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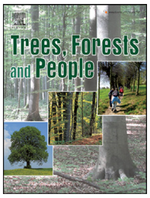

Quantifying the target state of forest stands managed with the continuous cover approach – revisiting Möller's "Dauerwald" concept after 100 years

Melissa Stiers[a,*], Peter Annighöfer[b], Dominik Seidel[a], Katharina Willim[a], Liane Neudam[a], Christian Ammer[a]

[a] *University of Göttingen, Faculty of Forest Sciences, Silviculture and Forest Ecology of the Temperate Zones, Büsgenweg 1, 37077 Göttingen, Germany*
[b] *Forest and Agroforest Systems, Technical University of Munich (TUM), Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany*

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ABSTRACT

Continuous cover forestry is often considered a management alternative to age-class forestry, in closer compliance with economic as well as societal demands. It is further thought to provide forest stands of high stability and resilience under conditions of climate change. The guiding principle for the stand structure of continuous cover forestry systems is to create managed forest stands that are multi-layered and hence of high structural diversity. Past studies of both these characteristics have been mostly qualitative. Here we used data from terrestrial laser scanning (TLS) to quantify differences in stand structure between forests managed for decades according to the continuous cover concept and forests managed otherwise. We found that the vertical distribution of plant material in the continuous cover stands was relatively homogeneous and similar to the vertical distribution found in primary European beech forests. We also found that the structural complexity of continuous cover forests was significantly higher than that of even-aged monocultures of Scots pine and Norway spruce. Based on these findings, a scaled index was developed that quantifies structural attributes of TLS point clouds and can significantly distinguish continuous cover forests from even-aged forests. This index may be a useful tool to quantify the difference in structure of a given continuous cover forest stand from a "target structure", meaning the theoretical structure describing an ideal continuous cover forest.

1. Introduction

An essential role of modern forest management is to create multifunctional and resilient forests that resemble natural forests (Brang et al., 2014; Gustaffson et al., 2012; Kuuluvainen 2009; Nagel et al., 2013; O'Hara 2001; O'Hara et al., 2007; Schall et al., 2018), and which accommodate the increasing societal demands on forest ecosystems (Felipe-Lucia et al., 2018). As a management type, continuous cover forestry (CCF) is considered one option with the potential to fulfill a variety of functions at the same time and location (Mizunaga et al., 2010). Most studies of CCF have addressed possible ways to convert even-aged forest stands into uneven-aged forest stands (v. Lüpke et al., 2004, O'Hara 2001) or to convert existing forest structures into steady-state structures (Pukkala 2016), but little is known about the quantification of the structural characteristics of CCF (Pommerening and Murphy 2004; Pukkala 2016).

The term "continuous cover forest" (in German: "Dauerwald") has a long and turbulent history in German forestry (e.g., Bode 1992; Schmidt 2009; Zingg 2003). It was first mentioned in 1920 by Alfred Möller to describe a management system developed in northeastern Germany (Möller 1920). Möller called for the abandonment of clearcuts in order to secure forests' constancy, by suggesting vertically structured forests. He also advocated ensuring this structure over time by carefully applying single-tree selection cuttings (Schütz, 1999, 2002). Although CCF does not ask for specific management practices to achieve constancy (Möller 1922), there are some guidelines for managers. Möller (1922) stated that the silvicultural methods applied in CCF should depend on and require adaptation to particular climatic and geographic conditions as well as to the target tree species. CCF does not involve classical rotation periods (age-based) and in order to preserve the constancy of the forest system, clearcuts are prohibited (Kraut 2010; Möller 1922; O'Hara 2016; Schabel and Palmer 1999; Stähr and Müller 2010; Zingg 2003). Natural regeneration is preferable, but it may be artificially supplemented with appropriate mixed tree species. Most common is selective thinning, which removes the competitors of the most vital and valuable trees. It is not maximum volume output that is sought, but rather that, which ensures maximum production of high-quality wood (Möller 1922; Stähr and Müller 2010). The concept comprises frequent but moderate group-, patch- or single-tree thinnings (Möller 1922; Zingg 2003), wherein rare mixed tree species should be promoted (Möller 1922; Pommerening and Murphy 2004). Consideration of all these factors should result in an uneven-aged, site-appropriate, species-rich and highly productive CCF. However, the CCF concept

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[*] Corresponding author.
E-mail address: melissa.stiers@forst.uni-goettingen.de (M. Stiers).

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is being applied successfully within pure European beech stands also (Fritzlar and Biehl 2006), since European beech is a very shade-tolerant species and is able to develop vertically structured stands.

Like all other management concepts, CCF is based on operational decisions by forest owners (Möller 1922; Zingg 2003). However, applying the CCF concept does not mean that all stands will immediately exhibit the desired structure. In contrast, it may last for decades until the desired structure is achieved. Therefore, it would be desirable if a target structure was defined and if a quantitative measure existed that could be used to decide comprehensively and objectively whether a specific stand has already reached that target structure. In the literature, the target state of CCF is qualitatively described as an uneven-aged, multi-layered, mixed, and healthy forest ecosystem with high vertical and horizontal heterogeneity (Kraut 2010; Pommerening and Murphy 2004; Stähr and Müller 2010). However, even after a century, there is no clear, objective quantification of this “ideal” structure. Therefore, development and establishment of a structural definition of this “target” state of a CCF stand based on some objective quantification is sorely needed. To capture forest structures reproducibly, we used terrestrial laser scanning (TLS). TLS generates 3D-point clouds, which reproduce a forest in spatial detail and make it possible to calculate several indices describing forest structure.

Perhaps the most important characteristic of the CCF target structure is a state of equilibrium in biomass and constancy of both the forest ecosystem and any compartments and subsystems (Hofmann 2010). Accounting for ways in which space is occupied and according to the plenter (selection) principle, each diameter class should be represented (Schütz 2002; Zingg 2003). Translated into three-dimensional space, this would mean that each stand layer is similarly filled with plant material horizontally and vertically. This state should result in maximum structural complexity (for our definition of complexity see below). Here, we used different indices based on three-dimensional structure to capture the different components of stand structure: the box dimension (Seidel 2018), space filling (Juchheim et al., 2017), and a stand structural complexity index (SSCI, Ehbrecht et al., 2016). In addition, as a measure of equality in space filling between the stand layers, we used space filling evenness, Gini-coefficient, and skewness. Using a combination of these indices and attributes, we hypothesized that it is possible to clearly distinguish conventional even-aged stands of different stages from stands that have been managed for decades according to the CCF concept, and which are widely recognized by practitioners to represent the ideal structure of a CCF.

We used eight stands that represented the CCF target structure. These were compared with a series of age-class forests and data from temperate European beech primary forests as unmanaged natural reference forests. Specifically, we tested the following hypotheses:

a) The plant material of CCF target stands is vertically evenly distributed.
b) The structures of CCF target stands differ significantly from even-aged managed reference stands, but not from unmanaged European beech primary forests, as quantified by a newly developed index of three-dimensional stand structure.

2. Materials and methods

2.1. Study sites

We selected eight forest stands in Germany, which are considered representative of the target state of CCF according to practitioners (members of the German section of Pro-Silva (in German: “Arbeitsgemeinschaft Naturgemäße Waldwirtschaft” (ANW)). All CCF target stands, except those in Hainich, were mixtures of at least two tree species. In Hainich European beech dominated and formed nearly pure stands. To cover a wide range of forest types, the study areas and plots represent different tree species compositions, ranging from forest stands dominated by broadleaved or coniferous tree species to mixed stands with similar proportions of broadleaved and coniferous tree species. The forests are located in Kasseedorf/Lensahn (Schleswig-Holstein), Rentweinsdorf, Teisendorf and Ebrach (Bavaria), Freudenstadt (Baden-Wuerttemberg), Gießen (Hesse), Wallmerod (Rhineland-Palatinate) and Hainich (Thuringia; Fig. 1 and Table 1). While the forest plots in Freudenstadt are dominated by coniferous tree species, in Rentweinsdorf and Kasseedorf/Lensahn both are found; mixed stands dominated by broadleaved tree species and mixed stands dominated by coniferous tree species. In Teisendorf, all forest plots consist of mixtures of broadleaved and coniferous tree species. In Gießen, Wallmerod, Ebrach and Hainich stands are predominately composed of broadleaved tree species (Table 1).

To distinguish between the target state of CCF and stands of other management systems and tree species, we chose reference forest plots in even-aged pure stands (EA) of Norway spruce (*Picea abies* L.; Swabian Alb, Baden-Württemberg), Scots pine (*Pinus sylvestris* L.; Schorfheide-Chorin, Brandenburg), European beech (*Fagus sylvatica* L.; Hann. Münden and Reinhausen, Lower Saxony), and plots in mixed stands of beech, pine and oak (*Quercus* sp.; Schorfheide-Chorin, Brandenburg). To reduce effects of age we selected stands at the stage of mature timber. Additionally, we used data from temperate European beech primary forests (PF) as an unmanaged reference (Table 1). The primary forests are located in eastern Slovakia (Rožok) and in western Ukraine (Uholka; for detailed information see Stiers et al., 2018 or Willim et al., 2019).

2.2. Terrestrial laser scanning and sampling design

At each study site, we collected data from a minimum of two forest plots (Table 1). The plots were located away from skidding trails and at a minimum distance of 10 m from roads. The two plots of a given study site were at least 50 m apart from each other. At the selected plots, an area of at least 40 × 40 m was scanned with a Faro Focus M70 (Faro Technologies Inc., Lake Mary, FL, USA) terrestrial laser scanner. The laser scanner was mounted on a tripod at breast height (1.3 m) and covered a field of view of 300° in vertical and 360° in horizontal directions with an angular step width of 0.035°, which resulted in 44.4 million measurements per scan. However, to enable efficient processing of the large point clouds we reduced the data to every 4th point in every 4th row (1/16 of initial resolution) as conducted in earlier studies (e.g. Seidel et al., 2013, Juchheim et al., 2017). Using phase-difference technology, the scanner emits laser beams into the forest and detects those beams reflected from surrounding objects at a maximum distance of 70 m. To reproduce these data as a highly detailed 3D-point cloud, we performed between 30 and 80 systematically arranged scans on each plot. The number of scans required depends on the density of the understory and the aim is to minimize occlusion effects within the plots (Ehbrecht et al., 2016). In their study, around 9 scans were needed to eliminate occlusion effects. With regard to our extremely high number of scans per plot occlusion effects should be negligible. Understory density is influenced by the number and diameter of stems and branches, which, in the case of young stands with small trees, can be very dense, with small gaps in the vegetation (Ehbrecht et al., 2016). For the co-registration of the individual single-scans, we evenly distributed 70 to 90 artificial checkerboard targets (laminated DIN A4 paper) in the plot area. Data from reference plots (primary and even-aged) and from Ebrach and Hainich were obtained from previous scanning campaigns in the course of other research projects. All data were collected during the vegetation period, when all trees were densely foliated. In total, we collected data from 55 forest plots located in 14 study areas (Table 1).

2.3. Point cloud processing and data analysis

To filter for erroneous points and spatial co-registration, we used the standard settings of the Software Faro Scene (Faro Technologies Inc., Lake Mary, FL, USA, and Version 7.1.1.81). For further processing, each 3D-point cloud was exported as an xyz-file. Each point cloud was then

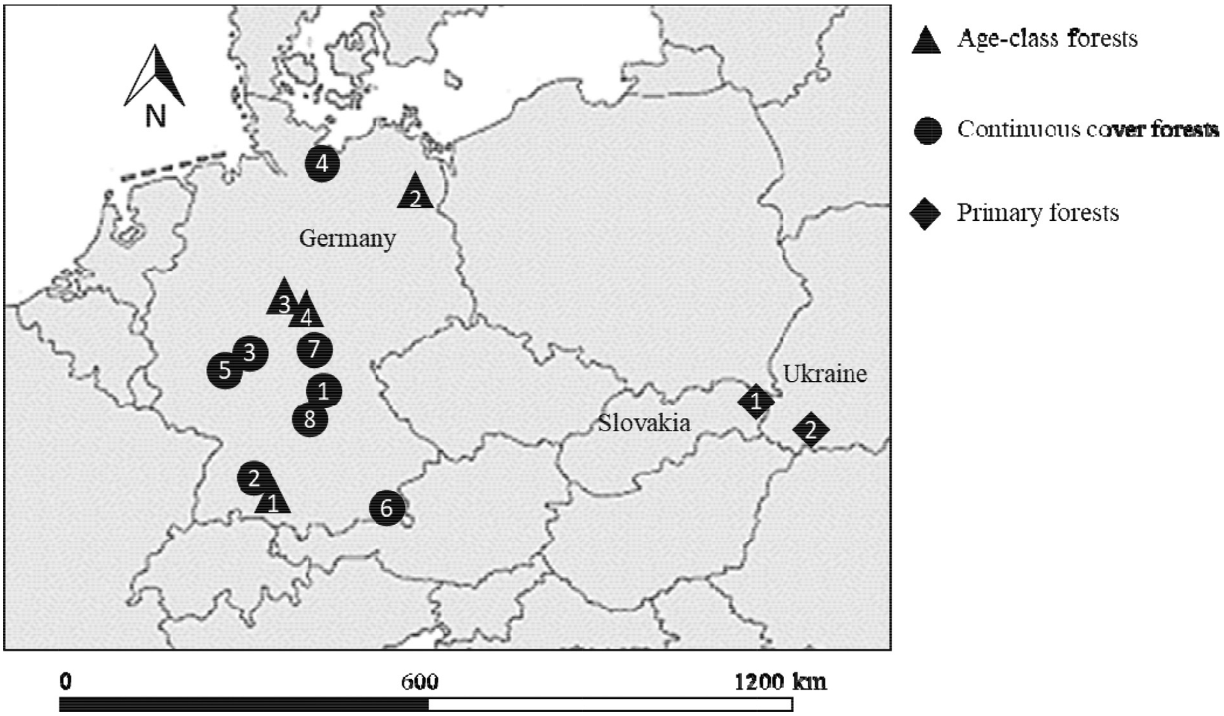

Fig. 1. Geographic locations of the study areas located in Germany, Slovakia, and Ukraine. Circles represent the eight study areas, which were classified as continuous cover target state forests (CCF), triangles represent the four even-aged forests, and diamonds represent the unmanaged forests.

Table 1
Detailed information on important climatic and geographical properties of the study plots: CCF = continuous cover forests, EA = even-aged forests, PF = primary forests, n = number of investigated plots, MAT = mean annual temperature, MAP = mean annual precipitation.

Country	Study area	MAT (°C)	MAP (mm)	Elevation (m a.s.l.)	Dominating class of tree species	Study plots
Germany	Rentweinsdorf (1)	8.5–10	750	250–300	equal coniferous/ broadleaved	CCF: $n = 3$
	Freudenstadt (2)	9	1300	750–800	coniferous	CCF: $n = 2$
	Gießen (3)	9.5–10	590	200–250	broadleaved	CCF: $n = 3$
	Lensahn (4)	9	500–700	15–50	equal coniferous/ broadleaved	CCF: $n = 3$
	Wallmerod (5)	9–9.5	650–800	85–100	broadleaved	CCF: $n = 3$
	Teisendorf (6)	7.5–8	1100	550–700	equal coniferous/broadleaved	CCF: $n = 3$
	Hainich (7)	7–8	600–800	330–380	broadleaved	CCF: $n = 5$
	Ebrach (8)	7–8	850	320–480	broadleaved	CCF: $n = 4$
	Swabian Alb (1)	6–7	700–1000	460–860	coniferous	EA: $n = 5$
	Schorfheide-Chorin (2)	8–8.5	500–600	3–140	coniferous ($n = 5$)/ mixed ($n = 6$)	EA: $n = 11$
	Hann. Münden (3)	6–7.5	750–1050	270–410	broadleaved	EA: $n = 4$
	Reinhausen (4)	8	740	190–310	broadleaved	EA: $n = 4$
Slovakia	Rožok (1)	6–7	780	580–745	broadleaved	PF: $n = 3$
Ukraine	Uholka (2)	7	1407	700–840	broadleaved	PF: $n = 2$

converted into a voxel model (voxel = volumetric pixel) with an edge length of 20 cm. The voxel size influences the calculations of the metrics. If voxels are chosen too small, it is likely that tree stems are represented as hollow “pipes” instead of solid bodies (Seidel et al., 2013). Also, occlusion effects may result in artificial gaps in the voxel model. Larger voxel sizes can be considered more conservative and are an effective tool to minimize occlusion effects (Ehbrecht et al., 2016) but may result in an overestimation of the actual space filling. If chosen too large, smaller gaps are missed and space filling increases. Here, we decided to use 20 cm voxels as they were shown to be a robust way to deal with occlusion for plots identical to ours in size (Ehbrecht et al., 2016) while still providing a high-resolution model of the forest preserving detailed structures (Fig. 2). This is because at the chosen scanning resolution the distance between two laser beams at maximum measuring distance of the scanner (70 m) is 4.3 cm. After point cloud reduction to 1/16 of the original (see above) for computability of the data, beam-to-beam distance increases to 17.3 cm at 70 m distance to the scanner. To ensure that there is no unsampled space between neighboring points 20 cm voxels are suitable and may be considered the smallest possible voxel model.

To account for uneven terrain, we normalized the topography by computing digital terrain models (DTM) through triangulation of the lowermost voxel in each grid cell. We then normalized the point cloud by correcting each voxel in the voxel model with the underlying terrain height obtained from the DTM. Details of the approach can be found in Juchheim et al. (2017).

Based on these normalized voxel models of 20 cm edge length, we used an algorithm written in R (R Core Team 2017) to calculate relative space filling for a predefined horizontal extent of 40 × 40 m. Space filling is the percentage of the total plot volume that is occupied by plant voxels (Juchheim et al., 2017; Seidel et al., 2019). Total plot volume was defined as ground area, which is $40 \times 40\ m = 1600\ \mathrm{m}^2$, multiplied by median stand height. To define the median height, which was used for further calculations, we separated the upper 20% of stand height, and calculated the median for these selected z-values (Fig. 2). This was done to eliminate shadowing within the dense leaf-on data, which could

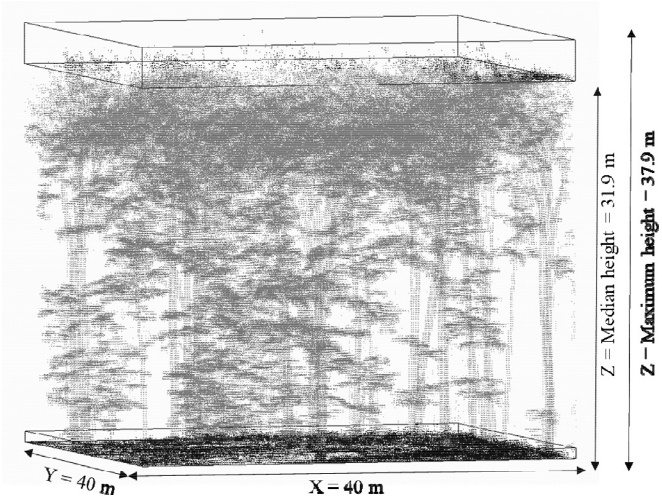

Fig. 2. Illustration of the voxel model and subdivisions. Black voxels mark the five lowermost bottom layers (< 1.0 m) in the voxel model, which were deleted before data analysis (bottom black voxels), and the voxels which were deleted through the reduction of maximum stand height to median stand height (top black voxels).

have resulted an underestimation of the upper canopy parts. Before the calculation of relative space filling, we deleted all voxels of the five lowermost voxel layers (0–1 m) (Fig. 2). If these points, representing ground, grasses, herbs, ferns, and leaf litter, had not been deleted, space filling would have been overestimated for the lower stand layers. Space filling was calculated for the space above the lowermost voxel layers and median stand height. The space that is occupied by voxels is determined by simply counting all voxels and multiplying them by their volume (0.008 m^3).

Here, space filling was also used to calculate the percentage of filled volume in predefined forest layers and thus to describe the spatial arrangement of plant material. Therefore, each plot was vertically subdivided into 50 equally thick layers relative to the median stand height. Sensitivity analyses showed that the results presented below were robust even with lesser layers (data not shown). In a next step, we calculated space filling in percentage of each layer from the total.

To analyze the spatial distribution of and disparity in space filling, we used accumulation curves, to display the cumulative arrangement of space filling in the vertical layers of the scanned forests. In addition, we calculated the Gini-coefficient, the evenness, the skewness, and the coefficient of variation to describe the inequality in space filling between the defined stand layers (Bendel et al., 1989). The evenness ($E_{1/D}$) using *'Simpson's measure of evenness'* (1) and the Gini-coefficient were applied to quantify the homogeneity of space filling in the vertical and horizontal layers. They vary between zero and one, with values close to one indicating a high homogeneity among the layers. The Gini-coefficient was computed with the R package "ineq" (Zeileis et al., 2009). Evenness was calculated as follows:

$$E_{1/D} = \frac{1/D}{s}; D = \sum p_i^2; p_i = space\ filling\ in\ layer\ i;$$
$$s = number\ of\ layers\ (50) \tag{1}$$

Since the Gini-coefficient, evenness, and coefficient of variation indicate the degree of homogeneity, but not the direction of possible deviations, we additionally calculated the skewness (skew) based on space filling in the vertical layers in order to determine where a potential disproportionality was located. Negative values indicate left-skewed distributions, which represent disproportionally filled canopy layers, while positive values describe right-skewed distributions, which indicate disproportionally filled lower stand layers. The closer the value to zero, the more homogeneous the distribution.

Furthermore, we calculated the box dimension (D_b), which addresses structural complexity based on fractal analysis. It links relative space filling to the spatial distribution of biomass and is thus a meaningful measure of three-dimensional complexity (Seidel 2018; Seidel et al., 2019; 2Seidel et al., 2019). D_b increases with increasing density and structural complexity of a forest stand. In addition, it accounts for the homogeneity of the spatial distribution of complexity, thus increases with increasing homogeneity, and can therefore be a helpful tool to quantify the structure of forest stands. D_b is defined as the slope of a linear model (least square fit) on the scale of log(N) over log(1/r), with log() being the natural logarithm, and N being the number of boxes of size r needed to enclose all points in a three-dimensional point cloud (Mandelbrot 1977, Seidel 2018). The D_b of a forest is defined to be greater than 1 (pole) and lower than the maximal value of 2.72, which is the dimensionality of the Menger sponge, a theoretical concept of infinite dimensionality and zero volume (introduced by Menger (1926); Seidel et al., 2019).

In addition to the voxel models derived from the multi-scans, we selected eight individual single-scans from each study plot located in six of the CCF target stands (Lensahn, Rentweinsdorf, Freudenstadt, Gießen, Wallmerod, and Teisendorf). These 144 single-scans were filtered with the standard settings of the Faro Software Faro Scene (Faro Technologies Inc., Lake Mary, FL, USA, Version 7.1.1.81) and then exported as separate xyz-files. Next, the "stand structural complexity-index" (SSCI, Ehbrecht et al., 2017) was calculated to generate further single-scan based structural measures for the description of structural complexity in CCF target stands. The SSCI was calculated using an algorithm written in Mathematica (Wolfram Research Champaign, IL, USA) and is based on the three-dimensional distribution of objects within a scanned forest scene. The SSCI considers the whole forest stand above diameter at breast height (1.3 m), and describes the relationship between the areas and perimeters of multiple vertical cross-sectional polygons through the forest scene, which are received from the scanner's perspective. The relationship between circumference and area of these cross-sectional polygons is used to mathematically describe the complexity of the stand. For more details on index construction and possible value-range, see Ehbrecht et al. (2017).

2.4. *Quantifying ccf target structure*

Based on consideration of the structural characteristics of CCF target structures, we designed another index composed of the variables D_b, skew, and height. The index ("index of structural constancy", ISC) is expected to yield a sensible quantification of the structure found in stands belonging to different forestry systems. Index values should approach a maximum value for stands most similar to the target structures of the CCF system. The ISC was computed for every study plot using the following formula:

$$ISC = D_{bw} * Skew_w * Height_w \tag{2}$$

D_b was normalized (D_{bw}) to range from 0 to 1 by using the mathematical minimum 1 and the assumed maximum of 2.72 for D_b. For CCF target stands, we hypothesized space filling to be homogeneous, which means that every stand layer was equally filled with plant material. The skewness-value for such forests would lie around zero. For index construction, the skewness was also normalized to range from 0 to 1. The necessary weighting was based on assumptions related to the *Standard normal distribution* (formula 3; Fig. 3a).

$$\frac{1}{\sqrt{2\pi\sigma^2}} e^{\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)} \tag{3}$$

Thus, forests plots with skewness values near zero would have the highest values for weighted skew. Weighting the skewness in a standard normal distribution penalizes stands in which the upper canopy layers contribute disproportionately to the total plot filling, i.e., stands with negative values for skewness. Thus, mono-layered stands with higher space filling in the canopy layers than in the lower layers would receive

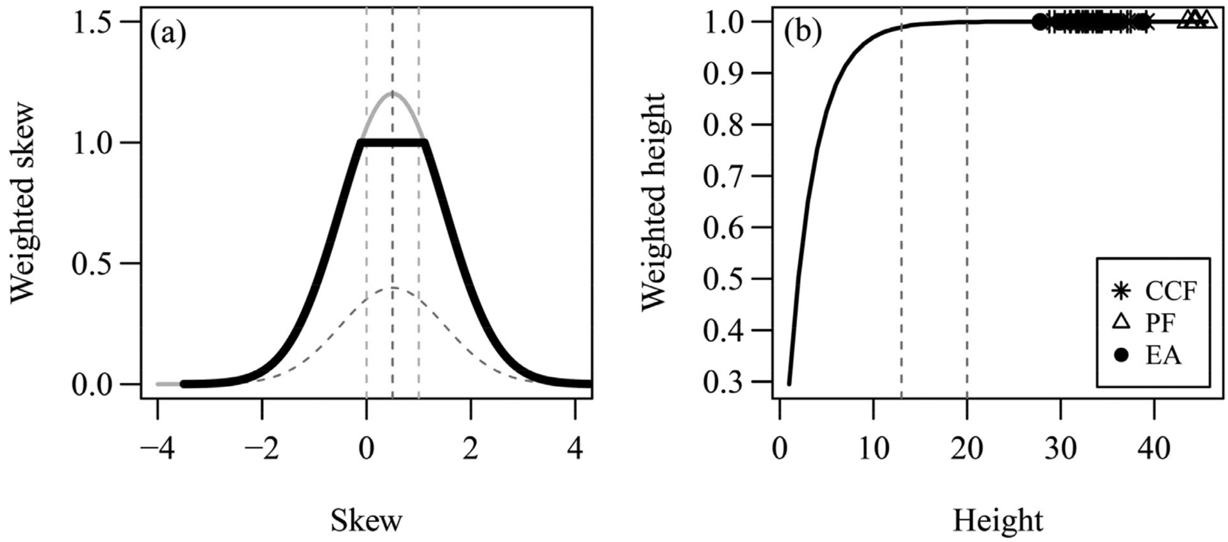

Fig. 3. (a) shows the weighted skewness in a standard normal distribution with stretched minimum function. The dashed horizontal lines mark the regular normal distribution (dark grey), while the dashed vertical lines mark skewness values of 0 and 1 (light grey) as well as the mean skewness (dark grey). The black solid line shows the weighted skewness with stretched values between 0 and 1. (b) shows the weighted height using a Chapman-Richards-function (4), while the dashed vertical lines represent the threshold values of 13 and 20 m.

low values for weighted skew. It would also likewise penalize stands in which space filling of lower stand layers was dominated by, i.e., stands with positive values for skewness. However, to account for the presence of abundant regeneration, which is essential for the CCF concept, we wanted to allow for a tolerance interval in which a higher space filling in lower stand layers was tolerated and did not lead to a reduction in the value of weighted skew. We defined this tolerance interval for skewness values between 0 and 1 and added a stretched minimum function to the standard normal distribution, which ensured that all plots with skewness values within this tolerance interval were assigned the value 1 for weighted skewness (Fig. 3a). The tolerance interval ranges to skewness values of 1, above which the skewness is considered to significantly deviate (Bulmer 1979). In our case, this meant that disproportionality in space filling in the lower stand layers would represent a significant deviation from the hypothesized equal distribution. The standard normal distribution is usually parameterized by setting $\mu = 0$ and $\sigma = 1$. For technical reasons, we had to change the local parameter μ. This was necessary both to establish the tolerance interval to range from 0 to 1 and because we could not completely exclude the possibility of underestimating the filling of upper layers due to occlusion effects, despite the large number of scans and a voxel side length of 20 cm (Ehbrecht et al., 2016). Occlusion effects would result in a bias towards a more right-skewed distribution of plant material. To compensate for this possible right-skewness resulting from methodological constraints, we slightly shifted the local parameter μ of the normal distribution to 0.5.

Stand height was included as a third index component. However, stand height was only included to control for a minimum forest height. The threshold (see below) was set to distinguish forest stands from other systems, such as cornfields, which might also show high D_b values and a skewness around 0. To set a reliable threshold of stand height, we used a *Chapman-Richards-function* (eq. (4)), with the parameters $k = 0.035$ and $p = 10$ (Fig. 3d).

$$y(x) = 1\left(1 - e^{-kx}\right)^{p} \tag{4}$$

Using these parameters, the weighted value for stand height (Height_w) lies around 1 for stands with a mean stand height greater than 20 m. For stand height decreasing from about 20 to 13 m, the values decrease slowly. Values for heights falling below 13 m decrease increasingly rapidly. These threshold-values were based on the assumption that regardless of species, age, and site factors, a CCF stand with heights greater than 13 m should have reached a forest structure with one or more distinct stand layers.

2.5. Statistical analysis

To test for differences between the stands of the different management types, we used parametric and non-parametric tests to analyze the data, depending on whether parametric assumptions (normal distribution and homogeneity of variance) were met. We used the Shapiro-Wilk-test as normality-test, because it is also applicable for small sample sizes. We tested for homogeneity of variance by using Levene's test. If the data met the requirements for parametric tests, we used One-way-ANOVA to test for differences between the variables followed by a TukeyHSD-test for posthoc comparisons. This way, we tested for differences in box dimension and skewness between the management types. In cases where the parametric assumptions were not met, we used the non-parametric Kruskal-Wallis-ANOVA and the Mann-Whitney *U test*. This was done to test for differences in space filling, vertical and horizontal evenness between management types, differences in ISC between management types, differences between the broadleaved, coniferous, and mixed forest types, as well as the mean deviation of the accumulation curves. For all statistical tests, we used a significance level of $p < 0.05$. The statistical analyses were conducted in the R environment (R Core Team 2017).

3. Results

3.1. Structural differences between the types of management

The accumulation curves of space filling showed varying proportions in the defined stand layers for CCF target stands, even-aged forests, and primary forests (Fig. 4). We found significant differences ($p < 0.001$) in mean divergence from the homogeneous vertical distribution of plant material between the CCF target stands and the even-aged forests ($p < 0.001$), as well as between the even-aged forests and the primary forests ($p = 0.048$), but not between the CCF target stands and the primary forests ($p = 0.755$; Table 2). Mean divergence was lowest in the primary forests, highest in the even-aged forests, and intermediate in the CCF target stands (Table 2). The skewness indicated that only the primary forests did not deviate significantly from the hypothesized homogeneous vertical distribution of plant material ($p = 0.718$), but both the even-aged forests ($p < 0.001$) and the CCF ($p = 0.002$) did.

Table 2

Descriptive statistics for the divergence from the homogeneous distribution of the continuous cover target forests (CCF), the even aged forest stands (EA), and the primary forests (PF). Mean sum positive and mean sum negative summarize all deviations in space filling in each layer from the hypothetical equal distribution. SD = Standard deviation, CV = Coefficient of Variation.

Type of Management	Gini-coefficient (mean)	Mean Sum positive	Mean Sum negative	Mean	SD	CV (%)
CCF	0.27	328.58	−41.70	5.91	4.97	3.08
EA	0.38	79.59	−458.14	−7.87	9.48	1.77
PF	0.25	226.40	−61.36	3.37	4.39	23.94

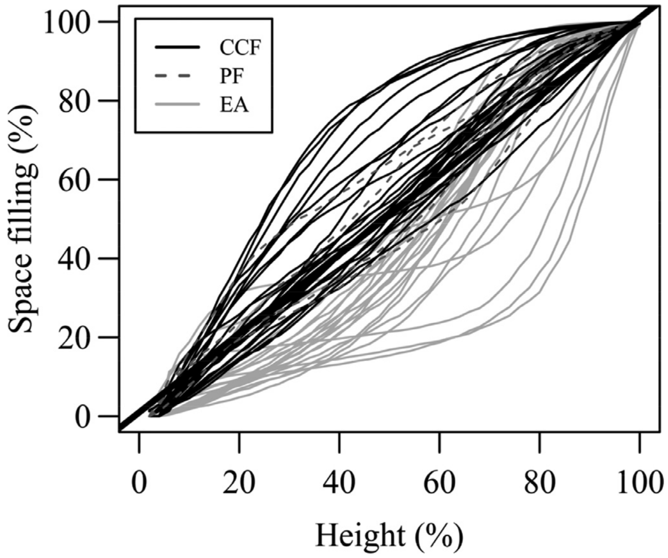

Fig. 4. Accumulation curves showing the cumulative relative space filling over relative stand height. The angle bisector marks the exemplary course for a homogeneously distributed space filling, which means each stand layer is equally filled.

Considering space filling not cumulatively, but separately in each of the defined stand layers, the spatial heterogeneity of vertical levels became clear through the coefficient of variation and the Gini-coefficient. Thus, the CV of space filling across layers indicated the most homogeneous distribution in the primary forests (CV = 0.456), slightly less homogeneous distribution in the CCF target stands (CV = 0.473), and the most heterogeneous distribution in the even-aged forest stands (CV = 0.727). The mean Gini-coefficients were significantly different between CCF and even-aged forests ($p < 0.001$), and between primary forests and even-aged forests ($p = 0.037$), but not between CCF and primary forests ($p = 0.966$).

Considering D_b, we found that all management types significantly differed from one another (PF-EA: $p <0.001$; PF-CCF: $p = 0.022$; CCF-EA: $p < 0.001$, Fig. 5a and Table 3). We also found that D_b was significantly higher in the CCF target stands than in the even-aged stands and was highest in the primary forests ($p < 0.001$, Fig. 5a). In the CCF target stands only, we observed no significant differences in D_b between stands dominated by broadleaved tree species ($D_b = 2.334$), equally mixed conifers and broadleaved tree species ($D_b = 2.378$), and coniferous-dominated CCF target stands ($D_b = 2.374$). However, we found significant differences in D_b between even-aged stands dominated by Scots pine and Norway spruce ($p = 0.032$), as well as between Scots pine and European beech (Fig. 5a, and Tab, 4; $p < 0.001$).

Space filling was highest in the CCF target stands. We found significant differences to the primary forests ($p = 0.014$; Fig. 5b and Table 3), but on average not to the even-aged forests ($p = 0.056$, Fig. 5b and Table 3). Vertical evenness was significantly higher in the CCF target stands than in the even-aged forests ($p = 0.013$). However, no significant differences were found with the primary forests ($p = 0.851$), which had the highest vertical evenness. There were no significant differences in horizontal evenness between the primary forests, the CCF target stands, and the even-aged stands ($p = 0.856$; Table 3).

Vertical evenness was found to be highest in the CCF. They differed significantly from the even-aged stands ($p = 0.013$), but not from the primary forests ($p = 0.851$). The same results were found for skewness. It was highest in CCF target stands, indicating a right-skewed distribution with disproportionally filled lower stand layers. Even-aged forests were the opposite ($p < 0.001$): disproportional filling of the canopy layer was expressed by left-skewed distributions (Fig. 5c and Table 3).

Linking the two main components of the newly developed index, skewness and box dimension before weighting, resulted in a clear separation of CCF and even-aged stands (Fig. 6). The highest values for D_b were found in stands with skewness values near zero or a small deviation to right-skewed distributions, which was the case for the primary forests and most of the CCF.

3.2. ISC and ssci in different types of forest management

ISC differed by different management and forest types (Fig. 7a). The mean index-value was highest in the primary forests (PF = 0.799). Significant differences were found between primary forestsand even-aged forests (EA = 0.471, $p < 0.001$), but not between primary forests and CCF targest stands (CCF = 0.768, $p = 0.19$). ISC of the CCF target stands was also significantly higher than that of the even-aged stands ($p < 0.001$). There was no overlap of the ISC values between the even-aged forest stands (ISC max = 0.691) and the continuous cover target stands (ISC min = 0.0694). No significant differences were found between stands of the different tree species when considering the even-aged stands (Table 4). However, the even-aged stands dominated by beech and the mixed even-aged forests were not significanly different from the mixed and coniferous CCF (Table 4).

We found significant differences in stand structural complexity (SSCI) between CCF target stands (SSCI = 6.564) and even-aged forests (SSCI = 5.664; $p < 0.001$) and between primary forests (SSCI = 6.632) and even-aged stands ($p = 0.004$). There were no significant differences in SSCI between CCF target stands and the primary beech forests considered here (Fig. 7b).

Within the group of CCF target stands we found no significant differences in ISC. Thus comparable results were obtained for CCF target stands dominated by broadleaved tree species, those with equal mixes of broadleaved and conifer species, and stands dominated by conifers.

4. Discussion

4.1. Quantifying the target structure of ccf stands

In this study, we tested whether the structure of CCF stands in the target stage can be quantitatively separated from even-aged stands. We used three structural measures (D_b, space filling, and its skewness) derived from terrestrial laser scanning (TLS) and a TLS-based index (SSCI), which was introduced recently (Ehbrecht et al., 2017). We further tested a new index (ISC), which combines D_b and skewness of space filling. This index aims to integrate three main structural attributes: the box dimension, which quantifies stand structural complexity based on fractal analysis (Seidel 2018), the skewness of space filling, and stand height.

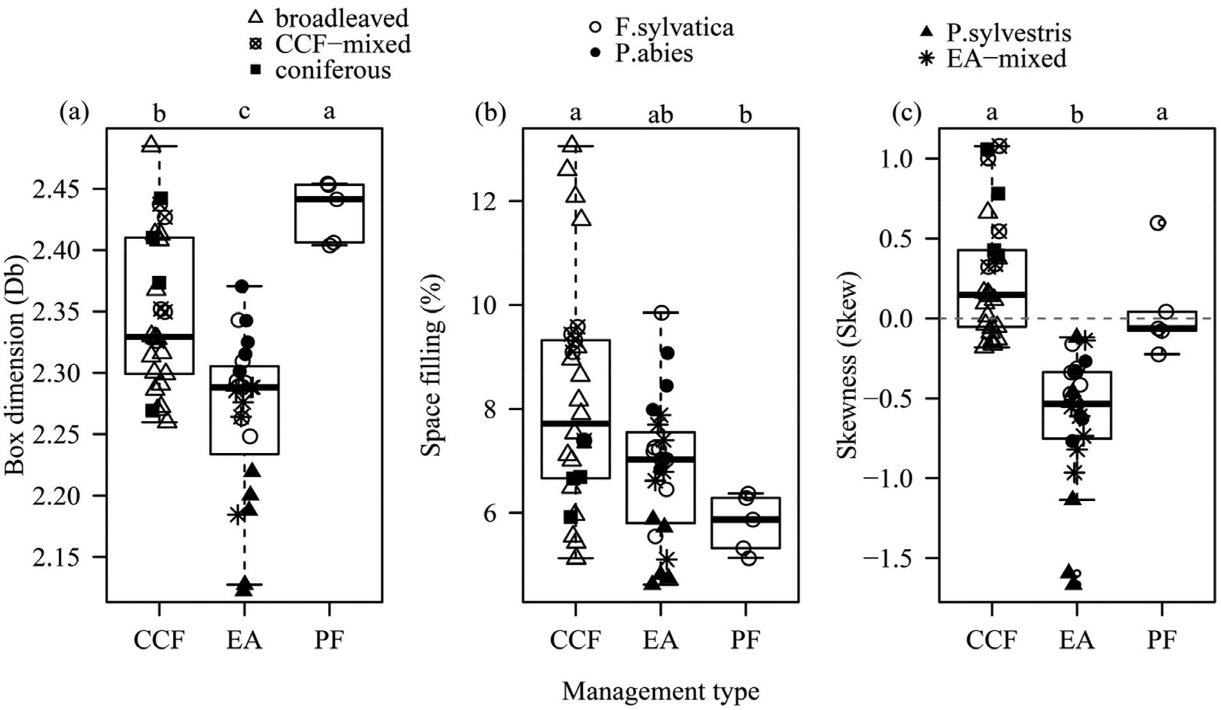

Fig. 5. Box-Whisker plots of box dimension (Db), relative space filling and skewness of different management types: continuous cover forests (CCF), even-aged forests (EA), and primary forests (PF). Black horizontal lines indicate the median. Lowercase letters indicate significant differences between the management types ($p < 0.05$). Sample sizes in CCF: $n = 26$, EA: $n = 24$, PF: $n = 5$.

Table 3
Descriptive statistics for box dimension (Db), relative space filling (SF), vertical (Ever) and horizontal (Ehor) evenness and skewness (Skew) of continuous cover forest target stands (CCF), even-aged forest stands (EA), and primary forests (PF). Min = minimum, Max = maximum, Var = variance, SD = standard deviation, CV = coefficient of variation. The lowercase letters indicate significant differences in the indices between management types ($p < 0.05$).

Type of Management	Index	Mean	Median	Min	Max	Var	SD	CV (%)
CCF	$\mathbf{D_b}$	2.35 ^{b}	2.33	2.26	2.48	0.063	0.004	2.69
	SF	8.23 ^{a}	7.72	5.12	13.06	2.223	4.942	27.02
	$\mathbf{E_{ver}}$	0.79 ^{a}	0.82	0.54	0.94	0.118	0.014	14.98
	$\mathbf{E_{hor}}$	0.96 ^{a}	0.96	0.92	0.98	0.020	0.000	2.05
	Skew	0.27 ^{a}	0.15	−0.18	1.08	0.384	0.148	143.86
EA	$\mathbf{D_b}$	2.27 ^{c}	2.29	2.12	2.37	0.064	0.004	2.84
	SF	6.84 ^{ab}	7.03	4.62	9.85	1.338	1.791	19.55
	$\mathbf{E_{ver}}$	0.67 ^{b}	0.72	0.35	0.91	0.148	0.022	21.98
	$\mathbf{E_{hor}}$	0.96 ^{a}	0.97	0.90	0.99	0.024	0.001	2.53
	Skew	−0.60 ^{b}	−0.53	−1.67	−0.12	0.404	0.163	−66.90
PF	$\mathbf{D_b}$	2.43 ^{a}	2.44	2.40	2.45	0.025	0.001	1.02
	SF	5.80 ^{b}	5.87	5.13	6.37	0.560	0.313	9.65
	$\mathbf{E_{ver}}$	0.83 ^{a}	0.83	0.78	0.90	0.043	0.002	5.23
	$\mathbf{E_{hor}}$	0.97 ^{a}	0.96	0.95	0.98	0.010	0.000	0.99
	Skew	0.06 ^{a}	−0.06	−0.22	0.60	0.318	0.101	576.88

Table 4
Mean values for Db, Space filling (SF), skewness, ISC, and SSCI for the different species compositions within and between management types. Lowercase letters indicate significant differences in the indices between management types ($p < 0.05$). For calculation of the SSCI in the even-aged and primary forests, single-scans were used. Therefore, only the beech forests were included in the analysis for EA, as the single-scans for the other tree species and compositions were not available.

Index	CCF broadleaved	CCF coniferous	CCF mixed	EA mixed	EA spruce	EA pine	EA beech	PF beech
Db	2.33 ^{b}	2.37 ^{ab}	2.38 ^{ab}	2.26 ^{b}	2.33 ^{b}	2.17 ^{c}	2.29 ^{b}	2.43 ^{a}
SF	8.38 ^{a}	6.66 ^{a}	8.97 ^{a}	6.92 ^{a}	7.88 ^{a}	5.16 ^{a}	7.20 ^{a}	5.80 ^{a}
Skew	0.06 ^{a}	0.66 ^{bc}	0.66 ^{c}	−0.64 ^{b}	−0.52 ^{bc}	−0.99 ^{a}	−0.39 ^{a}	0.06 ^{a}
ISC	0.76 ^{a}	0.79 ^{ab}	0.79 ^{ab}	0.44 ^{bc}	0.52 ^{c}	0.30 ^{c}	0.57 ^{bc}	0.80 ^{a}
SSCI	6.25 ^{a}	6.13 ^{a}	7.03 ^{a}	–	–	–	4.59 ^{b}	5.95 ^{a}

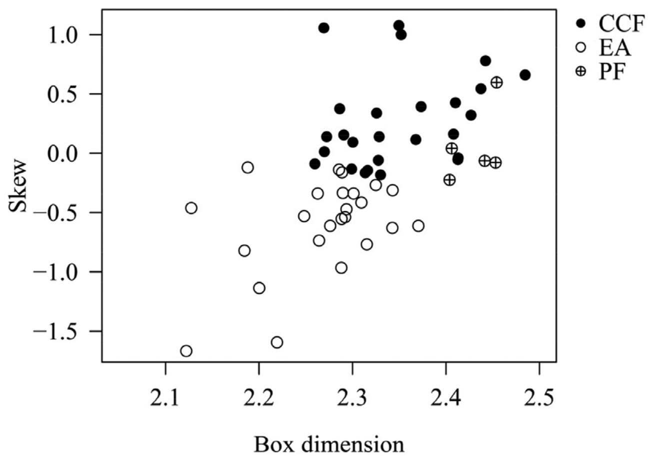

Fig. 6. Scatterplot of the Skewness over Box dimension. The different symbols mark the different management types investigated here. Sample sizes: CCF: $n = 26$, EA: $n = 24$, PF: $n = 5$.

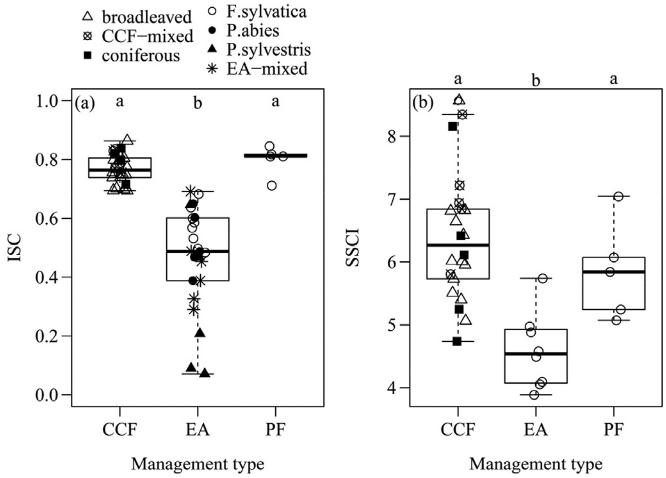

Fig. 7. (a) Box-Whisker plots of the index of structural constancy (ISC) (b) and stand structural complexity-index (SSCI) depending on management type and species composition: continuous cover forests (CCF), even-aged managed forests (EA), and primary forests (PF). Black horizontal lines indicate the median. Lowercase letters indicate significant differences between the management types ($p < 0.05$). Sample sizes in (a) CCF: $n = 26$, EA: $n = 24$, PF: $n = 5$. Sample sizes in (b) CCF: $n = 22$, EA: $n = 8$, PF: $n = 5$.

While the box dimension is a powerful tool and accounts for forest density, its disadvantage is that it cannot indicate in which direction the distribution of aboveground plant material deviates from a hypothetical even distribution in space. This disadvantage is compensated for by inclusion of the skewness of space filling into the index construction. Combining structural attributes is an appropriate way to reliably distinguish between different management types (Schall et al., 2018). As shown in Fig. 6, combining skewness of space filling with box dimension seems to be a suitable approach. According to McElhinny et al. (2005) every index for structural complexity should take a set of several stand structural attributes into account, which are then linked together as simply as possible in the index construction. The idea of using quantification of the structure of CCF target stands was based on the assumption that plant material is vertically homogeneously distributed in natural or near natural forests of the temperate zone, where light is the most limiting factor (Davi et al., 2008). This view follows Möller's (1922) early call for a state of equilibrium of plant material in space and time (Hofmann 2010). Thus, in any CCF target stand, plant material should be as homogeneously distributed as possible, irrespective of stand density.

Here we showed that the new index was able to distinguish quantitatively between forest management types, confirming our second hypothesis. It clearly separated CCF-target stands from EA-stands. SSCI also led to detection of significant differences between EA-forests and CCF target stands. However, in contrast to SSCI, the ISC values of the CCF target stands and those of the EA-stands did not overlap, which may make it possible to define a threshold value for a CCF target structures in the future (based on a larger database of scanned stands). The finding that mixed and beech-dominated EA-stands were not significantly different in ISC from the coniferous CCF indicates that they may already be in a state of transition between traditional and continuous cover management. This can also be seen in Fig. 6, which shows slightly overlapping boundaries of the different management systems for non-weighted D_b and skewness of space filling.

The ISC describes the resemblance of a forest to a spatially evenly distributed stand based on a simple measure ranging between zero and one. The index would tend towards zero in forests with strong dominance of a single vertical stand layer, such as single-layered "vault-like" forests without any understory. A different example of low values would be thickets with only scattered overstory-trees. If there were no overstory-trees left in the latter, the Chapman-Richards function of the weighted height would reduce the resulting index value. The lowest index values in this study were found in single-layered monocultures of Scots pine (ISC = 0.071; 0.090; 0.208). The highest index value was found in a CCF stand in Lensahn (ISC = 0.863). This indicates a fairly homogeneous vertical and horizontal distribution of plant material with slight disproportionality in space filling of the lower stand layers in the latter stand (Fig. 5, 6 and Fig. 7a).

We found no significant differences within the CCF stands irrespective of the dominant class of species (coniferous versus broadleaved). However, all CCF stands investigated here are mixed stands, which are known to have higher structural complexity (Juchheim et al., 2019) than pure stands, most likely because of complementary spatial niche occupation (Pretzsch 2014; Ammer 2019). Establishing and maintaining a certain degree of mixture is an essential part of silvicultural concepts such as "close-to-nature" or "continuous cover" (Brang et al., 2014; Schütz 2002, and Pommerening and Murphy 2004). Nevertheless, shade-tolerant tree species such as European beech can develop complex structures even in pure stands. This is seen in the high values of the primary forests, composed of more than 95% beech, and the even aged-pure beech stands of our study, neither of which differed significantly in their mean ISC values from that of the coniferous CCF target stands.

4.2. *Structural elements of ccf target stands*

As can been seen from Fig. 5, it is not space filling that makes the CCF target stands and primary forests similar to one another and different from the EA-forests, but the skewness of space filling with respect to the D_b (Fig. 6). This is underscored by the finding that space filling of the primary forests was significantly lower than that of the CCF target stands. Overall, CCF target stands and primary beech forests showed much less deviation from homogeneously distributed space filling than EA-stands (Fig. 4 and Table 2). In contrast to the EA-stands, neither CCF target stands nor primary beech forests were significantly different in the mean deviation of space filling from an evenly homogenous distribution of plant material, confirming our first hypothesis. The EA-stands, however, differed not only in the degree of deviation of plant material (here voxels) but also in the 'direction' of deviation (see Fig. 4 and Table 2).

Interestingly, CCF target stands could be statistically significantly distinguished from EA in a number of tested structural measures. D_b, Gini-coefficient, skewness and coefficient of variation of space filling between the vertical layers and vertical evenness values differed between management types (Table 3). The lowest values in both D_b

and space filling were found in even-aged monocultures of Scots pine. These stands were located outside the 75%-quantile of the CCF target stands and differed significantly in structure from the latter. The same was found for skewness of space filling (Fig. 5c). While even-aged Scots pine forests differed from CCF target stands in all structural indices considered here, D_b and space filling of even-aged monocultures of Norway spruce overlapped somewhat with the values of CCF target stands (Fig. 5a and 5b). This may be attributed to the higher foliage density and crown length of Norway spruce, which is more shade-tolerant than Scots pine. In the case of even-aged Norway spruce stands, skewness was decisive for separation from the CCF target stands (Fig. 5c). This also applied to the mixed EA-stands and EA-forest stands dominated by European beech. The skewness-values of the even-aged forests were exclusively negative. This indicated single-layered stands with clear dominance of the upper canopy layers. In contrast, the mean positive skewness of the CCF target stands reflected the multi-layered nature of CCF target stands (Table 3; , Zingg 2003Guericke and Gaffron, 2010). Thus, skewness is a suitable measure to distinguish the structure of CCF target stands from even-aged forest stands.

D_b, space filling and skewness were highly variable between CCF study areas (Fig. 5 and Table 3). This can be explained in part by the structural differences in the tree species involved, but there are also large variations between forests composed of single species. Apart from species-based variability, therefore, this could be an indication of a heterogeneous horizontal structure. However, in our stands this was not the case since variation in horizontal evenness within CCF target stands was low (Table 3). We found no significant differences at the horizontal level between management types, which was unexpected; numerous authors had identified horizontal heterogeneity as an important structural property of CCF (Kraut 2010; Stähr and Müller 2010). It may be, therefore, that we were not able to capture horizontal heterogeneity adequately in this study. We assume that a reliable estimation of this structural measure would have required larger plots than the 40 × 40 m used here.

5. Conclusions

In this study, we confirmed numerous structural characteristics of CCF target stands that had been addressed by others as well. Most of the CCF target stands showed only a small right skewed deviation from the homogeneous vertical distribution of biomass, and this was in favor of the lower stand layers. This means that the stands are multi-layered. This structure is in part the outcome of competition within cohorts of the same age, but also results from ongoing regeneration processes leading to different age classes occurring next to each other, as noted in Möller's (1922) concept.

It seems as if ISC, the new index suggested here, is a suitable tool to objectively quantify the specific forest structures of CCF target stands that distinguish them from even-aged stands. This study has once again highlighted the enormous range of possible applications of TLS. We are not aware of any other methods that provide objective and quantitative data on the vertical and horizontal spatial distributions of plant material. Therefore, in future studies of forest structures and their structural complexity, TLS will play an important role in obtaining detailed and objective data.

Comparing the three-dimensional structural complexity of CCF target stands and the European beech primary forests considered here, it can be concluded that the CCF concept can lead to structural complexity similar to that of natural, i.e., unmanaged European beech forests. It is assumed that structural complex forests are more resilient to climate change (Brang et al., 2014), but this remains to be seen (O'Hara 2016). Moreover, several studies suggest that structural diversity is a main driver of stand productivity (Hardiman et al., 2011; Ishii et al., 2004, and Dănescu et al., 2016) which can make CCF stands, once they have reached their target structure, a useful approach to forest management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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