complexity, the results showed differences in stem shape. The trees in managed forests and those in formerly managed forests showed similar stem shapes. This could confirm the assumption that the forests were managed in the same way at the beginning of their development. The trees from the dominant stand layer used for the comparison of stem shape therefore had the same shapes in both management types. Despite genetic predisposition, the stem quality is influenced by stand structure and stocking density, which control local competition intensities (van Leeuwen et al., 2011; Merganič et al., 2016; Höwler et al., 2017). The management of a forest thus has an influence on the stocking density and competition and can control the quality of the wood (Pretzsch, 2009). Higher competitive pressure leads to increased self-thinning and thus also to higher stem diameter and lower branchiness (Hein, 2008). The shape and length of a stem, as well as branchiness and branch diameter, are quality characteristics that considerably influence the value of the wood and can be controlled by stocking density and competition (Hein, 2008; Höwler et al., 2017). Larger stem diameters and dimensions increase the quality of wood and usually lead to rising timber prices (Knoke et al., 2006; Ammer, 2016). The management history of the study stands suggests that the focus was on the quality of the timber. The stems had a very straight stem shape and showed a high branch-free stem length up to the crown. Since the abandonment of forest interventions in the formerly managed stands, the stems have become even longer. The near-natural management concept of the managed forests has reduced the competitive pressure among the beech trees of the upper stand layer, which has resulted in increased stem diameters. Our data showed that with appropriate management, it is possible to promote natural structures and at the same time produce high-quality timber (long and straight stems without branches). Considering that near-natural management is not only about being "natural" but also about managing, it is important to produce high-quality timber. With our rugged landscape and limited space, it is important to treat the existing forest as efficiently as possible. Closeness to nature should always be the priority, but timber usability should also be ensured to reduce the need for timber import.

4.5 Conclusion

Although the trees of a comparatively young forest do not yet have the overall dimensions of trees from primary forests, it is nevertheless possible to achieve primary forest-like structures through targeted near-natural management. We can assume that the primary forest data of the present study were representative for primary beech forests in Central Europe. They showed the same age distribution and structure characteristic of primary forests in the literature. For some years now, Germany has been pursuing the goal of using forests as close to nature and as sustainably as possible (near-natural forest management). The data from the laser scanning made it possible to quantify the stand structure of primary forests and to compare this with data from forests where forestry interventions were abandoned and forests that are still managed under the close-to-nature paradigm. Although forests managed under this close-to-nature approach do not have the stem shapes as primary beech forests, they can nevertheless achieve similar structural complexity. Accordingly, it is possible to resemble primary forest-like structures through near-natural management. Assuming that forests with high structural complexity are better adapted to disturbances, it is of great advantage to improve the structural complexity of forests under management.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Liane C. Neudam: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. Kirsten Höwler: Methodology, Writing – review & editing. Dominik Seidel: Conceptualization, Software, Writing – review & editing, Supervision.

DECLARATION OF COMPETING INTEREST

The authors declare the following financial interests/ personal relationships which may be considered as potential competing interests: Liane Neudam reports financial support was provided by Fachagentur Nachwachsende Rohstoffe eV.

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Chapter 5

Synopsis

Considering the general hypotheses of this doctoral thesis:

(I) Laser scanning technology is sensitive enough to quantify changes within one year in the structural complexity of European beech forests to allow efficient and objective monitoring of forests for example with respect to climate change.

(II) With the help of math-based fractal analysis, it is possible to simulate silvicultural treatments on real forest data in order to quantify their effects on structural complexity even before they are implemented in practice.

(III) The laser scanning approach provides a way to evaluate different management concepts, which offers an advantage in making decisions for future silvicultural treatment.

the results of the three preceding research studies (chapters 2, 3, and 4) are summarized and discussed in the following chapter. Thereby, the laser scanning method is critically reviewed, the influence of management on structural complexity is evaluated, and an outlook for further research is given.

5.1 Possibilities and limitations of laser scanning to quantify structural complexity

As a basis for the monitoring and management of forests, information on their current state is needed. For this purpose, the forest field inventory is usually used as the most important instrument to capture the forest dynamics, structure, and distribution over time (Liang et al., 2018). Since an inventory of all trees would be too time-consuming, several sampling circles are usually established across an area of interest. Data collection on plot-level is then used to estimate stand summary measures, such as basal area, stem density or volume, or to calculate structural indices quantifying structural complexity (Newnham et al., 2015; Bauwens et al., 2016). As information on tree characteristics such as species, age, height, number, DBH, and health status are usually recorded manually. A repeated assessment of established sample plots may be used to analyze forest dynamics and can thus be used for national (BMEL, 2015; Lorenz et al., 2018) and international (Oberthür and Ott, 1999) reporting (Newnham et al., 2015). However, the number of field inventories is limited by the time and costs involved in individual manual measurements. The efficiency of new techniques and instruments is therefore a top priority. The use of laser-based measuring instruments revolutionized the possibilities of remote sensing and enabled the forest inventory to digitize forests more accurately, quickly, and automatically.

According to Liang et al. (2018), the first terrestrial laser scanner was used for remote sensing in 1998 and since then the technology in terms of size, weight, scanning performance, and price has developed rapidly. For example, the scanners used in the present studies measure several million points per second at a measuring distance of up to 100 m with a scanning accuracy of up to 30 mm (see chapter 2, 3, and 4). New technologies must bring an additional value compared to existing technologies in order to be accepted in practice (Liang et al., 2018). Laser scanning offers new possibilities to quantify the structural complexity and thus the three-dimensional distribution of plant material using mathematically based fractal analysis (e.g. Seidel, 2011; Bauwens et al., 2016; Ehbrecht et al., 2016; Willim et al., 2019). It makes it possible to assess competition within a stand (Seidel et al., 2015; Olivier et al., 2016), records details of the tree architecture and consequently provides a quick insight into the relationship between structural complexity at single-tree level (Liang et al., 2018; Dorji et al., 2019) and structural complexity at stand level (Seidel et al., 2019).

However, the scan shows exactly the forest image that the scanner captured, so that occlusion, inhomogeneous point densities, and noise in the data set can be a challenge. The scanner's perspective on the forest is a limiting factor if leaves, branches, trunks, or other plant material are not scanned, as they are obscured by other elements closer to the scanner (Dassot et al., 2011; Bayer et al., 2013; Bauwens et al., 2016; Liang et al., 2018; Campos et al., 2020). In dense stands, the occlusion effect due to shadowing for that reason increases and information that was not visible to the scanner can be lost. In consequence, it is possible that the actual complexity is underestimated (Seidel et al., 2019). When capturing individual trees, the occlusion effect can be reduced and the result improved by minimizing the distance between the scanner and the scanned object (van der Zande et al., 2010; Astrup et al., 2014; Béland et al., 2014; Zhao et al., 2015), by high scanning resolution (Arseniou et al., 2021), and high laser beam density (Ehbrecht et al., 2016), or by making subsequent corrections to the scan data (Lovell et al., 2011; Seidel and Ammer, 2014; Ehbrecht et al., 2016). In our first study, we investigated the effect of leaves (emergence vs. fall) on forest structural complexity and analyzed the potential of the laser scanning approach (here: MLS; see chapter 2). Our results showed that repeated scans on the same plot and at the same time provided reliable results and allowed quantification of seasonal changes in structural complexity of forests if the measurement methodology (walking direction through the forest scene) was standardized. Increasing sampling intensity from varying directions led to different perspectives on the forest stand and could hence also reduce the occlusion effect. Using the mobile laser scanning method, the forest stand was also scanned from different perspectives (see chapter 2). Nevertheless, ground-based scanners are limited to the view below the tree crown (Krooks et al., 2014). It therefore remains questionable how much information about the crown could be lost.

Mathes et al. (2023) quantified the occlusion effect by comparing ground-based and aerial scans and found that this effect was relevant for the crown architecture measurements of trees. When processing the data at stand level, it is possible to select the voxel size for quantifying structural complexity in such a way that the occlusion effect is reduced while retaining sufficient detail (Béland et al., 2014; Mathes et al., 2023). In order to avoid leaf occlusion effects in deciduous forests, it is also possible to scan them only in "leaf-off" conditions, as this allows a better assessment of the canopy architecture (Arseniou et al., 2021). We found that laser scanning was sensitive enough to detect such changes in structural complexity due to seasonal variations (I; see chapter 2).

Consequently, laser scanning is a method of forest inventory that enables millimeter-precise, rapid, automatic, and detailed digitization of forests (Liang et al., 2018). Based on the literature the laser scanning method is suitable for quantifying changes in the structural complexity of forests in an efficient and objective way (Dassot et al., 2011; Atkins et al., 2018; Stiers et al., 2020; Willim et al., 2020; Arseniou et al., 2021; Dorji et al., 2021; Ehbrecht et al., 2021; Seidel and Ammer, 2023). Thus, laser scanning provides the basis for forest monitoring that could decide on their planning, control, and management. The application of laser scanning in forest inventories is particularly limited by the factors of accuracy, cost, and ease of use (Liang et al., 2018). According to Holopainen et al. (2013), data collection and the automation of processing are constantly evolving. For example, attempts are currently being made to address the challenging task of automatically recognizing tree species from laser scan data using deep learning (Guan et al., 2015; Seidel et al., 2021; Liu et al., 2023; Mokros and Kottilapurath Surendran, 2023). The weight of the scanners has been reduced in recent years, making them easier to handle, their use has been simplified, and the availability of processing software has been increased. Recording all forest landscapes is currently very time-consuming, as it requires extensive data processing. It can be assumed that laser scanning technology and the processing of point clouds will continue to develop. One advantage of the technology is already the ability to detect changes in structural complexity based on repeated scans, enabling large-scale global monitoring.

5.2 Comparison of different management concepts of beech forests

The forest inventory provides information on the condition of the forests. It is then a matter of recognizing and classifying changes, on the basis of which the future of the stand can be planned. The quantification of the stand structure enables an objective comparison of forests and also an assessment of the previous management history. This can be used in practice to answer questions about how close to nature the forest structures are, what needs to be changed, and what should remain. Research is being conducted around the world to propose innovative ways of managing forests to provide a wide range of services and biodiversity on the one hand, and greater resilience and adaptability on the other (e.g. Kuuluvainen et al., 2021; Aszalós et al., 2022). Forest scientists are focusing on the development of forest management techniques that are based on the dynamics of „natural" forest ecosystems (e.g. Puettmann et al., 2015).

As mentioned in the introduction to this doctoral thesis, despite its competitiveness and large ecological amplitude, it is unclear whether beech can adapt to a rapidly changing climate (see chapter 1.1.1). The IPCC's climate projections indicate that heatwaves and droughts will become more frequent (Intergovernmental Panel on Climate Change, 2021). Bolte et al. (2007) assume that the beech will spread to new areas towards Scandinavia, the British Isles and the Baltic States as a result of the warming and extension of the growing season. In southern Europe, the southern edge of its distribution, the beech will retreat to higher mountain areas due to rising temperatures and more intensive dry phases (Peñuelas and Boada, 2003). In Central Europe, a warming and lengthening of the growing season with higher precipitation could have a positive effect on growing conditions on the one hand, while on the other hand more frequent and more intensive dry phases could lead to an increased risk of drought. A combination of higher beech productivity and a simultaneous increase in the risk of drought stress and branch dieback is also possible (Bolte et al., 2007). Typically, beech responds to drought with a more pronounced reduction in growth in the year following the drought event (Granier et al., 2007). These drought-related changes in structural complexity can be determined with the help of laser scanning (Heidenreich and Seidel, 2022). Research has shown that beech is adaptable to environmental changes due to its phenotypic plasticity (e.g. changes in shoot:root ratios, or pre-senescent leaf fall; Leuschner, 2020). According to Thiel et al. (2014) and Dounavi et al. (2016), populations or origins from drier regions usually cope better with drought. Even if the drought in the years 2018 and 2019 led to increased beech mortality in southern Germany, the risk can be countered by the targeted selection and propagation of more drought-hardy genotypes and the promotion of mixed stands (Bolte, 2016). Leuschner (2020) concluded from several studies that beech is less susceptible to drought than *Acer pseudoplatanus* and *Picea abies*, but more drought-sensitive than many other deciduous trees of the *Quercus, Carpinus, Thilia, Sorbus, Fraxinus*, and individual *Acer* species. Mixed stands increase the structural complexity of a stand through variations in the tree architecture of different species. Forest management enables the control of competition and light conditions (Bolte et al., 2007) and can therefore have both positive and negative effects on the resources of the European beech. The choice of forest management concepts will become more important in view of the predicted climatic changes and the associated increase in drought, and must offer solutions as quickly as possible.

To answer the question, which management method is most suitable to maintain a high structural complexity and achieve the highest possible net return, we simulated and evaluated different silvicultural treatments based on 3D point clouds (see chapter 3). Our results showed that each treatment initially led to a decrease in structural complexity at the time of harvest. However, no contradiction was found between the objectives of keeping structural changes to a minimum and achieving the highest possible economical gain. The simulated treatments "group cut" and "shelter cut" showed minor changes in structural complexity with simultaneously high net returns. In both treatments, individual trees and small groups of large trees (trees with diameter greater than 85 % diameter quantile; see chapter 3.2.4) were removed. As already indicated in the introduction, these treatment methods are also frequently used for beech forests in order to reproduce natural disturbances and regeneration processes (Ammer et al., 2018) while at the same time ensuring high wood quality (Messier et al., 2015). Single tree and group selection and irregular shelterwood cuttings based on target diameter distribution with small- to medium sized openings, led to an uneven-aged and multi-layered forest structure.

We initially hypothesized that it is possible to simulate silvicultural treatments on real forest data to quantify structural complexity with the help of math-based fractal analysis (II). Depending on the respective silvicultural treatment, we found a varying negative influence of different treatments (at the time of harvest) on the structural complexity of the forests. Fractal analysis enables 3D forest data to be processed and the spatial structure of forests to be quantified in a single number. This offers the possibility to evaluate treatments with real forest data before their practical implementation.

The treatments simulated in the study evaluated the change in structural complexity immediately after the interventions and could not make any statement about the long-term effects on how the forest stands will develop in the future (see chapter 3). For the evaluation of a silvicultural concept, however, it is also necessary to include future forest development (Coates, 2000). For this purpose, several models have been established in the past that simulate the growth of trees and thus predict their development also with regard to climate change (e.g. Döbbeler, 2004; Baumbach et al., 2019; Del Martinez Castillo et al., 2022). More recent approaches combine structural data with ecosystem process models and climate data (Seidl et al., 2012; Ammer et al., 2018). Against this background, we asked the question whether it is possible to use the laser scanning approach to compare forests with each other in terms of their structural complexity and hence to evaluate their previous silvicultural treatment (III). Based on the assumption that primary forests best represent the natural processes of a forest, we used scan data of primary forests from another project to compare the study areas of the present thesis with regard to their “naturalness”. On this basis, we were able to evaluate the management history of the forests and consequently critically assess their management concepts. Our results from chapter 4 showed that even if the studied managed forest stands do not have the shape of primary forest trees at individual stem level, they can still achieve primary forest-like structures at stand level. For this reason, it is possible to manage forests in such a way that they resemble the natural structures of real primary forests. These structures are characterized by a multi-layered canopy, a high number of mature trees, and a high variation in tree size and age (Brunet et al., 2010; Schütz et al., 2012; Trotsiuk et al., 2012) and can so be expected to be highly stable, biodiverse, and adaptable (Stiers et al., 2018; Seidel and Ammer, 2023).

We can conclude, that laser scanning offers the possibility to quantify the structural complexity of forests related to many ecosystem functions and services. This makes it possible to compare different forests and management concepts. Using fractal analysis based on real forest data, it is possible to simulate the effects of silvicultural treatments. In that account, depending on the silvicultural objective, the most suitable treatment can be selected before implementation in practice. Furthermore, it is possible to evaluate already treated forests with regard to their structural complexity and to adapt their silvicultural concepts if there is a need for action. In the future, forests could be monitored and evaluated across the board, which could help to keep an overview of changes in forest ecosystems in view of a rapidly changing climate.

5.3 Influence of management on structural complexity

The primary objective of forest management should be to preserve the forest ecosystem. Sustainable forest management is possible by creating complex forest structures and thereby adaptable forests. Structural complexity has a direct influence on forest ecosystems. This includes the resilience of the forest (e.g. D'Amato et al., 2011; Ehbrecht et al., 2017), resistance (e.g. Knoke and Seifert, 2008), the biodiversity (e.g. Neill and Puettmann, 2013; Bohn and Huth, 2017; Lelli et al., 2019), the stability of the ecosystem (e.g. Messier et al., 2015; Bauhus et al., 2017), and microclimatic regulation (e.g. Ehbrecht et al., 2019; Seidel et al., 2020), as well as forest productivity (Gough et al., 2019). It is therefore ideally suited as a measure for evaluating forests, and could help to deal with uncertainties under the observed and modeled climate trends. The aim of the subproject on which the present thesis is based was to quantify the stand structure of mature beech forests and evaluate the horizontal and vertical distribution of the plant material of forests with different management history. Based on the scans from the 19 study plots in February 2021 with the mobile laser scanner, we found no relationship between the structural complexity of the stand (D_b) and stem density, or the coefficient of variation (CV) of tree height. However, the test of the relationship between CV of DBH and D_b was significant (Figure 5.1). An increase in the CV DBH means a greater variance in the diameter at breast height, i.e. trees with different dimensions. Consequently, these also have a higher structural complexity.

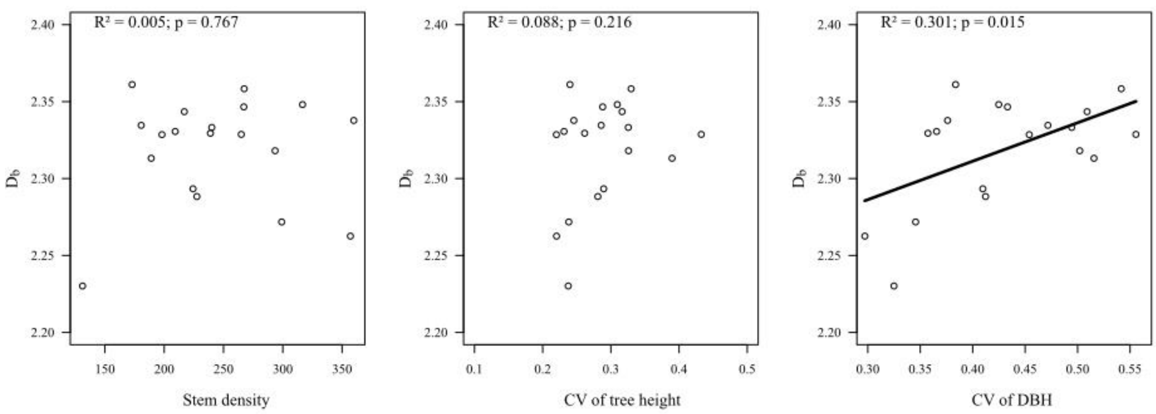

Figure 5.1 Relationship between the stand characteristics a) stem density (number of trees per ha); b) CV (coefficient of variation) of tree height; c) CV of DBH (diameter at breast height) and stand structural complexity, expressed as box-dimension (D_b) from 19 study plots.

It is known that the management of forests can regulate competition and light supply, for this reason having a direct influence on the diameter growth of trees. The diameter distribution of a stand in turn has a direct effect on the structural complexity (see Figure 5.1). This relationship can be confirmed by many studies (e.g. Brunet et al., 2010; Dassot et al., 2011; Duncker et al., 2012; Ehbrecht et al., 2016; Höwler et al., 2017; Juchheim et al., 2017; Calders et al., 2020; Guzmán et al., 2020; Willim et al., 2020; Heidenreich and Seidel, 2022; Seidel and Ammer, 2023). The aim is to increase structural complexity, i.e. uneven-aged stands with a reverse J-shaped diameter distribution (many small and few very large mean diameters; e.g. Westphal et al., 2006; Ehbrecht et al., 2019). This can be achieved by single tree selection or group selection (e.g. Pommerening and Murphy, 2004; Schütz et al., 2012; Puettmann et al., 2015; Schall et al., 2018). For some years now, this goal has also been prescribed in many management guidelines and directives for the management of forests in Central Europe and America (e.g. Messier et al., 2013; Ehbrecht et al., 2019).

Another method being discussed is the abandonment of forest management. Forests in Europe that are no longer managed, called “Naturwaldreservate” or “Strict Forest Reserves”, are intended to serve as reference for natural forest dynamics and as a substitute for primary forests (Meyer, 2005). According to Stiers et al. (2020), the abandonment of management in the optimum phase of the forest, after the main growth stage, leads to an extension of the period for entering the structurally more complex decay phase. We observed the same results in our study plots (see chapter 2,3, and 4). Moreover, close-to-nature managed study plots showed more primeval forest-like structures than the plots where management had been abandoned for 28 to 100 years (chapter 4). This shows that a potentially long period of low structural complexity can be counteracted by silvicultural management methods such as close-to-nature management. This knowledge could be used to increase the structural complexity of forests before they are abandoned by creating gaps such as those found in primary forests (Stiers et al., 2018). To summarize, silvicultural methods can accelerate or slow down development of specific forest structures. Besides to the location, the phase of development of the forest and the intensity of the silvicultural intervention (from no management to intensive management) are decisive factors.

Laser scanning offers the possibility of quantifying other ecosystem services as well as the information from traditional timber-based inventories. According to Knoke et al. (2021) these can include forest attributes that promote carbon storage, biodiversity (such as habitat trees and natural clearings), and recreational opportunities (factors such as open water bodies and soil damages). The use of laser scanning technology makes it possible to integrate these ecosystem services and biodiversity into future forest inventories (Liang et al., 2014).

The influence of management on structural complexity thus also has a direct impact on the entire forest ecosystem and its functions. Many projects are investigating the extent of this influence and how exactly the interrelationships work. Understanding the forest as a complex ecosystem is necessary to understand the spatial consequences of fragmentation, habitat loss and the surrounding matrix and to develop effective conservation strategies (Ammer et al., 2018). In addition to conventional timber production, the objectives of forest management can also include carbon storage or sequestration, the preservation of habitats and the creation of recreational and aesthetic opportunities (Vauhkonen, 2018). Quantifying structural complexity at the level of individual trees and stands is an important tool for future forest planning.

5.4 Forestry 4.0

For further forestry planning under the rapid and extreme changes in climate, it should be an encouragement for us all to use our resources to gain the necessary knowledge. The technical possibilities in forestry have changed rapidly in recent years. Using information technologies (IT), tasks can be transferred from humans to computers, performed by algorithms, work processes accelerated with the help of computer programs, and improved by artificial intelligence (AI). Digitization offers the opportunity to optimize processes and to obtain and handle more information about the forest. It is possible to quantify the structural complexity of forests using 3D point clouds from laser data and use this to monitor development and evaluate forests. The structural complexity could also be used as an indicator of its adaptability (Seidel and Ammer, 2023). Against the background of predicted climatic changes, this is the key factor in protecting and preserving the forest ecosystem. Human-induced climate change is accelerating changes in long-term temperatures and weather patterns. In order to increase the adaptability of forests, it is first necessary to get an unbiased overview of the current state of the forests and to have an instrument that can directly measure the smallest changes. Then is it possible to improve the structure of forests in a targeted manner in order to prepare forests for the uncertain future environment (Seidel and Ammer, 2023). With the help of NASA’s Global Ecosystem Dynamics Investigation (GEDI), a space-based lidar mission in the orbit around the International Space Station (ISS), it is even possible to assess the structural complexity of forests on a global scale (e.g. Hancock et al., 2019; Duncanson et al., 2020; Schneider et al., 2020). The use of deep learning makes it possible to recognize tree species (e.g. Seidel et al., 2021) and the newest developments combine two measurement methods (mobile and stationary flash scans, see FARO Orbis; FARO, 2023) in one scanning device or make it possible to record data using smartphones applications (e.g. new iPhones with LiDAR sensors; Mikita et al., 2022). New scanners with even higher resolutions produce such a detailed image of the forest that the smallest changes in the structural complexity of forests can be detected. To give a few instances of how technology has evolved and still grows.

In order to overcome the challenges of climate change on a global level, it is necessary to combine the expertise of different research disciplines, work together with practitioners on an interdisciplinary basis, and be open to new technologies.

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List of publications

In the following, all publications are listed that were produced during the PhD program. In addition to the three first authorships used for this dissertation, there are five co-authorships in which colleagues from the same research group as well as from other universities and projects were supported:

Journal articles

Annighöfer, P., Stiers, M., Seidel, D., Willim, K., **Neudam, L.**, and Ammer, C. (2021). Über die Quantifizierbarkeit der 100-jährigen Dauerwaldidee. *AFZ Der Wald*, 23–27.

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Declaration of honor

I, Liane Carolin Neudam, declare that I independently prepared this dissertation entitled "From points to forests – The potential of 3D point clouds to evaluate the structural complexity of differently managed beech forests" and that I did not use any literature or resources other than those indicated. I further declare that the digital version is identical with the printed version in content and wording.

Additionally, I confirm that this dissertation has never been submitted in any form as part of any other dissertation procedure

Liane Neudam

Göttingen, 15. Februar 2024