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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.

1. Introduction

Forests provide many different functions and services. Both national and international policy guidelines suggest to facilitate multipurpose 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

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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, 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.

2. Materials and methods

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; Fig. 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 (Fig. 1).

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 Fig. 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 9953.97 to 21934.42 m^2 (mean ± standard deviation: 15271.04 ± 3544.77 m^2).

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. 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.

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 ($n = 19$), modeling 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 modeling runs. Every modeling 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

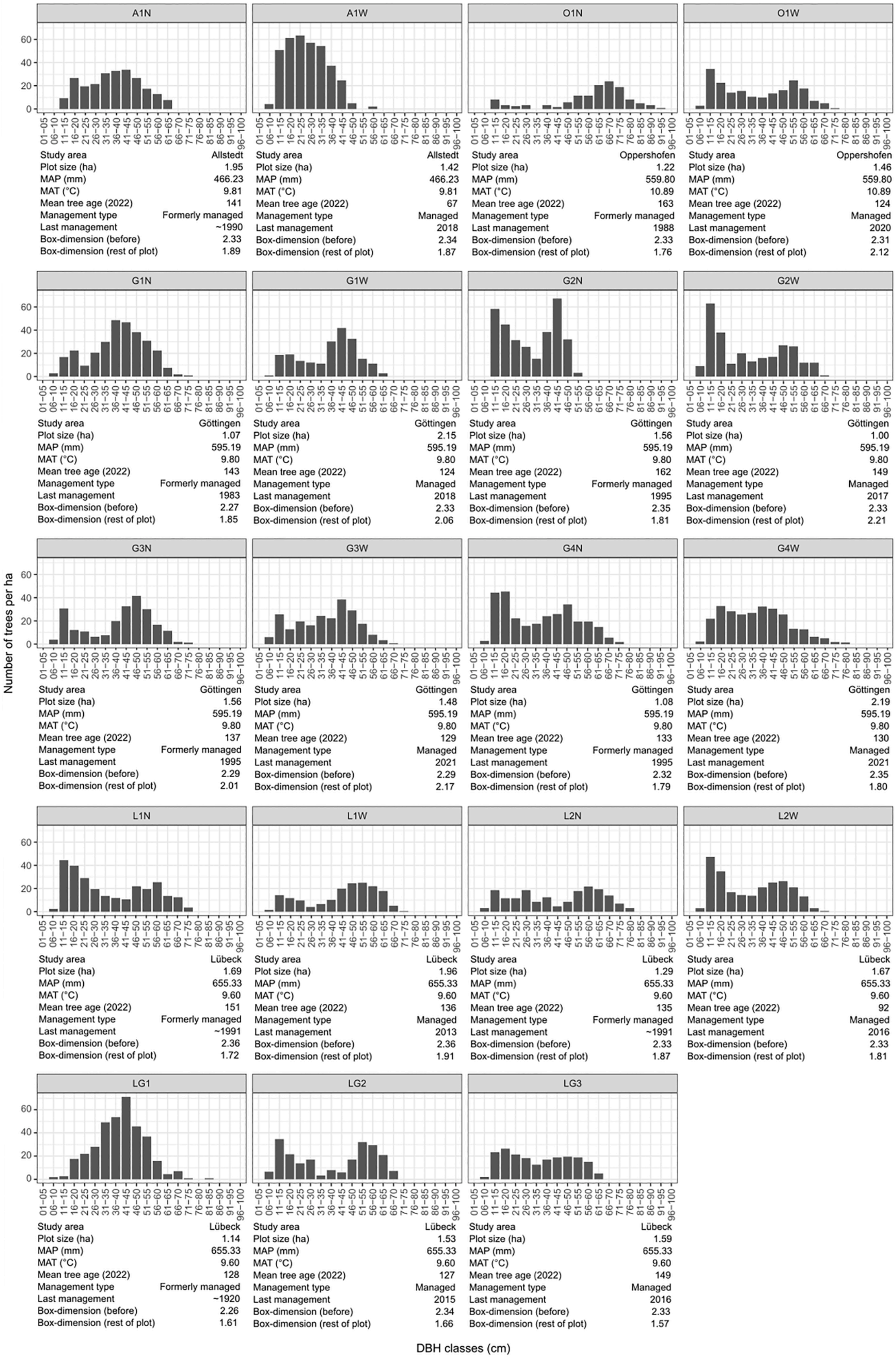

Fig. 1. Diameter distributions, climatic and geographic conditions of the study areas, average age of the study stands and their structural complexity (box-dimension before=structural complexity prior to simulated silvicultural interventions; box-dimension rest of plot = structural complexity of the understory and ground). MAP = mean annual precipitation (2010–2020); MAT = Mean annual temperature (2010–2020).

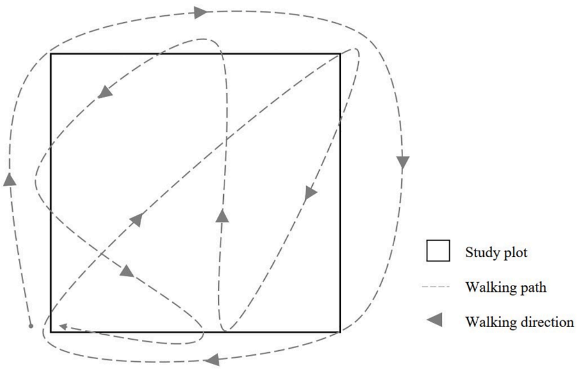

Fig. 2. Standardized measurement scheme applied to all plots indicating the trajectory (walking path) within the plot margins and the walking direction. After defining a starting point at a random plot edge and marking it temporarily (e.g. by placing a backpack or a cap on the position) the scanner was 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).

the following, each silvicultural intervention applied is briefly described and visualized in Fig. 3. Fig. 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.

2.4.1. 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.

2.4.2. 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 Fig. 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 1000 m^2 (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.

2.4.3. 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.

2.4.4. 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 m^2 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.

2.4.5. 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 Fig. 3) in order to provide a solid database for an

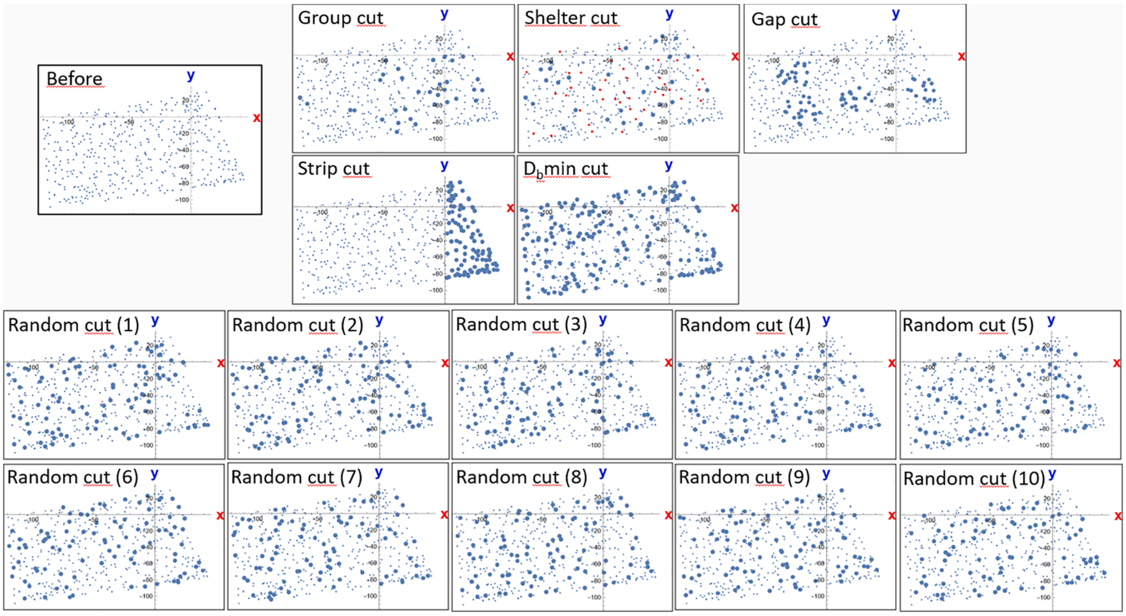

Fig. 3. Visual overview of the virtual silvicultural treatments as applied to an exemplary plot (L1N). For each treatment, all trees in the plot are shown as small dots and the harvested trees as larger dots. For *shelter cut*, red dots indicate retained shelter trees.

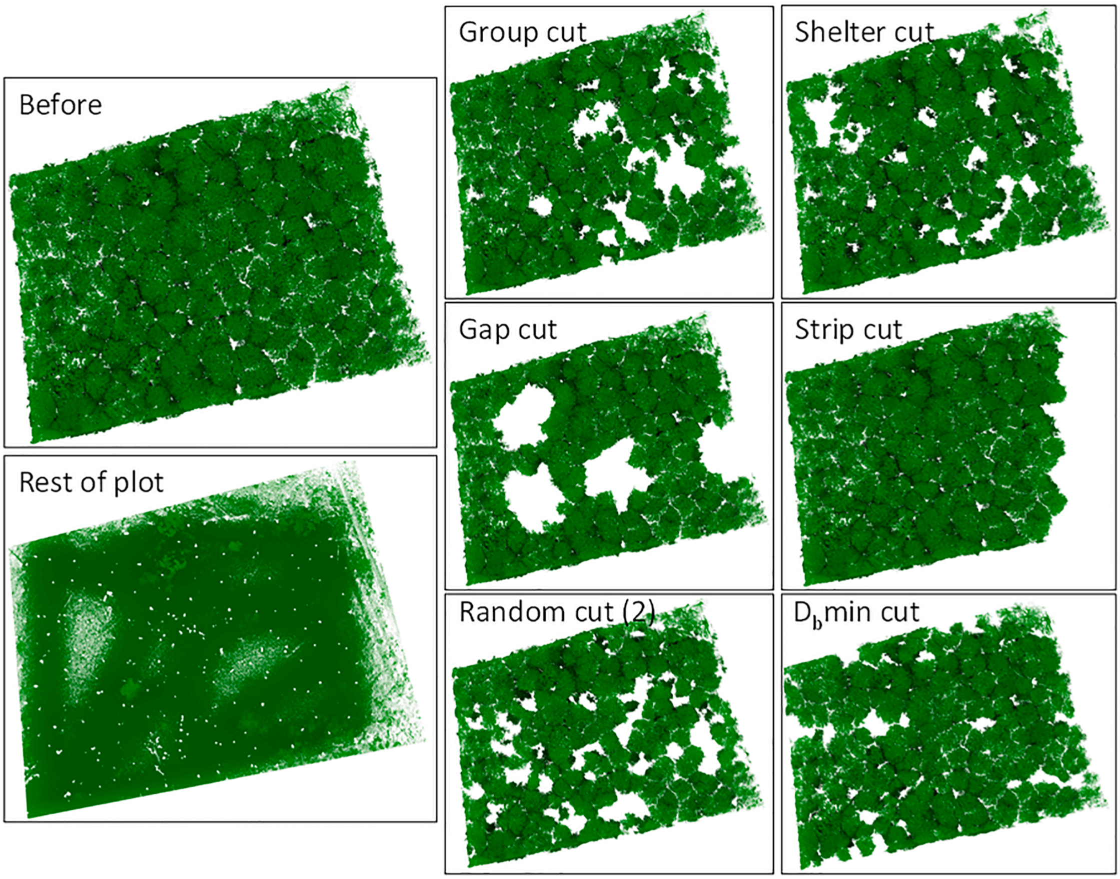

Fig. 4. 2D representation (top view) of the 3D point cloud of exemplary plot L1N before the treatments, and after applying *group cut, shelter cut, gap cut, strip cut* and D_b min *cut*, as well as after one of the ten *random cuts*. For comprehensiveness, the 'rest of plot' data, containing all shrubs, ground, downed wood which were not classified as trees by LiDAR360 is also displayed.

evaluation of this approach when compared to others.

2.4.6. 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).

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.

2.6. Statistical analyzes

To test for differences of the mean stand structural complexity, expressed as D_b, before and after treatment, we analyzed 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 analyzed 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 analyzes for this study were carried out in the R software language, version 4.1.2 (R Core Team, 2021). Statistical significance was assessed at $p < 0.05$.

2.7. *Economic consequences of 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 calcula,ted, as,:

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

For the virtual treatments on our plots, the resulting net revenues for the volume over bark ranged from 19.2 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 to 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. Results

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 (Fig. 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* (Fig. 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.

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 (Fig. 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*.

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* (Fig. 8). However, the differences were not statistically significant.

3.3. *Quantification of the 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 (Fig. 9). Interestingly, the latter were all significantly different from each other.

The net revenue of the treatment *minimum complexity cut* was lowest

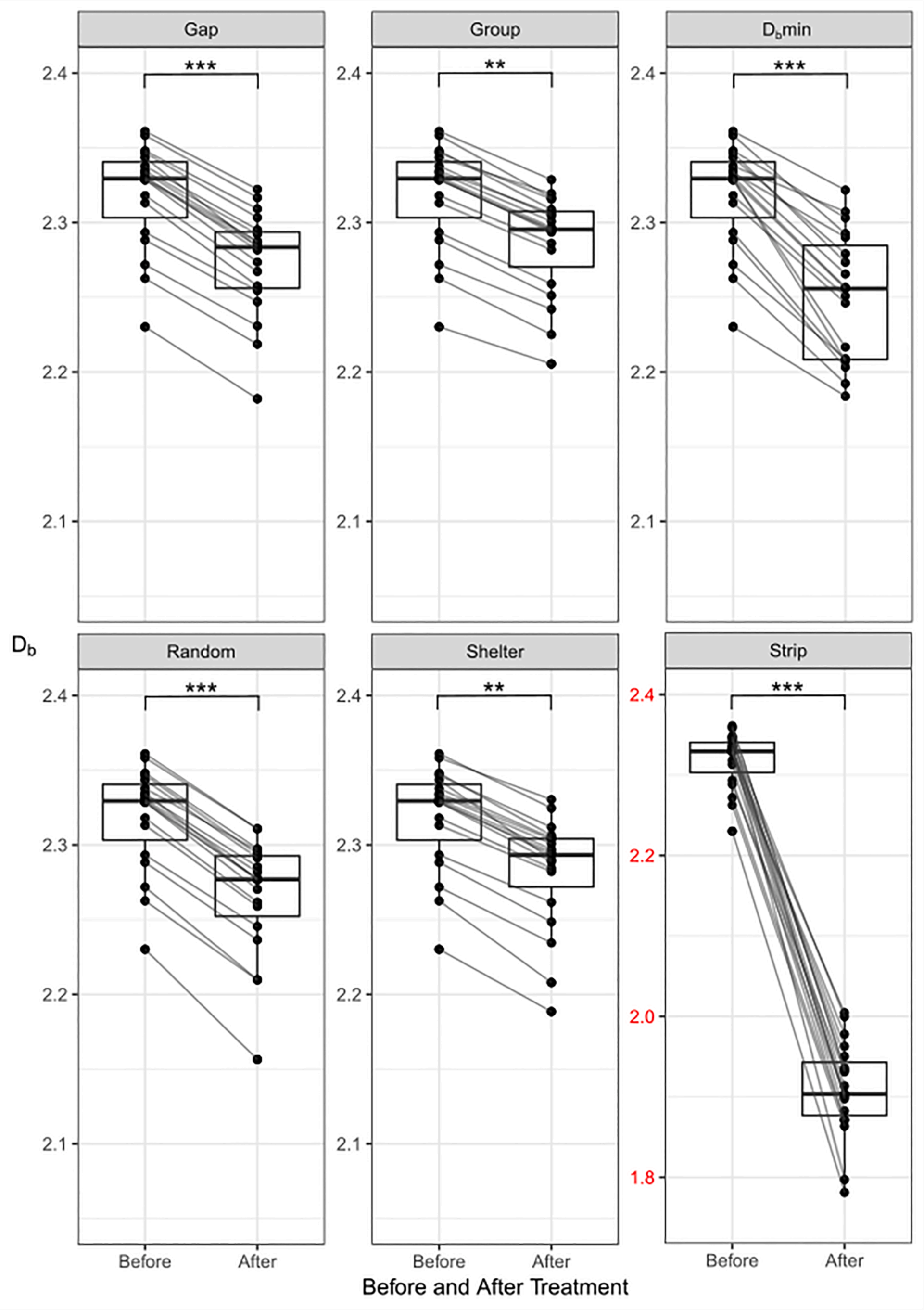

Fig. 5. Box-Whisker plots of stand structural complexity, expressed as box-dimension (D_b), before and after the treatment for all 19 study plots and each of the six treatments. The ten different *random cuts* were averaged per plot and averaged to one value. The differences in the scale needed to illustrate 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 $p < 0.001$ (***).

and differed significantly from the treatments *group cut* and *shelter cut*. No other significant differences between treatments were observed (Fig. 10a). The differences between the economic consequences of the silvicultural treatments even decrease when analyzing our predicted short-term net economic gain (Fig. 10b) instead of the direct net revenues. The income from harvesting can be invested in other projects (gain in income from interest in Fig. A1, Appendix). 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 Fig. A1, Appendix). Under our assumption of an interest rate of 1.5%, the *group cut* has the highest median for the resulting net economic gain (Fig. 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 Fig. A2, Appendix. 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 (Fig. A2, Appendix).

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 (Fig. 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*

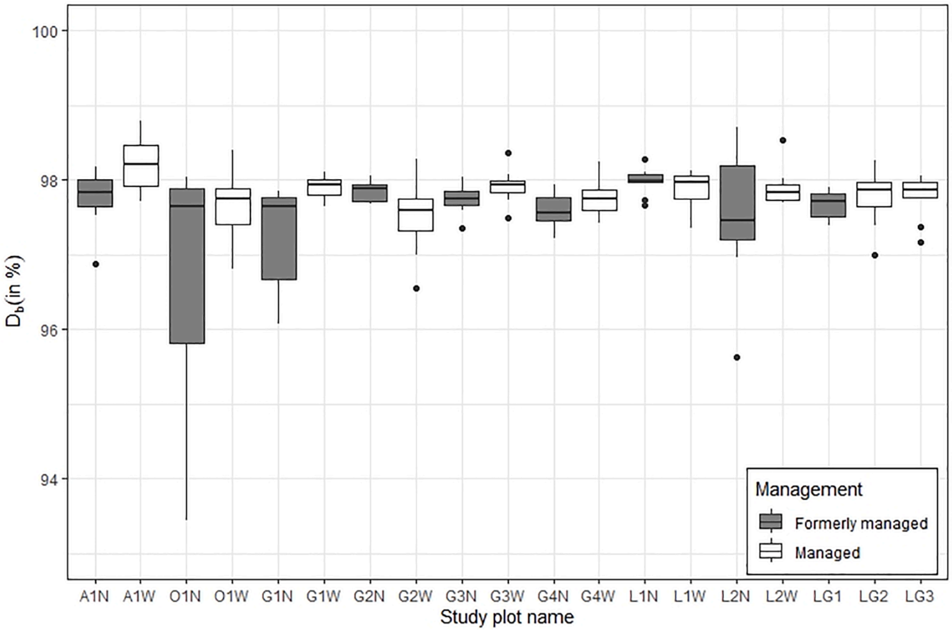

Fig. 6. Box-Whisker plots of the structural complexity, expressed as box-dimension (D_b), after the ten simulations of the treatment *random cut* in percent of the structural complexity before the treatment for all 19 study plots and shown separately for the management status.

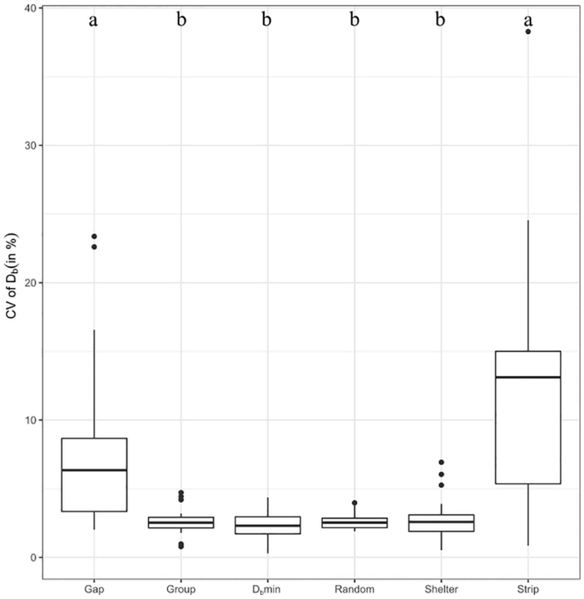

Fig. 7. Box-Whisker plots of the coefficient of variation of the remaining structural complexity, expressed as box-dimension (D_b), for all 19 study plots after the treatments. The ten different treatments *random cut* were averaged per plot and combined as one. Black horizontal lines indicate the median. Different lowercase letters indicate significant differences among the conditions at the level of $p < 0.05$.

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.

4. Discussion

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, 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

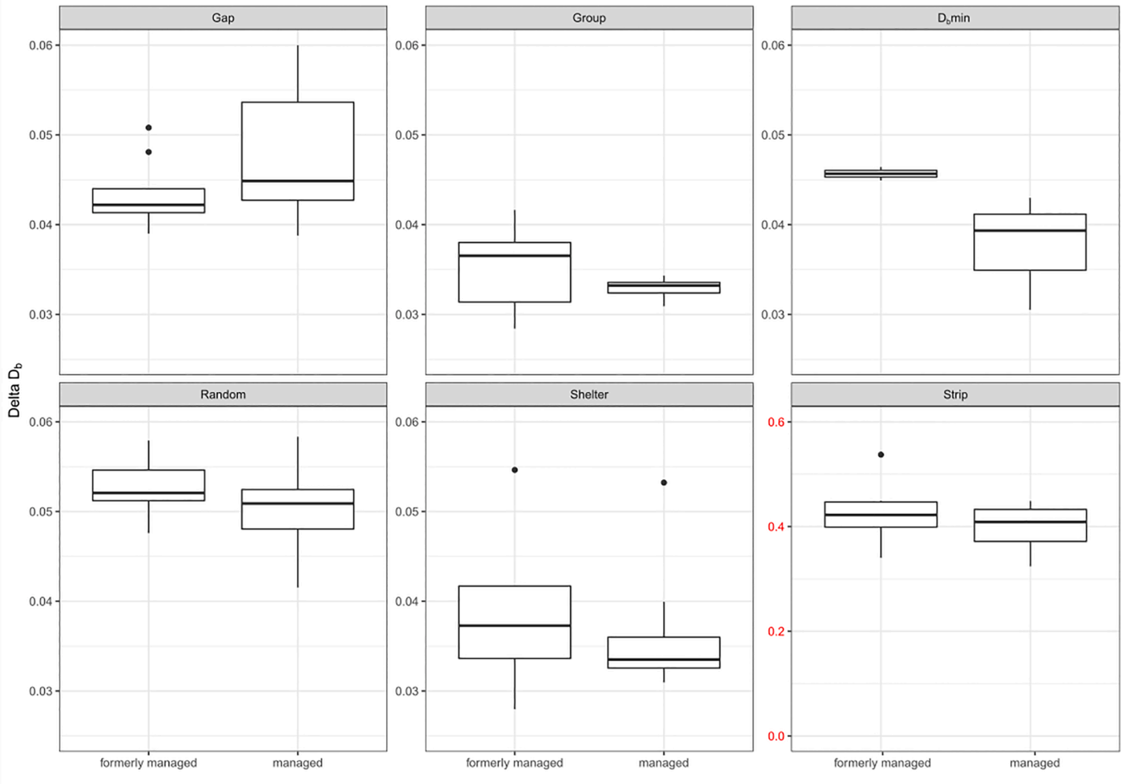

Fig. 8. Box-Whisker plots showing the difference in box-dimension (Delta D_b) resulting from structural complexity before and after the treatment in all 19 study plots, between stands of different management history. The ten different treatments *random cut* were averaged per plot and combined as one. 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.

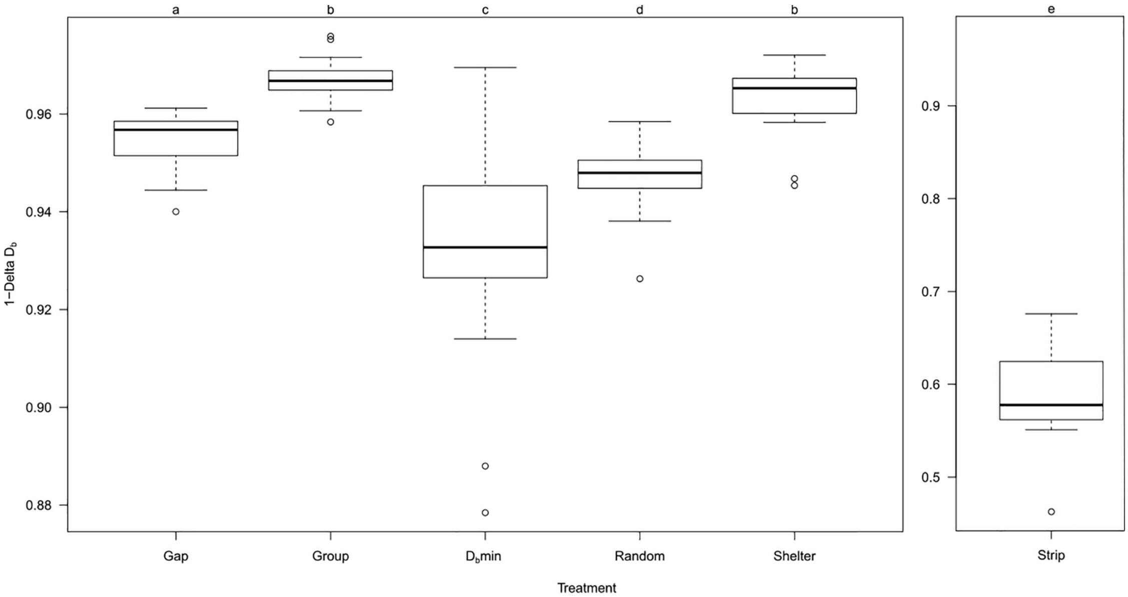

Fig. 9. Box-Whisker plots of the difference in box-dimension (Delta D_b) resulting from the structural complexity before and after treatment in all 19 study plots. The 10 different treatments *random cut* were again averaged per plot. The treatment *strip cut* has a different scale. Black horizontal lines indicate the median. Different lowercase letters indicate significant differences among the conditions at the level of $p < 0.05$.

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

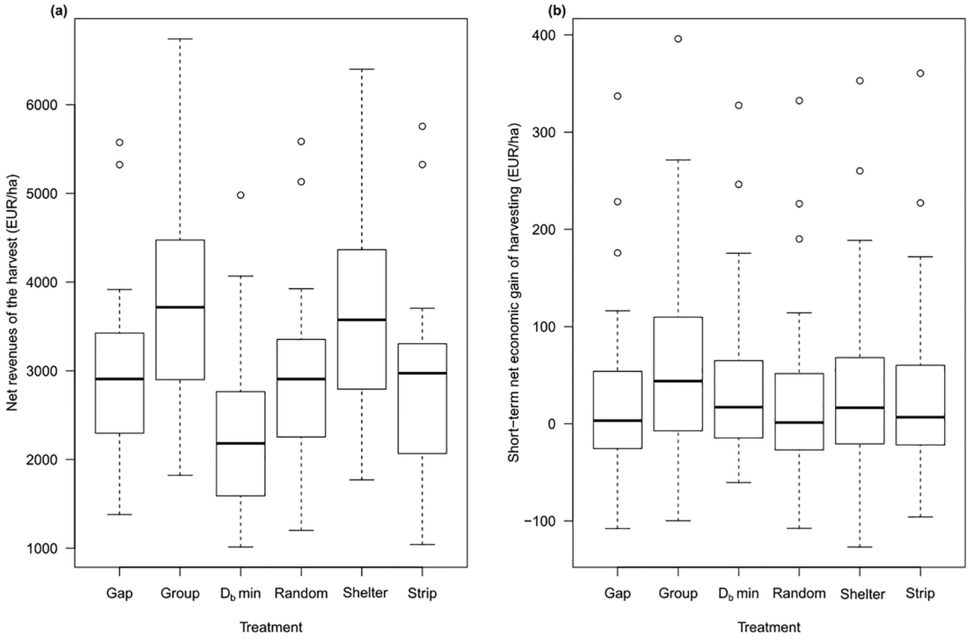

Fig. 10. Box-Whisker plots of net revenues in €/ha at the time of harvesting (a) and short-term net economic gain of harvesting in €/ha at the end of the following 5-year period (b) of the simulated silvicultural treatments for all 19 study plots. The 10 different treatments *random cut* were averaged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

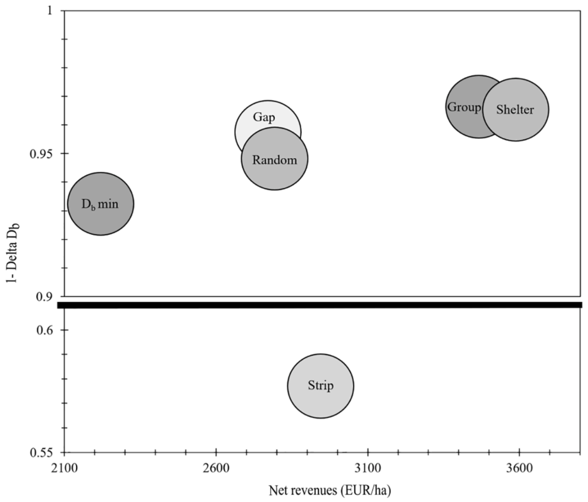

Fig. 11. Combining the results of the change in structural complexity (Delta D_b) and net revenue (see Figs. 9 and 10a) of the different simulated treatments. The ten different *random cut* simulations were averaged per plot as before. The scale is compressed in the range from 0.6 to 0.9 on the y-axis for better illustration.

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).

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.

4.3. Quantification of the consequences of harvest measures on structural complexity and net revenue

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 (Fig. A2, Appendix). 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.

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.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2023.100372.

References

Albert, M., Nagel, J., Schmidt, M., Nagel, R.V., Spellmann, H., 2022. Eine Neue Generation von Ertragstafeln für Eiche, Buche, Fichte, Douglasie und Kiefer. Zenodo [Data set].

Arseniou, G., MacFarlane, D.W., Seidel, D., 2021. Measuring the contribution of leaves to the structural complexity of urban tree crowns with terrestrial laser scanning. Remote Sens 13, 2773. https://doi.org/10.3390/rs13142773 (Basel).

Atkins, J.W., Fahey, R.T., Hardiman, B.H., Gough, C.M., 2018. Forest canopy structural complexity and light absorption relationships at the subcontinental scale. J. Geophys. Res. Biogeosci. 123, 1387–1405. https://doi.org/10.1002/2017JG004256.

Bauwens, S., Bartholomeus, H., Calders, K., Lejeune, P., 2016. Forest Inventory with Terrestrial LiDAR: a Comparison of Static and Hand-Held Mobile Laser Scanning. Forests 7, 127. https://doi.org/10.3390/f7060127.

Boncina, A., 2000. Comparison of structure and biodiversity in the rajhenav virgin forest remnant and managed forest in the dinaric region of slovenia. Glob. Ecol. Biogeogr. 9, 201–211. https://doi.org/10.1046/j.1365-2699.2000.00155.x.

Brunet, J., Fritz, Ö., Richnau, G., 2010. Biodiversity in European beech forests-a review with recommendations for sustainable forest management. Ecol. Bull. 77–94.

Calders, K., Origo, N., Burt, A., Disney, M., Nightingale, J., Raumonen, P., et al., 2018. Realistic forest stand reconstruction from terrestrial LiDAR for radiative transfer modelling. Remote Sens. 10, 933. https://doi.org/10.3390/rs10060933 (Basel).

Camarretta, N., Ehbrecht, M., Seidel, D., Wenzel, A., Zuhdi, M., Merk, M.S., et al., 2021. Using airborne laser scanning to characterize land-use systems in a tropical landscape based on vegetation structural metrics. Remote Sens. 13, 4794. https://doi.org/10.3390/rs13234794 (Basel).

Clark, P.J., Evans, F.C., 1954. Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology 35, 445–453. https://doi.org/10.2307/1931034.

Coates, K., 2000. Conifer seedling response to northern temperate forest gaps. For. Ecol. Manag. 127, 249–269. https://doi.org/10.1016/S0378-1127(99)00135-8.

Commarmot, B., Bachofen, H., Bundziak, Y., Bürgi, A., Zingg, A., 2005. Structure of virgin and managed beech forests in Uholka (Ukraine) and Sihlwald (Switzerland). For. Snow Landsc. Res. 79, 45–56.

D`Amato, A.W., Bradford, J.B., Fraver, S., Palik, B.J., 2011. Forest management for mitigation and adaptation to climate change: insights from long-term silviculture experiments. For. Ecol. Manag. 262, 803–816. https://doi.org/10.1016/j.foreco.2011.05.014.

Dassot, M., Constant, T., Fournier, M., 2011. The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges. Ann. For. Sci. 68, 959–974. https://doi.org/10.1007/s13595-011-0102-2.

Dorji, Y., Schuldt, B., Neudam, L., Dorji, R., Middleby, K., Isasa, E., et al., 2021. Three-dimensional quantification of tree architecture from mobile laser scanning and geometry analysis. Trees. https://doi.org/10.1007/s00468-021-02124-9.

Dove, N.C., Keeton, W.S., 2015. Structural Complexity Enhancement increases fungal species richness in northern hardwood forests. Fungal Ecol. 13, 181–192. https://doi.org/10.1016/j.funeco.2014.09.009.

Ehbrecht, M., Schall, P., Ammer, C., Seidel, D., 2017. Quantifying stand structural complexity and its relationship with forest management, tree species diversity and microclimate. Agric. For. Meteorol. 242, 1–9. https://doi.org/10.1016/j.agrformet.2017.04.012.

Feldmann, E., Drößler, L., Hauck, M., Kucbel, S., Pichler, V., Leuschner, C., 2018. Canopy gap dynamics and tree understory release in a virgin beech forest, Slovakian Carpathians. For. Ecol. Manag. 415-416, 38–46. https://doi.org/10.1016/j.foreco.2018.02.022.

Fuchs, J.M., Husmann, K., v Bodelschwingh, H., Koster, R., Staupendahl, K., Offer, A., et al., 2022. woodValuationDE. Wood Valuation Germany.

Füldner, K., 1995. Zur Strukturbeschreibung in Mischbeständen. Forstarchiv 235–240.

Guzmán, Q.J.A., Sharp, I., Alencastro, F., Sánchez-Azofeifa, G.A., 2020. On the relationship of fractal geometry and tree–stand metrics on point clouds derived from terrestrial laser scanning. Methods Ecol. Evol. 11, 1309–1318. https://doi.org/10.1111/2041-210X.13437.

Hardiman, B.S., Bohrer, G., Gough, C.M., Vogel, C.S., Curtisi, P.S., 2011. The role of canopy structural complexity in wood net primary production of a maturing northern deciduous forest. Ecology 92, 1818–1827. https://doi.org/10.1890/10-2192.1.

Heidenreich, M.G., Seidel, D., 2022. Assessing forest vitality and forest structure using 3D data: a case study from the Hainich National Park, Germany. Front. For. Glob. Chang. 5 https://doi.org/10.3389/ffgc.2022.929106.

Heidrich, L., Bae, S., Levick, S., Seibold, S., Weisser, W., Krzystek, P., et al., 2020. Heterogeneity-diversity relationships differ between and within trophic levels in temperate forests. Nat. Ecol. Evol. 4, 1204–1212. https://doi.org/10.1038/s41559-020-1245-z.

Hunter, M.L., Hunter, M.L., 1999. Maintaining Biodiversity in Forest Ecosystems. Cambridge University Press, Cambridge.

Iglhaut, J., Cabo, C., Puliti, S., Piermattei, L., O’Connor, J., Rosette, J., 2019. Structure from motion photogrammetry in forestry: a review. Curr. For. Rep. 5, 155–168. https://doi.org/10.1007/s40725-019-00094-3.

Jonckheere, I., Nackaerts, K., Muys, B., van Aardt, J., Coppin, P., 2006. A fractal dimension-based modelling approach for studying the effect of leaf distribution on LAI retrieval in forest canopies. Ecol. Model. 197, 179–195. https://doi.org/10.1016/j.ecolmodel.2006.02.036.

Juchheim, J., Ehbrecht, M., Schall, P., Ammer, C., Seidel, D., 2019. Effect of tree species mixing on stand structural complexity. Forestry 93, 75–83. https://doi.org/10.1093/forestry/cpz046 (Lond).

Jung, K., Kaiser, S., Böhm, S., Nieschulze, J., Kalko, E.K.V., 2012. Moving in three dimensions: effects of structural complexity on occurrence and activity of insectivorous bats in managed forest stands. J. Appl. Ecol. 49, 523–531. https://doi.org/10.1111/j.1365-2664.2012.02116.x.

Kaye, B.H., 1994. A Random Walk Through Fractal Dimensions. Wiley, Weinheim.

Knoke, T., Paul, C., Gosling, E., Jarisch, I., Mohr, J., Seidl, R., 2022. Assessing the economic resilience of different management systems to severe forest disturbance. Environ. Resource Econ. https://doi.org/10.1007/s10640-022-00719-5.

Koster, R., Fuchs, J.M., 2022. Opportunity costs of growing space – an essential driver of economical single-tree harvest decisions. For. Policy Econ. 135, 102668 https://doi.org/10.1016/j.forpol.2021.102668.

Kublin, E., 2003. Einheitliche beschreibung der schaftform - methoden und programme -BDATPro. A uniform description of stem profiles - methods and programs -BDATPro. Forstwissen Centre 122, 183–200. https://doi.org/10.1046/j.1439-0337.2003.00183.x.

Lindenmayer, D.B., Margules, C.R., Botkin, D.B., 2000. Indicators of biodiversity for ecologically sustainable forest management. Conserv. Biol. 14, 941–950. https://doi.org/10.1046/j.1523-1739.2000.98533.x.

Messier, C., Puettmann, K., Chazdon, R., Andersson, K.P., Angers, V.A., Brotons, L., et al., 2015. From management to stewardship: viewing forests as complex adaptive systems in an uncertain world. Conserv. Lett. 8, 368–377. https://doi.org/10.1111/conl.12156.

Meyer, P., 2005. Network of Strict Forest Reserves as Reference System For Close to Nature Forestry in Lower Saxony. Forest Snow and Landscape Research, Germany.

Meyer, P., Tabaku, V., Lupke, B., 2003. Die struktur albanischer rotbuchen-urwalder - ableitungen fur eine naturnahe buchenwirtschaft. structural characteristics of albanian beech (Fagus sylvatica L.) virgin forests - deductions for semi-natural forestry. Forstwissen Centre 122, 47–58. https://doi.org/10.1046/j.1439-0337.2003.02041.x.

Möhring, B., 2001. Nachhaltige Forstwirtschaft und Rentabilitätsrechnung – ein Widerspruch? Allg. Forst und J. 61–66. Ztg.

Mori, A.S., Lertzman, K.P., Gustafsson, L., 2017. Biodiversity and ecosystem services in forest ecosystems: a research agenda for applied forest ecology. J. Appl. Ecol. 54, 12–27. https://doi.org/10.1111/1365-2664.12669.

Nagel, T.A., Zenner, E.K., Brang, P., 2013. Research in Old-Growth Forests and Forest Reserves: Implications for Integrated Forest Management. Integrative Approaches As An Opportunity for the Conservation of Forest Biodiversity. European Forest Institute, pp. 44–50.

Neudam, L., Annighöfer, P., Seidel, D., 2022. Exploring the potential of mobile laser scanning to quantify forest structural complexity. Front. Remote Sens. 3 https://doi.org/10.3389/frsen.2022.861337.

Offer, A., Staupendahl, K., 2018. Holzwerbungskosten-und Bestandessortentafeln. HessenForst, Kassel.

Parkatti, V.P., Tahvonen, O., 2020. Optimizing continuous cover and rotation forestry in mixed-species boreal forests. Can. J. For. Res. 50, 1138–1151. https://doi.org/10.1139/cjfr-2020-0056.

Pretzsch, H., 2005. Stand density and growth of Norway spruce (Picea abies (L.) Karst.) and European beech (Fagus sylvatica L.): evidence from long-term experimental plots. Eur. J. For. Res. 124, 193–205. https://doi.org/10.1007/s10342-005-0068-4.

Saarinen, N., Calders, K., Kankare, V., Yrttimaa, T., Junttila, S., Luoma, V., et al., 2021. Understanding 3D structural complexity of individual Scots pine trees with different management history. Ecol. Evol. 11, 2561–2572. https://doi.org/10.1002/ece3.7216.

Sabatini, F.M., Burrascano, S., Azzella, M.M., Barbati, A., Paulis, S.D., Di Santo, D., et al., 2016. One taxon does not fit all: herb-layer diversity and stand structural complexity are weak predictors of biodiversity in Fagus sylvatica forests. Ecol. Indic. 69, 126–137. https://doi.org/10.1016/j.ecolind.2016.04.012.

Sanaei, A., Ali, A., Yuan, Z., Liu, S., Lin, F., Fang, S., et al., 2021. Context-dependency of tree species diversity, trait composition and stand structural attributes regulate temperate forest multifunctionality. Sci. Total Environ. 757, 143724 https://doi.org/10.1016/j.scitotenv.2020.143724.

Schall, P., Gossner, M.M., Heinrichs, S., Fischer, M., Boch, S., Prati, D., et al., 2018. The impact of even-aged and uneven-aged forest management on regional biodiversity of multiple taxa in European beech forests. J. Appl. Ecol. 55, 267–278. https://doi.org/10.1111/1365-2664.12950.

Scherzinger, W., 1996. Naturschutz Im Wald: Qualitätsziele einer Dynamischen Waldentwicklung. Ulmer, Stuttgart.

Seidel, D., 2018. A holistic approach to determine tree structural complexity based on laser scanning data and fractal analysis. Ecol. Evol. 8, 128–134. https://doi.org/10.1002/ece3.3661.

Seidel, D., Annighöfer, P., Ehbrecht, M., Ammer, C., Schall, P., 2018. Applying fractal analysis to stem distribution maps. Ecol. Indic. 93, 243–246. https://doi.org/10.1016/j.ecolind.2018.05.016.

Seidel, D., Annighöfer, P., Ehbrecht, M., Magdon, P., Wöllauer, S., Ammer, C., 2020. Deriving stand structural complexity from airborne laser scanning data—what does it tell us about a forest? Remote Sens. 12, 1854. https://doi.org/10.3390/rs12111854 (Basel).

Seidel, D., Annighöfer, P., Stiers, M., Zemp, C.D., Burkardt, K., Ehbrecht, M., et al., 2019a. How a measure of tree structural complexity relates to architectural benefit-to-cost ratio, light availability, and growth of trees. Ecol. Evol. 9, 7134–7142. https://doi.org/10.1002/ece3.5281.

Seidel, D., Ehbrecht, M., Annighöfer, P., Ammer, C., 2019b. From tree to stand-level structural complexity — which properties make a forest stand complex? Agric. For. Meteorol. 278, 107699 https://doi.org/10.1016/j.agrformet.2019.107699.

Seidel, D., Ehbrecht, M., Dorji, Y., Jambay, J., Ammer, C., Annighöfer, P., 2019c. Identifying architectural characteristics that determine tree structural complexity. Trees 33, 911–919. https://doi.org/10.1007/s00468-019-01827-4.

Seidel, D., Leuschner, C., Müller, A., Krause, B., 2011. Crown plasticity in mixed forests—Quantifying asymmetry as a measure of competition using terrestrial laser scanning. For. Ecol. Manag. 261, 2123–2132. https://doi.org/10.1016/j.foreco.2011.03.008.

Seidel, D., Stiers, M., Ehbrecht, M., Werning, M., Annighöfer, P., 2021. On the structural complexity of central European agroforestry systems: a quantitative assessment using terrestrial laser scanning in single-scan mode. Agroforest Syst. 95, 669–685. https://doi.org/10.1007/s10457-021-00620-y.

Simons, N.K., Felipe-Lucia, M.R., Schall, P., Ammer, C., Bauhus, J., Blüthgen, N., et al., 2021. National Forest Inventories capture the multifunctionality of managed forests in Germany. For. Ecosyst. 8 https://doi.org/10.1186/s40663-021-00280-5.

Smith, T.J., Robertson, A.I., Alongi, D.M., 1992. Forest structure. Tropical Mangrove Ecosystems. American Geophysical Union, Washington, D. C, pp. 101–136.

Stiers, M., Annighöfer, P., Seidel, D., Willim, K., Neudam, L., Ammer, C., 2020. Quantifying the target state of forest stands managed with the continuous cover approach – revisiting Möller's "Dauerwald" concept after 100 years. Trees For. People 1, 100004. https://doi.org/10.1016/j.tfp.2020.100004.

Stiers, M., Willim, K., Seidel, D., Ehbrecht, M., Kabal, M., Ammer, C., et al., 2018. A quantitative comparison of the structural complexity of managed, lately unmanaged and primary European beech (Fagus sylvatica L.) forests. For. Ecol. Manag. 430, 357–365. https://doi.org/10.1016/j.foreco.2018.08.039.

von Arnim, G., Möhring, B., Paul, C., 2021. Constrained liquidity during forest calamities: an explorative study for adaptation in private forest enterprises in Germany. Aust. J. For. Sci. 138, 395–412.

von Bodelschwingh, H., 2018. Ökonomische Potentiale von Waldbeständen. Konzeption und Abschätzung im Rahmen einer Fallstudie in Hessischen Staatswaldflächen: [Economic Potentials of Forest Stands and Their Consideration in Strategic Decisions]. Schriften zur Forst- und Umweltökonomie.

Vonderach, C., Kublin, E., Bösch, B., and Kändler, G. (2021). rBDAT: Implementation of BDAT Tree Taper Fortran Functions. doi:10.1046/j.1439-0337.2003.00183.x.

Westphal, C., Tremer, N., Oheimb, G.von, Hansen, J., Gadow, K.von, Härdtle, W., 2006. Is the reverse J-shaped diameter distribution universally applicable in European virgin beech forests? For. Ecol. Manag. 223, 75–83. https://doi.org/10.1016/j.foreco.2005.10.057.

Willim, K., Stiers, M., Annighöfer, P., Ammer, C., Ehbrecht, M., Kabal, M., et al., 2019. Assessing understory complexity in beech-dominated forests (fagus sylvatica l.) in central europe-from managed to primary forests. Sensors 19. https://doi.org/10.3390/s19071684 (Basel).

Zeide, B., Pfeifer, P., 1991. A method for estimation of fractal dimension of tree crowns. For. Sci. 37, 1253–1265.