



Trend to increasing structural diversity in German forests: results from National Forest Inventories 2002 and 2012

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Received: 12 May 2017 / Accepted: 14 November 2017 / Published online: 12 December 2017
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Abstract

• **Key message** Six structural diversity indices were calculated from the German 2002 and 2012 National Forest Inventory (NFI) data. We found a slight trend of increasing structural diversity in German forests both for broadleaved and coniferous stand types. The results correspond well with current findings in forest ecology and silviculture and might serve as an initial step for further refinement of NFI analyses.

• **Context** Structural diversity, i.e., the variability in forest stand structures, is an integral part of current forest ecology discussions. We addressed the question of whether the scope of the German National Forest Inventory (NFI) can be widened by evaluating structural diversity indices. Diversity indices are neither an explicit subject of the current NFI protocol nor have they been derived from NFI data yet.

• **Aims** Six spatially inexplicit indices were applied to NFI data and methodologically discussed. An initial contribution for further methodological refinement of the NFI should be provided. Using these indices, changes in structural diversity between 2002 and 2012 were subsequently quantified and discussed.

• **Methods** Mean values and changes of the diversity indices were calculated for indicative forest stand types using tree data from angle count sampling. Estimation techniques for single stage cluster sampling were applied.

• **Results** With few exceptions, the results showed slight increases for each index and stand type. The results correspond well with current findings in forest ecology and silviculture and supplement published results of the NFI.

• **Conclusion** The indices proved to be appropriate within the framework of the NFI. This study should be considered as a cornerstone that supplements published results of the German NFI. It might be helpful within future discussions about structural diversity in German forests.

Keywords National Forest Inventory · Species profile index · Diameter differentiation · Shannon index · Angle count sampling · Biodiversity · Stand structure · Diversity indices

Handling Editor: Erwin Dreyer

Contributions of the co-authors Christoph Fischer: Data analysis and writing of the manuscript.
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1 Introduction

Decision-making processes require the availability of appropriate input information. In forestry, this information is usually obtained by forest inventories. These inventories aim at estimating means and totals of forest characteristics within a defined area. The underlying spatial units can range from a single forest stand to large-scale entities such as landscapes or national territories. While forest inventories on the levels of single stands or forest districts mainly serve for planning and management purposes, large-scale forest inventories provide essential information for decision processes within the framework of forest and environmental policy.

National Forest Inventories (NFI) were originally established for the estimation of forest resources, i.e., forest area, woody biomass, increment, and changes in timber volume on the level of national territories. However, a growing number of international agreements and commitments led to increasing information needs, resulting in frequent reporting requests and in reports with extended content (Tomppo et al. 2010). An issue that has become particularly important, in line with the *Convention on the Biological Diversity* (CBD, signed in 1992), is the assessment of forest biodiversity. Examples of relevant parameters that might be assessed by forest inventories are dead wood volume, shrub species, naturalness of the tree species composition, and structural diversity, i.e., the variability in stand structures (Winter et al. 2008; Chirici et al. 2011; Sabatini et al. 2015).

Forest structural diversity can be characterized by three components: tree species composition, the spatial distribution of trees, and variations in tree size (Pommerening 2002; McRoberts et al. 2010). Following the environmental heterogeneity hypothesis (Huston 1994), a pronounced structural complexity in forest stands (i.e., the heterogeneity of horizontal and vertical stand structures) can be expected to result in an increase of both forest biodiversity and woodland species population density. The main driving mechanism behind this process is the increasing diversity of ecological niches and food resources (McCleary and Mowat 2003; Jung et al. 2012; Bouvet et al. 2016).

Structural complexity, however, is a relative rather than absolute concept, and McElhinny et al. (2005) stress that uniformly high levels of structural attributes will not maximize biodiversity, since the presence of stands with naturally simple structures can increase the diversity of habitats at the landscape level. Furthermore, an increased heterogeneity of horizontal and vertical stand structures is linked to greater ecological stability, particularly in terms of resistance against biotic and abiotic disturbances (Scherer-Lorenzen et al. 2005; Knoke et al. 2008; Thompson et al. 2009). As recent studies show, structural diversity can also be a factor that promotes the productivity of mixed, often uneven-aged forest stands (Dănescu et al. 2016; Liang et al. 2016; Pretzsch et al. 2016).

Several indices were developed for quantifying structural diversity in forestry. The most relevant measures were summarized and discussed by Pommerening (2002) and Pretzsch (2009). Traditionally, diversity indices have been key variables in studies dealing mainly with forest structure at the stand level (e.g., Varga et al. 2005; Sterba and Zingg 2006). Recently, there is an increasing demand for large-scale biodiversity information so that methodological aspects of structural diversity assessment in forest inventories have been addressed in several studies (Pommerening 2002; Sterba 2008; Motz et al. 2010). Examples of applications in this field are presented in studies by McRoberts et al. (2008), Lei et al. (2009), or Alberdi et al. (2014).

In Germany, the first sample-based National Forest Inventory (NFI 1) was conducted in 1987. However, it was limited to the ten federal states of former West Germany. In 2002, after the German reunification, the second National Forest Inventory (NFI 2) was conducted throughout all 16 federal states. This inventory was repeated in 2012 (NFI 3) and the present NFI scheme is aimed at repeated inventories in 10-year intervals. The database of the German NFI allows for numerous evaluations, such as status and changes of the forest area, coverage of tree species, regeneration, growing stock, increment, timber harvest, and deadwood volumes (Thünen-Institut 2014). The NFI was originally designed for estimating timber stocks and the forest area. In order to account for various ecological developments, the methodology has been continuously adapted (Polley et al. 2010; BMEL 2014a), so that most of the 16 key variables for biodiversity assessment defined by Winter et al. (2008) are already included. Structural diversity indices, however, are neither an explicit subject of the current NFI protocol nor have they been derived from NFI data yet.

Our objective, therefore, is twofold. First, we present six appropriate and easy-to-calculate measures for describing structural diversity that can be applied within the current framework of the German NFI. This step should be considered as an initial contribution for further methodological refinement of the NFI with respect to the assessment of structural diversity. Secondly, we apply the selected structural diversity measures to indicative stand types using individual tree data from NFI 2 and NFI 3. By doing this, changes in the structural diversity in German forests within the 10-year period between 2002 and 2012 can be quantified. The results obtained should serve as one component of an evidence base and might be considered within future key discussions on biodiversity in German forests.

2 Material and methods

2.1 Data

The data used for this study was drawn from the second and third NFI in Germany (Thünen-Institut 2015). The second inventory (NFI 2) was carried out between 2001 and 2003 and this was repeated between 2011 and 2013 (NFI 3). The NFI is a cluster sample with permanent sample plots. The sample plots are arranged in a 4-km square grid which is based on the Gauß-Krüger coordinate system. In several regions, the grid is 2.83×2.83 km or $2 \text{ km} \times 2 \text{ km}$ in size. Accordingly, the NFI consists of three strata differing in sampling density. Each sample plot consists of a square with sides of 150-m length, where the south-west corner of each square is the intersection point of the grid. If one corner of the square is forested (according to the forest definition of the German NFI; see

Polley et al. 2010), that corner becomes the center of a subplot (=cluster) and data for different objects are recorded. Trees ($dbh \geq 7$ cm) are surveyed by means of the angle count sampling method with a basal area factor of $4 \text{ m}^2 \text{ ha}^{-1}$. Tree species, dbh, age, stand layer, and the base-of-the-trunk coordinates are recorded for each monitored tree. Tree height is measured for a subsample of trees and the heights of the remaining trees are derived from standard height curves. We refer to Polley et al. (2010) for detailed methodological information about the German NFI and for further relevant literature.

For the present study, we selected only subplots which contained sample trees both in NFI 2 and NFI 3. A stand type was assigned to each subplot using the tree data from NFI 2. Depending on the dominant species, we defined six groups of stand types: beech type (*Fagus sylvatica*), oak type (*Quercus* spp.), other broadleaved type, spruce type (*Picea* spp.), pine type (*Pinus* spp.), and other coniferous type. The dominant species was defined as the species with the highest proportion by total basal area per subplot. The number of subplots per stand type is displayed in Table 1.

2.2 Diversity measures

Several of the commonly used indices to assess structural diversity in forestry require explicit spatial information. That means that the positions of the neighboring trees of a given reference tree need to be known. Since tree data in the German NFI stem from angle count sampling, it was not possible to calculate spatially explicit indices. We therefore focused on six spatially inexplicit measures to describe tree species diversity, heterogeneity in vertical stand structure, and variability in tree diameters. For the NFI, 87 different tree and shrub species are distinguished (e.g., eight types of pines). In order to obtain a more comprehensive classification, we aggregated species of the same genus resulting in a list of 42 species groups. In the following, “species” will refer to these designated species groups.

As a simple measure for tree species diversity, we first calculated the number of tree species, i.e., tree species richness *SR*, per subplot.

The Shannon index H' (Shannon and Weaver 1948) was used as the second measure for describing species diversity. In contrast to the number of species, this index is more detailed with respect to the proportion of each species in a given population:

$$H' = - \sum_{s=1}^k p_s \ln p_s \quad (1)$$

where p represents the s -th species' proportion of the total basal area per subplot and k is the number of species. If there

Table 1 Number of subplots per stand type containing sample trees both in NFI 2 and 3. Beech stand type: *Fagus sylvatica*, oak stand type: *Quercus* spp., other broadleaved type: all other broadleaved tree species, spruce stand type: *Picea* spp., pine stand type: *Pinus* spp., other coniferous type: all other coniferous tree species

Stand type	Subplots
Beech	8257
Oak	4640
Other broadleaved	5977
Spruce	13,656
Pine	10,116
Other coniferous	3617
All types	46,263

is only one species recorded on the subplot, the Shannon index H' takes the value zero. For k species with equal proportions, H' corresponds to $\ln(k)$.

Based on the Shannon index, Pretzsch (1996) developed the species profile index A . This measure summarizes both species diversity and vertical spatial occupancy. In its original form, the index requires tree height as one input variable. Since height values are not measured for the majority of trees in the NFI but estimated from dbh-based height curves, we used stand layer as the input variable instead. Stand layer is categorical and can take three values: main story (economically most important stand layer), lower story (beneath the main story), and upper story (above the main story). The modified species profile index is then defined as

$$A = - \sum_{l=1}^z \sum_{s=1}^k p_{ls} \ln p_{ls} \quad (2)$$

with l being the index for the stand layer and z being the number of stand layers per subplot. A is equal to the Shannon index, if there is only one stand layer. From Eq. (2), it becomes obvious that any deviation from a single-layered pure stand results in an increase of A .

As a second measure for vertical structure, we calculated the number of stand layers per subplot.

The coefficient of variation of the tree diameters CV is frequently used to quantify tree size diversity within a stand (Pretzsch 2009).

$$CV = \frac{\sqrt{\frac{1}{n-1} \sum (dbh_i - \overline{dbh})^2}}{\overline{dbh}} = \frac{s_{dbh}}{\overline{dbh}} \quad (3)$$

CV is zero if all trees have identical diameters, while increasing values for CV indicate an increasing variation in tree diameters.

Following Sterba (2008), we used the *skewness* to characterize the symmetry of the dbh distribution:

$$skewness = \frac{1}{n-1} \frac{\sum (dbh_i - \overline{dbh})^3}{s_{dbh}^3}. \quad (4)$$

Positive values indicate a right-skewed distribution, which is rather typical for uneven-aged stands, while homogenous stands usually follow a symmetric distribution. The underlying assumption is that uneven-aged stands are characterized by a higher structural diversity than homogeneous stands. As Sterba (2008) noted, *skewness* is appropriate to monitor the shift from even-aged management to the uneven-aged individual tree selection system.

For the calculations of *CV* and *skewness*, the represented stem number of each sample tree i per hectare n_{rep} was considered according to the methodology of angle count sampling (BAF = 4), that is $n_{rep} = BAF / (dbh_i^2 \cdot \pi / 4)$.

2.3 Estimators

The diversity measures presented above were calculated for each subplot of the sample. The standard estimation techniques for the German NFI are based on Cochran (1977) and have been thoroughly compiled by Dahm (2006) and Polley et al. (2010). For obtaining mean values and variances for both NFI 2 and NFI 3, we strictly followed this methodology. The mean value of the variable of interest per stratum (area with equal sampling density) h is

$$\bar{x}_h = \frac{1}{m_h} \sum_{i=1}^{n_h} \sum_{j=1}^{m_i} x_{hij} \quad (5)$$

where m_h is the total number of subplots within the forest in stratum h , n_h is the number of sample plots within the forest in stratum h , i is the index for the sample plot, and j is the index for the subplot. Note that

$$m_h = \sum_{i=1}^{n_h} m_{hi} \quad (6)$$

where m_{hi} is the number of subplots within the forest in sample plot i in stratum h .

The total mean is then obtained by weighting the strata mean values

$$\bar{x} = \sum_{h=1}^L W_h \bar{x}_h \quad (7)$$

with

$$W_h = \frac{A_h}{A} \quad (8)$$

where L is the number of strata, A_h is the area of stratum h , and A represents the total land area of Germany. These values were taken from official statistics and are assumed to be error free (Polley et al. 2010).

The variance of the total mean is estimated by

$$v(\bar{x}) = \sum_{h=1}^L W_h^2 \frac{1}{m_h^2} \frac{N_h}{N_h-1} \sum_{i=1}^{n_h} (x_{hi} - \bar{x}_h m_{hi})^2 \quad (9)$$

where N is the total number of sample plots (forest and non-forest).

Changes in diversity measures between NFI 2 and NFI 3 were tested for statistical significance ($\alpha = 5\%$). In doing so, we calculated the change z of the mean values

$$z = \sum_{h=1}^L W_h (\bar{x}_h'' - \bar{x}_h') \quad (10)$$

with \bar{x}_h'' being the estimated mean value in stratum h for NFI 3 and \bar{x}_h' being the estimated mean in stratum h for NFI 2 according to Eq. (5).

The variance of the change is defined as:

$$v(z) = \sum_{h=1}^L W_h^2 \left(v(\bar{x}_h'') + v(\bar{x}_h') - 2\text{cov}(\bar{x}_h'', \bar{x}_h') \right). \quad (11)$$

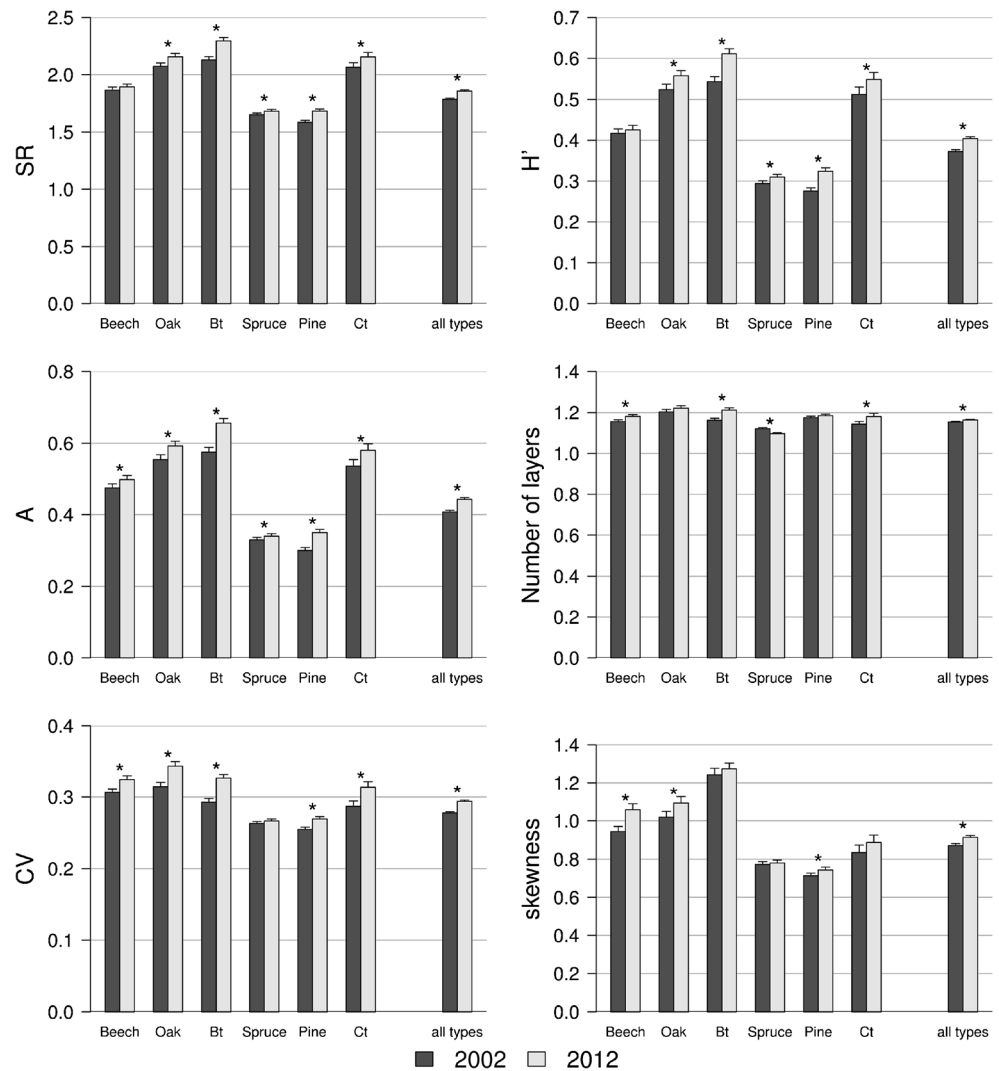
Subsequently, we used $v(z)$ to calculate the 95% confidence interval for z . If the interval did not include the value zero, z was assumed to be different from zero with an error probability of 5% and hence changes in \bar{x} were found to be statistically significant.

Estimations were conducted for both the whole sample and for each subsample (stand type) separately (Table 1).

3 Results

Species richness (*SR*) and Shannon index (*H'*) were higher in broadleaved-dominated forests than in coniferous forests (Fig. 1). With the exception of beech stands, each stand type showed an increase in *SR* and *H'*. Taking into account the vertical occupation pattern (*A*, number of layers), beech forests also revealed a slight increase, while the number of layers in pine stands seemed to remain unchanged. The comparatively low values for *A* in both spruce and pine forests confirmed that the proportion of monospecific and single-layered stands in these forest types was usually higher than in other types. The variation of tree diameters (*CV*) increased in all stand types except in spruce stands. The heterogeneity of diameters, however, tended to be higher in broadleaved stands than in stands dominated by coniferous species. A similar pattern was observable for *skewness*. It ranged from about 0.8 (spruce and pine) to 1.2 (broadleaved stand types), meaning that the

Fig. 1 Mean values and standard errors of the presented diversity indices in German forests by stand type (see Table 1), as well as for the whole sample (all stand types). Bt: all other broadleaved tree species; Ct: all other coniferous tree species. *Significant changes between 2002 (NFI 2) and 2012 (NFI 3) with a probability of error equal to or less than 5%



distributions of tree diameters in all stand types were slightly right skewed, although broadleaved forests tended more to indicate patterns that are typical for uneven-aged stands. While *skewness* tended to increase in each forest type, statistical significance was only given in beech, oak, and pine stand types. When considering all stand types together, each of the six indices showed a slight, but statistically significant, increase.

Correlation was found to be high between indices that use species number as a common input variable. This held for *SR*, *H'*, and *A* (Table 2). The number of layers was consistently correlated to *A* (0.4) but still showed a higher correlation to *CV* (0.52), indicating that with increasing vertical mixture, the variability in tree diameters becomes higher. Correlations of *CV* and *SR* or *H'*, respectively, indicated a positive effect of species diversity on diameter heterogeneity. *Skewness* seemed to be independent from the number of layers (0.08) but was moderately positive correlated to each of the remaining parameters (0.22 to 0.51).

4 Discussion

4.1 Methods

For the six selected stand types, we obtained reliable estimations of mean values showing standard errors of at most 4%. There are numerous examples for the use of *SR* (Alberdi et al.

Table 2 Pearson correlation coefficients between the presented diversity measures. *SR*: tree species richness, *H'*: Shannon index, *A*: species profile index, *CV*: coefficient of variation of tree diameters

	<i>SR</i>	<i>H'</i>	<i>A</i>	Number of layers	<i>CV</i>
<i>H'</i>	0.95				
<i>A</i>	0.91	0.95			
Number of layers	0.27	0.25	0.40		
<i>CV</i>	0.36	0.36	0.46	0.52	
<i>Skewness</i>	0.22	0.25	0.31	0.08	0.51

2014), H' (Motz et al. 2010), A (Lei et al. 2009), CV (Sterba and Zingg 2006), or *skewness* (Sterba 2008) for characterizing structural diversity using forest inventories. Due to the comparatively high number of related examples and the fact that these indices are deemed to be proven (see literature cited above), we consider the selected measures as suitable for an application within the framework of the German NFI. They allow for an objective description of structural diversity as an indicator of forest biodiversity (Huston 1994). For further interpretation, however, one should consider that some indices (H' , A) rather represent entropies but not the true diversity in the sense of biologists' theoretical or intuitive concept of diversity (Jost 2006). Additionally, it may be of interest to include the spatial patterns of the indices in future analyses, taking into account that they might respond differently at regional scales (e.g., McRoberts et al. 2008).

Since tree data stemmed from angle count sampling and thus the true neighborhood relationships of the sampled trees were unknown, only spatially inexplicit measures could be considered. The main advantages of these indices are that they are easy to calculate and that edge effects (i.e., a potential neighbor of a tree lies outside the sample) need not be taken into account (Pommerening 2002). On the other hand, spatially explicit measures would allow for a wider range of evaluation possibilities and thus provide more detailed information in terms of spatial patterns and neighborhood relationships. Frequently used indices are, for example, Pielou's index of segregation (Pielou 1961), the mingling index (Füldner 1995), the aggregation index (Clark and Evans 1954), the mean directional index (Corral-Rivas 2006), the uniform angle index (von Gadow et al. 1998), or the diameter differentiation index (Füldner 1995). In the context of the current protocol of the German NFI, the application of spatially explicit measures would require the additional assessment of the neighboring trees for each sample tree. As only some of the identified neighbors fell into the angle count sample, the additional recording of the remaining trees would be laborious and time-consuming. Taking into account a total of about 480,000 sample trees in the NFI 3 throughout all Germany, the costs of the inventory would increase considerably. Sterba (2008) provided an approach to reduce the measurement effort by means of assessing only the nearest neighbor of each sample tree, irrespective if that neighbor is part of the angle count sampling. As Sterba (2008) argued, this approach does not serve for indices related to groups of neighbors, but does permit an evaluation of some additional spatially explicit indices, such as the segregation index, the aggregation index, or the diameter differentiation index. Further, Sterba (2008) found that the aforementioned derived indices only show a low correlation with spatially inexplicit measures (CV , *skewness*) and therefore seem to provide additional information. With that in mind, Sterba's approach seems suitable if future adaptations of the NFI methodology focus more on the evaluation of

structural diversity. However, several aspects such as the duration of additional surveys and the resulting costs have to be questioned.

Parameters SR and H' were highly correlated (0.95), meaning that one index does not provide additional information if the other one is already considered. This is plausible, because species number is the common input variable in both measures. Nevertheless, we think it worthwhile to display both indices side by side, because SR is intuitive and much easier to interpret but H' takes into account the species proportions, making it more reasonable from the methodological point of view. The same argument holds when considering A and the number of layers. For the calculation of A , we recommend the modified form presented here using the stand layer to which the tree belongs as an input variable. In its original form, A is derived by assigning each tree to a stand height zone depending on the individual tree height (0–50, 50–80, and 80–100% of the maximum tree height; Pretzsch 1996). Note that, in the NFI, height for the majority of the sample trees is estimated by dbh-based height curves, meaning that the division of the height zones merely reflects the underlying dbh distribution. In contrast, stand layer is assessed for each sample tree and should therefore be preferred as it is a reliable input variable. The missing tree height measurements meant that the coefficient of variation of tree heights (analogous to CV) could not be calculated. This is a useful index for describing the vertical structure if sufficient tree height measurements are available (e.g., Varga et al. 2005).

We also found moderate positive correlations between heterogeneity of tree diameters (CV) and species diversity (SR , H'). This seems plausible, because ecological characteristics differ between species and, consequently, species mixing leads to an increasing occupation of ecological niches. CV also showed a moderate positive correlation with *skewness*. This means that right-skewed diameter distributions, which rather characterize uneven-aged stands, seem to be associated with a higher variation of tree diameters. Interestingly, the coefficient of correlation between both indices (0.52) is almost the same as the one determined by Sterba (2008) for a forest district in Austria (0.53). As pointed out by Sterba (2008) and Alberdi et al. (2014), the combination of CV and *skewness* can also provide useful information for distinguishing between different forest management regimes. These indices should therefore be part of further evaluations.

4.2 Results

For the German forests, our findings showed a slight but statistically significant increase for each of the six diversity indices. Forests seem to become more diverse in species composition (SR , H'), in vertical structure and vertical occupation patterns by tree species (A , number of layers) and in tree diameter variation and uneven-agedness (CV , *skewness*). Even

when considering each stand type separately, a slight increase could be observed in most cases, with very few exceptions. This seems remarkable in light of the fact that the length of the observation period between NFI 2 and NFI 3 is only 10 years and, thus, comparatively short for detecting changes in the tree layer. Since the survey instructions for the assessment of living trees (by angle count sampling) did not change between NFI 2 und NFI 3, any effect of differing methodology on the results can be excluded.

When analyzing the causes of shifting trends in forest structural diversity, it is of major interest to consider driving factors such as silvicultural treatment type, management history (including stand origin), stand development stage, or occurrence of natural disturbances between the sample periods. The German NFI data, however, does not contain explicit plotwise information about these factors. Evaluations are therefore necessarily descriptive and can hardly be carried out by determining partial effects in the sense of a controlled experiment (e.g., comparing groups of certain stand types with and without silvicultural treatment; cf. Leuschner et al. 2009). However, the obtained results provide essential information and can be related to general developments in German forests as well as current silvicultural concepts.

Our findings both confirm and supplement the results of the NFI compiled by the German Federal Ministry of Food and Agriculture (BMEL 2014b) and the Thünen Institute (Thünen-Institut 2014). Accordingly, the area of mixed-species stands (+ 5%), as well as that of two-layered or multilayered stands (+ 28%), increased between 2002 and 2012 in the German forests. This is in line with the observed increases in *SR*, *H'*, *A*, and number of layers for the majority of stand types and the overall average. Further, the comparatively low values for *A*, *CV*, and *skewness* in conifer-dominated forests indicate that the proportion of even-aged and less structured stands is higher than in deciduous forest types. According to the results of the NFI 3, 12% of the deciduous forests in Germany are monospecific stands and 25% are single-layered, whereas for coniferous forests, the proportions of monospecific and single-layered stands are 23 and 37%, respectively.

The changes of *CV* and *skewness*, especially for beech and oak stand types, seem to reflect the observed increase in the proportion of older forests, hence the number of trees with larger diameters. For oak, for example, the number of trees with diameters larger than 60 cm has increased about 40% and for beech about 30% between NFI 2 und NFI 3. It is known that the number of microhabitats is generally higher for thicker trees (Bütler et al. 2013), so that these results may be regarded as an important message with respect to the contribution of forests to biological diversity. Only for stands dominated by Norway spruce does the diameter variation remain unchanged. This might be explained by the age class

distribution of spruce forests in Germany, with a maximum between 40 and 80 years. Since current management objectives aim to reduce coniferous monocultures, the area of Norway spruce has declined to about 240,000 ha (− 8%) between 2002 and 2012. Intensive harvest of stands within the economic relevant age interval (40–80 years), large windfalls caused by the hurricanes “Kyrill” in 2007 and “Emma” in 2008, and a decrease of spruce regeneration are probably the driving factors preventing an increase of the diameter variation for spruce. A similar pattern might be expected for Scots pine, which is also affected by forest conversion programs and shows a similar age distribution to spruce for historical reasons (e.g., large-scale afforestations after the Second World War). However, due to its longer rotation period (~ 100–120 years), the pine stands are transformed at a slower rate. This assumption is supported by the fact that the area of pine has decreased only slightly (− 3%) compared to Norway spruce. However, in contrast to Norway spruce, the growing stock is still increasing (+ 7%).

When looking in detail at the changes in the structural diversity of beech and oak stand types between 2002 and 2012, the results correspond well with current findings in forest ecology and silviculture. With regard to oak forests, the common application of silvicultural schemes that aim at maintaining a permanent canopy cover is fostering the regeneration of shade-tolerant tree species, but constraining the regrowth of oaks. Hence, tree species such as beech, hornbeam, limes, and maples spread out in many oak-dominated forest stands and lead to an increase in tree species richness and structural diversity (von Lüpke 1998; Götmark 2007; Härdtle et al. 2005; Ligot et al. 2013). Since the main tree layer, however, frequently consists of older oaks, the number of stand layers does not increase significantly (Hauck 2016). With regard to beech stand types, the competitive strength of *F. sylvatica* commonly prevents any increase in tree species diversity (Mölder et al. 2014). So, the rise of structural diversity between 2002 and 2012 may be mostly attributed to silvicultural measures that have diversified the stand structure merely with regard to beech (Wagner et al. 2010; Heinrichs et al. 2012). To a lesser extent, increasingly successful natural beech regeneration due to frequent masting years and high anthropogenic N deposition may also be held responsible for this development (Paar et al. 2011; Dirnböck et al. 2014).

With regard to the pine and spruce stand types, the results might indicate not only the common vulnerability of spruce stands in terms of storm damages (cf. Schütz et al. 2006) but also the successful silvicultural practice of converting coniferous monocultures into mixed stands. This practice, which is a vital component of integrative, multifunctional, and close-to-nature forest management

programs, aims at increasing the stability, species and structural diversity, and health of forests while maintaining timber production (Bieling 2004; Knoke et al. 2008; Borrass et al. 2017). Since conifer monocultures are commonly diversified by admixing deciduous tree species, particularly beech, a gradual development towards more natural forest types is to be expected at most sites (Budde et al. 2011; Vrška et al. 2016).

Several recent studies (e.g., Nadrowski et al. 2010; Jung et al. 2012; Mölder et al. 2014) support the assumption that tree species richness and structural diversity in Central European forests have several direct and indirect effects on the species composition and diversity of other organism groups, such as vascular plants, insects, or bats. The concrete nature of the interactions involved, however, is not always clear and deserves further research (Normann et al. 2016; Ujházy et al. 2017). Keeping this in mind, we hypothesize that the observed trend to increasing structural diversity in German forests may influence the diversity and community patterns of several forest plant and animal species.

5 Conclusions

The diversity measures selected in the present study proved to be practical evaluation tools within the current framework of the German NFI. Our objective was not to elaborate a full methodical concept for the assessment and the evaluation of forest structural diversity as a complement of the existing NFI protocol. This would have exceeded the scope of our paper and should be investigated in detail by the institutions supervising the NFI. Nevertheless, the methodological part of the present work might serve as an initial step for further refinement with respect to the evaluation of forest structure and composition by means of the NFI.

Our evaluation should be considered as a cornerstone that supplements and supports published results of the German NFI and might serve as an evidence base within discussions about structural diversity in German forests. Results of the NFI 4 will be available in 2022, so that future analyses will be of interest in order to ascertain if the tendencies presented above can be confirmed.

With very few exceptions, our results showed slight increases in the selected diversity indices for each stand type between 2002 and 2012. The conclusion might be drawn that structural diversity in German forests tends to increase due to two driving factors that overlap: (1) current forest management paradigms and regimes and (2) forest stand dynamics.

Acknowledgements We are indebted to three anonymous reviewers and to editor Erwin Dreyer for suggestions that have greatly improved the

paper. Furthermore, we thank Peter Meyer for valuable comments on an earlier draft of this article and Robert Larkin for language polishing.

Statement on data availability The datasets analyzed during the current study are available in the German National Forest Inventory repository, <https://bwi.info/Download/de/BWI-Basisdaten/>.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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